# Regime transition identification for water utilization in river basin developments

**Shuang Song**[a, b], **Shuai Wang**[a, b, 1], **Bojie Fu**[a, b], **and Xutong Wu**[c, d]

[a] State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, P.R. China ; [b] Institute of Land Surface System and Sustainability, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, P.R. China ; [c] College of Urban and Environmental Sciences, Peking University, Beijing 100871, P.R. China ; [d] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, P.R. China

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**For water utilization as blood that sustains social developments, humans have harnessed basins, modified river cycles and triggered a range of regime shifts all around the world. Here, considering three important dimensions of water utilization (stress, priority and configuration), we develop an Integrated Water Resources Utilization (IWRU) Index at a basin scale to indicate regime shifts. By applying this index to the Yellow River Basin, China, our results suggest there were two regime shifts over half a century, whose drivers were economic growths, managements and efficiency improvement. Differ from previous onefold descriptions, IWRU captures various considerations intertwined in water utilization, based on which we proposed a transition framework of relationships associated regime shifts with developments. By predicting widespread development dilemmas in transition regimes of water utilization, it can be a useful guideline for big river basins to develop in a coordinated way.**

Regime shifts | Human-water relationship | Water resource management | Water utilization | Sustainable development

Water, at the centre of the planetary drama of the Anthropocene, is not only essential for myriad Earth system processes, but also supporting development of human societies in various aspects. However, human's modification has profoundly influenced the water cycle which may lead adverse changes to functions of human-water systems, resulting in development dilemmas (1, 2). Facing major challenges in the Anthropocene, many of the world's big river basins, also hot spots of economy and civilization, are urgently in need for integrated water resources management toward sustainability (3). Therefore, understanding the complex relationship between human societies, water resources utilization and their transitions provides underlying supports for developing in a coordinated and sustainable way at a basin scales.

Regime is a stable state of systems structure and function, whose large and persistent changes may lead to substantive impacts on the outcomes of system with widespread cascading effects, defined as regime shifts (4–6). Water have several key functions within a human-water system, the most important of which is supplying for human societies in further developments based on water utilization. However, interplayed human interference, involving water withdrawal, dam constructions and water managements have significantly changed water functions and induced changes in water use (7). These gradual or abrupt drivers triggered regime shifts as societies' development strengthen their interlinks to water utilization and deepening dependences on them. As a result, most large river basins had gone through phases of accelerated exploitation, over-exploitation, and integrated management, for which it is a reasonable assumption that there is a general transition pattern in water utilization. Identifying the regime shifts in water utilization and sketching a general pattern, therefore, can help to understand and predict developing trajectories of basins, which are crucial for integrated management and coordinated development towards sustainability.

Features of water utilization has been depicted and studied from various intertwined perspectives so far. Firstly, water stresses are of increasing importance and concerns because of scarcity. Greater water utilization stresses had become a major constraint to development, because of significant increment in water withdrawals and larger shares of inflexible water use, while store of water resource in reservoirs are helpful to relief of (8–10). Secondly, as the need of developments, priority of water utilization changed with and there are noticeable growths in economy profits of industry or services and their priority in water use, leading potential conflicts between different sectors (11, 12). Thirdly, since development are inherently regional concerns, where heterogeneous regions attempt to develop themselves by economically competitive sectors, configuration of water resources also plays as an important aspect. As a result, while only 10% of available water is withdrawn on global average, about 30% of population settles in severe water-stressed regions for higher level of development (13, 14). Taken together, existing researches have evaluated the three dimensions of water resource utilization regarding a series of crucial questions: "How much water resources?", "How to use them?" and "Used for whom or in where?". As these dimensions haven't been well integrated by quantitative methods, however, there is still lacking a co-

## Significance Statement

Water, a key resource to support the sustainable development of human societies, whose natural cycle has been modified by growing socio-economic processes. We propose a new method with an integrated index to detect water utilization regimes and applying it to the Yellow River Basin, a typical overexploited basin in China. After sketching changes of relationships between social development and water utilization within the Yellow River Basin, we summarized a general transition framework. By predicting widespread development dilemmas, it can be a useful guideline for basins all around the world in their sustainable developing trajectories.

Shuai Wang and Bojie Fu designed this research, Shuang Song performed the research and analysed data, Shuang Song, Xutong Wu wrote the paper.

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[1] To whom correspondence should be addressed. E-mail: shuaiwang@bnu.edu.cn

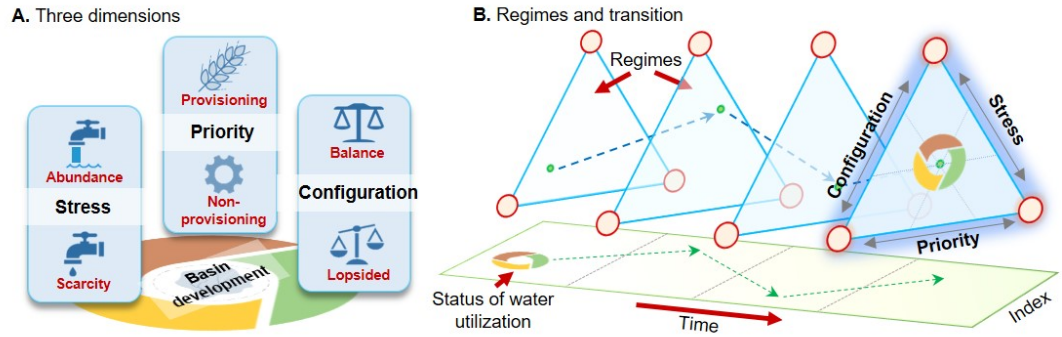


**Fig. 1.** A framework for understanding the changing relationship between watershed development and water resources. **A,** three dimensions (stress, priority and configuration) of water resources utilization. Each dimension has two poles (denoted in red) which indicates the two potential directions of water resources utilization changes along that axis. (1) Stress of water utilization shifts between scarcity of water resources and abundance of water resources, which means there is shortage of water supply or not. (2) Priority of water utilization can move between a provisioning part or a non-provisioning one, indicating how much water were used in food supporting to human societies. (3) configuration can move between balanced or lopsided, when allocation of water resources between different sectors or regions changed. We presume that water utilization regimes equally weighted by these basic dimensions, whose combination can highly relate to basin development. **B,** the changes after combining the three dimensions. Because the above three dimensions are changing with the development of society, their combined water resource utilization status is also different. When abrupt transitions occur during this process, they may indicate a regime shift in water utilization, so we need an indicator to monitor this change.

herent interpret of regime shifts regard to social development and water utilization.

Here, by integrating three above mentioned dimensions of water utilization, we develop an Integrated Water Resources Utilization (IWRU) Index at a basin scale to give a sketch of relationships between human societies and their water utilization (Figure 1). Then, by applying this index to the Yellow River Basin, China, we analysed water utilization regimes shifts and their drivers in this typical basin of anthropogenic impacts. Finally, we proposed a transition phases framework of development echoing to the regime shifts, which can be a useful guideline for basins to predict dilemmas in water utilization and to develop in a coordinated way.

## Results

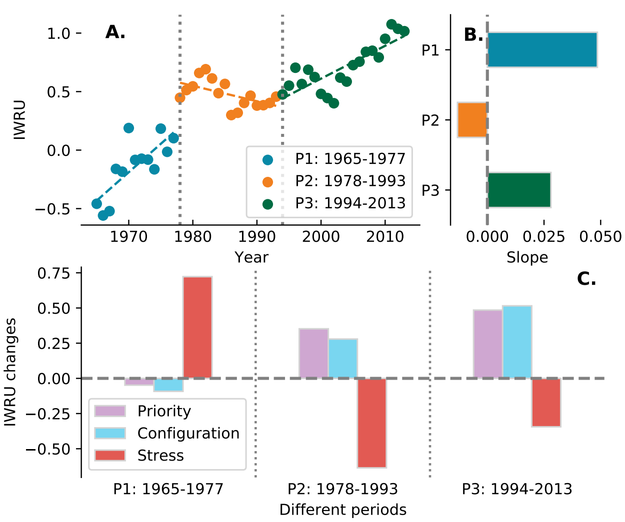


**Fig. 2.** Changes of the IWRU index. **A,** two change points in 1978 and 1994, three periods were detected in changing trend of the IWRU. **B,** changes of IWRU in three periods have various slopes, while the second period have a negative growths rate. **C,** changes of the IWRU within three periods, which have different main contributors.

**Water utilization regimes.** With two significant points, the trend of IWRU index are detected into three periods, whose slopes of changing are various and mainly contributed by different dimensions (stress, priority or configuration of water utilization, see *Methods* and *SI Appendix* Methods S4) (Figure 2). In the first period (P1, 1965-1978), the IWRU index had a rapidly increasing and the lightening of water stresses made the most striking positive contribution (83.7%), while priority and configuration of the water utilization had slight negative contribution (5.6% and 10.7%). In the second period (P2, 1979-1994), though increased positive contributions of priority and configuration (27.8% and 22.0% respectively), the IWRU index experienced a drop because of stresses on water resource playing a larger negative role (50.2% contribution but in negative). However, as the further increasing of positive contributions of priority (36.1%) and configuration (38.3%), and decreases of water stresses in negative contribution (25.6%) in the third period (P3, 1995-2013), a positive growth of the IWRU returned. As a result, each period has a different most striking positive contributor to IWRU: P1 is stress (83.7%); P2 is priority (27.8%); and P3 is configuration (38.3%).

While the above three dimensions (stress, priority and configuration) also have own variation (see *SI Appendix* Methods S4 and Fig. S4), combination of their contribution ratios clustered clearly by different time periods, indicating three regimes (Figure 3). At the very beginning (1965) and throughout the whole P1, water utilization regime dominated by high stresses. After then, it experienced a shift to low stresses since 1978, with a change in the proportion of contributions between priority and configuration, too. Finally, the contribution of three dimensions were much similar in P3 (32.91%, 31.87% and 35.21% for priority, configuration and stress respectively), making the points highly concentrated at the centre of the ternary diagram in that period.

**Drivers of water utilization regime shifts.** Some main drivers caused the above changes of water utilization regime. (1) The expansion of irrigated area and the economic growth of industry and services are keys to the changes in the priority of

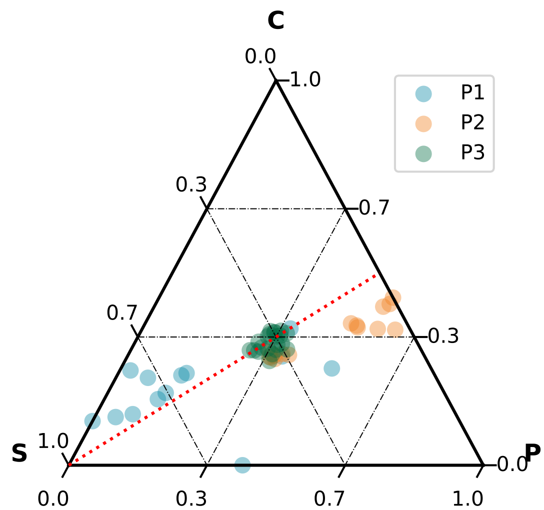


**Fig. 3.** Combination of contributions regards three dimensions in different periods (S: stresses; P: priority; C: configuration). The closer a point to an angle of the triangle, greater the proportion of the contribution of this dimension. The red indicator line in this ternary plot denotes 1:1 contributions between priority (P) and configuration (C). When the points are bellow this line, the contribution ratio of configuration is lower than that of priority, and vice versa.

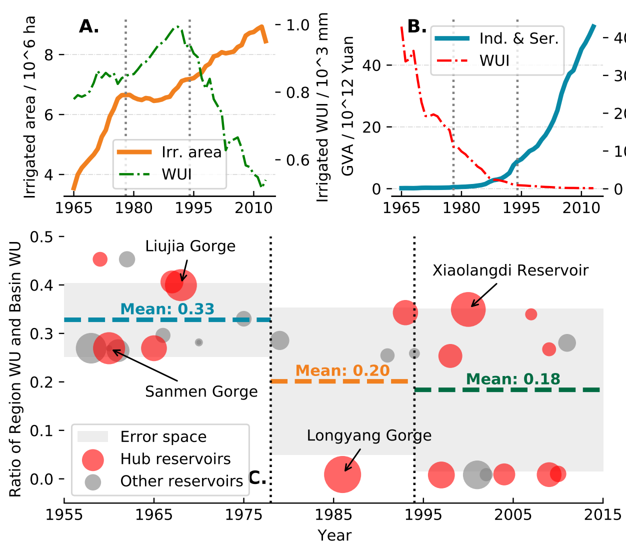


**Fig. 4.** Drivers of water utilization regime shifts: economy growths, efficiency changes, and management practices. **A.** Changes of total irrigated area, and water consumptions in per unit of area (*SI Method* S2). **B.** Changes of gross values added (GVA) of industry and services, and their water use density (WUI) respectively (*SI Appendix* Method S2). **C.** Constructions' finished time of each new reservoir and their located regions' water use percentages in basin's total water use (WU), at that time. Red ones denote hub reservoirs in the basin, which plays a role in basinal integrated water management. Size of the points indicates their magnitude of water storage capacities. Some important or special reservoirs' name denoted: (1) Xiaolangdi reservoir and Sanmen Reservoir were constructed mainly responsible for managing sediments of the Yellow River. (2) Liujia Gorge, Longyang Gorge, were constructed mainly responsible for managing water flood discharge and storage. These marked reservoirs, therefore are significant for the entire basin, far crucial than regional development.

water utilization between P1 and P2 (Figure4A). During the P1, irrigated agricultural area in the Yellow River basin expanded rapidly at a rate of $0.25 * 10^6 ha/yr$, and irrigation water was the dominant utilization way (81.56% of the total water use in 1965, and 83.17% in 1978, see *SI Appendix* Fig. S7). Entering P2, however, while the expansion of irrigated area stalled, industry and services gradually took off and took up more water resources (Figure4 B), leading to 8% reduction of proportion of irrigation water (*SI Appendix* S7).

(2) During the P3, irrigation had noticeable changes in its efficiency, whose water consumptions were reduced but still dominant. Although irrigated area resumed expansion, and both industry, urban services were boosting their gross added values (GVA), water use density (WUI) experienced significant declines and reached the lowest points (Figure4A and Figure 4B). It means, water utilization ways have changed, along with technological solutions and a range of water conservation practices (*SI Appendix* Fig. S8). As a result, the differences between the sectors of water use reduced while the total water consumption remains stable, during the P3 (*SI Appendix* Fig. S7).

(3) Changing water management practice contributed throughout all three periods. In the P1, most of the reservoirs are built in regions with high water demands, as ratio of regional water use and basinal water use for each new reservoir are significantly higher (Figure 4C, $p<0.01$). In the P2, on the other hand, the number of new reservoirs decreases significantly with little increment of total storage capacities (*SI Appendix* Fig. S6). Entering the P3, however, the number of new reservoirs are even much higher than that in the P1, and most of them were built in regions with lower ratio of regional water use and basinal water use (Figure 4C and *SI Appendix* Fig. S6).

## Discussion

**Shifted water utilization regimes with development.** The IWRU index captures, with three dimensions (stress, priority and configuration), the complex human-water feedbacks that links social development and water resources utilization. Our results show that three distinct regimes of water utilization within YRB, which have been driven by different causes regarding the three above dimensions. Before 1978, the contribution of agriculture in the YRB to GDP was nearly a half (46% in 1965), much higher than that of industry or services (33% and 26% in 1965, respectively see *SI Appendix* fig. S9). Given that downstream industrial water had not depended on Yellow River yet, and the provincial estimates are exaggerated in industrial or services GDP (*SI Appendix* Methods S3), this figure still greatly understates the dependence on agriculture for social development then. At that time, one of the main tasks of the Yellow River Conservancy Commission (YRCC), therefore, was to set up agencies for water infrastructure (*SI Appendix* Table S2), and the new reservoirs were mostly distributed in regions with high water demands (Figure 4 C). As a result, this regime is characterized by a rapid expansion of irrigation water to support development of agriculture.

The regime, however, nearly came to an end with the water resource crisis, as the water consumption of the Yellow River had accounted for about 80% of the natural runoff. In 1972, the Yellow River was dried up for the first time with a length of 310 km for 19 days, and continued to be dried up for many years since then (*SI Appendix* Fig. S10). Came to the

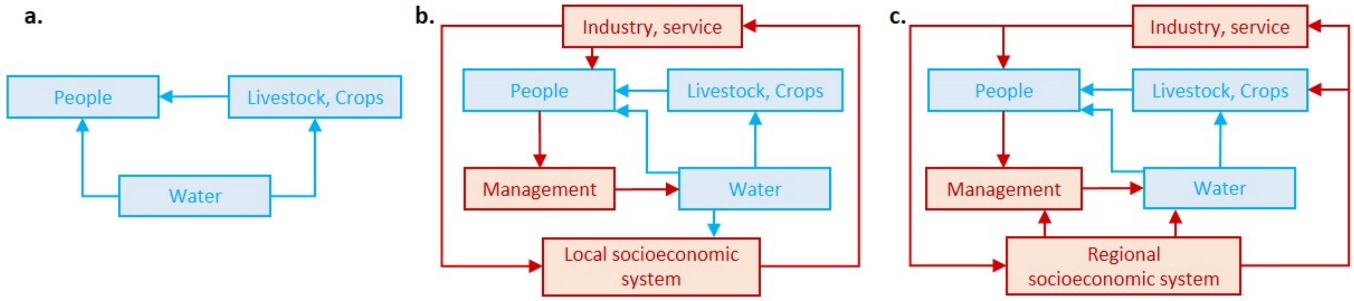


**Fig. 5.** Transition framework towards a comprehensive water utilization, where water undertakes more socio-economic functions and needs to be considered holistically. Blue pathways dominated by natural water loop while red ones dominated by socio-economic loops. **A. Natural phase:** As an indispensable provisioning resource, the main functions of water resource is to support crop, livestocks and human-beings, which are the basic ecological services. **B. Local phase:** With local socio-economic systems developing, industry and services (also known as the secondary and the tertiary industry) calling for further water consumptions. However, as their ecological services generated through the socio-economic path, water resource are non-provisioning. What's more, better organized socio-economic system and developed technology gives humans abilities in better managing water resources, with intensive intervention in the natural water cycle. **C. Regional phase:** With further developed and economically efficient industries and services, trade-off between whose water demands with provisional water demands becomes prominent. Rather than determined by local socio-economic systems, water withdrawals and management act as considerations within the entire basin more, therefore.

regime since 1978, the YRCC undergone a reorganization and received instructions from the Ministry of Water Resources (called Ministry of Water Resources and Electric Power then) to resume and strengthen work related to hydrology and basin management in YRB. Since then, the expansion trend of agriculture has been constrained in this regime (Figure 4A), while the importance of industry began to increase with the opening up of Chinese market. In addition, most laws and regulations have been successively implemented (*SI Appendix* Table 2). For an example, the far-reaching 87 Water Diversion Scheme, which was put forward in 1987, limited the amount of water withdraw for each province as a constant in the YRB.

The next regime shift was not occurred by a significant increase in water use efficiency in about 1993. After more than a decade of development, the focus of economy had shifted to industry and services whose contribution of GDP in YRB are 45% and 31%, while agriculture accounting for only 23% (*SI Appendix* Fig. S9). A rapid increase in industrial demand for water has been accompanied by economic growth, which had led to water-saving reforms in inefficient agriculture. As a result, water use efficiency improved significantly in both agriculture and industry during the third regime (Figure 4A and Figure 4B), with engineered water-efficient irrigation reaching nearly half (48.6%) of the total irrigated area (*SI Appendix* Fig. S7), allowing the average water consumption per unit of irrigated area to drop about tenfold (Figure 4A).

In short, agricultural expansion, industrial services expansion, water resources management, as well as scientific and technological progress and water use efficiency improvement are intertwined in human-water system. Since they have driven the YRB to change regimes twice between 1965 and 2013 along with social development, it can be interpreted as a transition process towards comprehensive water utilization.

**Transition framework in water utilization.** The association between the above transition process and the regime shifts of water utilization may be pervasive as socio-economic pathways are gradually dominating human-water systems in most river basins. As such, we summarized a transition framework, which conceptualizes a general trajectory towards a comprehensive water utilization where regional socio-economic pathways dominating stage by stage (Figure 5).

Throughout the transition phases, three dimensions of water utilization are various in discipline of changes. (1) Firstly, while stresses on water resources increases when economic expansion boosting water demands, socio-economic progress can response to resource scarcity by better management or efficiency. Water resources were becoming more scarce in the YRB from P1 to P3 (*SI Appendix* Fig. S3). However, water utilization stresses changes a lot rather than always increasing with, because of expansions of farmland, constructions of reservoir, and the increased water use efficiency were all responses and played roles (Figure 4). Since the scarcity of water resources is directly perceptible and sensitive for utilization, its stresses on societies is one of the most striking drivers to regime shifts within human-water systems (10). (2) Secondly, the non-provisioning part of water demands growths with secondary and tertiary industries developing, leading priority of water utilization continually tilted to the socio-economic part. As original region of Ancient Chinese Civilization, the Yellow River Basin used to be dominated by agricultural but in its way to an energy industry zone now (15). As a result, saving water consumption in agriculture and making concessions for industry and energy is widely recognized as solutions for the competing (16, 17). Anyhow, this changes of priority reflect a truth that growing socio-economic parts are responding to scarcity of water resources and contributing to regime shifts. (3) Last, with tighter socio-economic links and comparative advantages between regions and sectors, the geographic scope of water resource supply and demand allocation is expanding, leading to changing configurations of water utilization. In the Yellow River Basin, the gap of water consumptions between regions and sectors are narrowing, as the result of a carefully designed allocation (18). However, the configuration of water utilization is determined on the basis of regional and sectoral economic contexts and developing trajectories(18). The changes in water utilization configurations along with regime shifts, therefore, are the outcomes of feedbacks within complex human-water systems.

By combining the above three dimensions, these changes gradually transformed water utilization regimes in a "natural phase" (Figure 5A) to one in local or regional phase (Figure 5 B and C), towards a comprehensive. In addition to the YRB, human-water relations in major river basins around the world can be explained by the framework. For examples, Indus River, Mississippi River, and Danube River, whose water utilizations have all gone through a relatively natural regime, rapid developments and integrated management regimes. (3, 19). In summary, some similar pattern of water utilization can be revealed by the transition framework with basins development.

## Dilemmas and future directions

Since our transition framework can identify regime shifts of water utilization, it helps to predict possible dilemmas in development. According to cases all around the world, big river basins often face resource dilemmas after resources-dependent developments, while highly developed ones need to resolve structural problems more often (*SI Appendix* Fig. S11). After the successive exploitation of agriculture, industry and services (refers from natural phase to a local phase in the framework, Figure 5), it is easy for basins to get into a resource dilemma. As an example, the YRB proposed a clear transformation towards integrated basin management to get rid of the severe resource dilemma, with several management practices. The most important of these is the 87 Water Allocation Scheme, which adopts a top-down approach in allocating water resources to all regions and sectors (18). Since then, the scheme has been revised and refined, and a comprehensive water resources utilization system has gradually been formed that takes the basin scale into account (18). These integrated management practices made the utilization of water resources into a regime of unified scheduling since the P3 in the Yellow River Basin, to escape from the resource dilemma. Accelerated development has been followed by severe water scarcity and a series of ecological problems, similar dilemmas are pervasive in basins highly dependent on water resources, where in need of moving towards integrated governance as well (3, 19, 20).

In addition, further dilemmas has not been completely solved as basins developments tighter interlinked to the ecosystems after integrated management and move to a regional phase (refers from a local phase to a regional phase in the framework, Figure 5). Firstly, in line with paradox of irrigation efficiency, significant improvement in agricultural irrigation efficiency has been accompanied by re-growths in irrigated area, resulting in a usually unabated trend of water resources stress (21). Secondly, the changing priority between non-provisioning (i.e. industry or services) and provisioning (i.e. domestic and irrigation water use) may rigidify the inflexibility of water use (10). Take the YRB as an example again, after getting rid of the resource dilemma, the stresses on water resources were still growing, while inflexible water use (domestic and thermal uses) growth most strikingly (supplementary Fig. S4). It can be a warning to river basins around the world in comprehensive developments, since these may lead to a reduction in resilience of basins and leave highly coupled human-water systems facing greater vulnerability to collapse –as a structural dilemma (19).

Taken together, based on the identification of current phases and development dilemmas by the transition framework, further transformative governance is still needed to achieve a high-quality sustainable development of the basin, because development is not a panacea for every dilemma (22).

## Materials and Methods

Here, we constructed the Integrated Water Resources Utilization (IWRU) Index which consists of three dimensions and identified the changes periods of the index over time by change points detection. Each dimension is reflected by an independent indicator after normalization, and water utilization regime were characterized by combination of impacts of each dimension in periods. In addition, the contribution to changes of IWRU index along with each main indicators were decomposed and calculated separately for each regime (i.e. period).

**Integrated Water Resources Utilization (IWRU) Index.** We believe that water resources utilization system is closely related to the social developments in three dimensions below (see *SI Appendix* Methods S4 for details):

- Social development is usually accompanied by a change of priority in water use towards social and economic systems because of higher returns:
$$Dev. \propto P$$
- Social development usually lead to more complex structure in configuration of water resources, which is a result of division and cooperation between regions and sectors for developing:
$$Dev \propto C$$
- Further social development can only be achieved by effectively alleviating the water resource stresses generated in the process of development through technological means:
$$Dev \propto S^{-1}$$

We combine the above three dimensions for an integrated index, remaining their positive or negative relationship with social development:
$$Dev. \propto P * C * S^{-1}$$

To effectively represent the three dimensions, we select an appropriate indicator ($I_x$, $x = P$, $C$ or $S$ corresponding to Priority, Configuration and Stress respectively) for each dimension after which, the above equation is transformed into a natural logarithm to facilitate calculation:

$$Dev. \propto ln(I_P) + ln(I_C) - ln(I_S)$$

Assuming they have equal weights, the Integrated Water Resources Utilization (IWRU) Index:

$$IWRU = I'_T + I'_P - I'_S$$

where $I'_x$ is a normalization of log-transformed indicator $I_x$ for a certain dimension:

$$I'_x = normalize(ln(I_x))$$

***Normalization.*** We log-transformed and standardized the three sub-indicators for elimination of differences between indicators. It means for actual values of each indicator $I_{indicator}$, we performed:

$$I' = (I - I_{min})/(I_{max} - I_{min})$$

Where $I$ is log-transformed series of actual values for $I_F$ and $F$ can be P: Priority, C: Configuration or S: Stress.

***Sub-indicator of Stresses.*** We refer to the scarcity-flexibility-variability (SFV) water stress index proposed in Qin et al., 2019 to evaluate water scarcity in a certain region $SFV_i$ as indicator (10). The index takes into account management measures (such as the construction of reservoirs) and the impact of changes in the industrial structure of water use on the evaluation of water scarcity:

$$SFV_i = a * V_i + b$$
$$V_i = \frac{A_i + B_i + C_i}{3}$$
$$a = \frac{1}{V_{i,max} - V_{i,min}};$$
$$b = \frac{1}{V_{i,min} - V_{i,max}} * V_{i,min}$$

where $A_i$, $B_i$, and $C_i$ are sub-indicators of scarcity, flexibility and variability of water in a certain region $i$(see *SI Appendix* Methods S4). For the whole basin, we use the average NPS as indicator of stress $I_S$:

$$I_S = \frac{1}{n} * \sum_{i=1}^{n} SFV_i$$

.

***Sub-indicator of priority.*** To priority $I_P$, we use Non-Provisioning Shares (NPS) of water use as an indicator. While provisional water use ($WU_{pro}$) includes domestic, irrigated and livestock water uses, the non-provisioning water use ($WU_{non-pro}$) includes industrial and urban services water uses. Then, we can calculate the non-provisioning shares by:

$$NPS_i = \frac{WU_{non-pro,i}}{WU_{pro,i} + WU_{non-pro,i}}$$

Where $i$ refers a certain region, or the whole basin (i.e. $I_P = NPS_{basin}$).

***Sub-indicator of configurations.*** To description of configurations $I_C$, we designed an indicator by imitation of information entropy, called Configuration Entropy Metric (CEM). CEM is a metric to measure the degree of evenness of water configuration (see *SI Appendix* Methods S4), basin development is often accompanied by the reduction of regional differences and sectors' differences in the whole basin, but there is a complement of sectors between regions, i.e.:

$$I_C = \frac{CEN_r * CEN_s}{CEN_{rs}}$$

where $CEN_r$ and $CEN_s$ are Configuration Entropy Metric in different regions and different sectors. $CEN_{rs}$ is differences between sectors in a certain region to the whole basin (see *SI Appendix* Methods S4).

**Change points detection.** The method makes no assumptions about the distribution of the data and detects breakpoints based solely on the probability of the data coming from different distributions before and after the breakpoint. The approach after Pettitt (1979) is commonly applied to detect a single change-point in hydrological series or climate series with continuous data (23). It tests the $H0$: The variables follow one or more distributions that have the same location parameter (no change), against the alternative: a change point exists. The non-parametric statistic is defined as:

$$K_t = max|U_{t,T}|$$

where:

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} sgn(X_i - X_j)$$

The change-point of the series is located at $K_T$, provided that the statistic is significant. We use 0.001 as the threshold of p-value, which means the probability of a statistically significant change-point judgment being valid is more than 99.9%. Since this method only can return one significant change point, we repeat it Until all significant change points were detected.

**Contribution decomposition.** We have decomposed the amount of variation in each index at different stages in order to observe the contribution of each influencing factor to them. Use Integrated Water Resources Utilization (IWRU) Index as an example, which influenced by three dimensions: stress ($I_S$), priority ($I_P$) and configuration ($I_C$) (indicated by their own index respectively. Since $I_F$ refers log-transformed of indicator $F$ ($F$ can be one of P: Priority, C: Configuration or S: Stress), we calculate log-transformed IWRU index $ln(IWRU)$ by:

$$ln(IWRU) = I_P + I_C - I_S$$

Since the changes of IWRU $\Delta IWRU$ can be expressed as $\Delta IWRU = ln(IWRU_2) - ln(IWRU_1)$, while $IWRU_2$ and $IWRU_1$ are ending and beginning values of IWRU in a certain time period, combining the above equations we can get:

$$\Delta IWRU = ln(\frac{S_1}{S_2}) + ln(\frac{T_2}{T_1}) + ln(\frac{P_2}{P_1}) = -\Delta I_P + \Delta I_C + \Delta I_S$$

Then, we can calculate contributions of a certain factor $F$ in a certain period by:

$$Cn_F = \frac{|\Delta C_F|}{\sum_{i=1}^{n} |C_{Fi}|}$$

where $Cn_F$ denotes the net contribution of factor $F$, $|\Delta C_{Fi}|$ refers net change of the factor $F$, and $|C_{Fi}|$ refers net change of the factor $F_i$. The factor $F_i$ to $F_n$ are $n$ elements in the same level involved in changes of the index.

**Dataset for calculating indicators.** In order to calculate IWRU, we need to calculate multiple indicators and sub-indicators. All the datasets used are listed in the *SI Appendix* table S1. A detailed description of the data can be seen in the supplementary materials *SI Appendix* Methods S2.

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