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

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In the context of regime shifts, understanding the complex relationship between human societies and water resources utilization provides underlying supports to development in a coordinated way at a basin scale. However, there is still lacking of effective method to detect regime shifts of water utilization, with much fewer attempts to develop theoretical models to explain their transition phases as well. Here, by integrating three different dimensions of water utilization (stress, tendentiousness and pattern), we develop an Integrated Water Resources Utilization (IWRU) Index at a basin scale to detect regime shifts. By applying this index to the Yellow River Basin, China, we summarized a general transition framework of regimes, which gives a sketch of relationships between human societies and their water utilization. Based on the framework, transition phases within the three regimes and accompanying development traps can be well understood, as a useful guideline for the Yellow River 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 (1). At the same time, however, human's modification has profoundly influenced the water cycle which may lead adverse changes to functions of human-water systems, resulting in various development traps (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 and water resources utilization, and its evolution provides underlying supports to development in a coordinated way, at a basin scale.

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). Within human-water systems, water have several key functions, the most important of which is supplying for human societies in sustainable development based on a complex structure of water utilization. However, inter-connected human interference, involving water withdrawal, dam constructions and water managements have significantly changed water functions and induced regime shifts in water utilization (5). These regime shifts, triggered by gradual or abrupt drivers, are likely to occur more often as societies' development increasing their pressure or stuck in traps at a basin scale. As a result, many large river basins had gone through water utilization regimes of accelerated exploitation, over-exploitation, and integrated governance, as such it is a reasonable assumption that there is a transition pattern within regime shifts. Sketching the transition of water utilization regimes, therefore, can help to understand and predict development traps, which is crucial for integrated management and coordinated development towards sustainability at a basin scale. Despite pervasive and important, there is still lacking of effective method to define the water utilization regimes and detect regime shifts, with much fewer attempts to develop theoretical models to explain their transition phases as well.

Development of societies by using water resources has been going on for at least thousands of years. Although its regime shifts and transition phases are not fully understood yet, water utilization has been depicted and studied from different dimensions. Firstly, since water resources are scarce, the most widespread concern is the rising stresses on human societies to use water resources. Even though the stocks of water in artificial reservoirs are helpful to water resources availability, greater water utilization stresses had become a major constraint to development, because of significant increment in water withdrawals and larger shares of inflexible water utilization during the last century. (6–8) Secondly, as the need of industrial and ecological developments, tendentiousness of water utilization changed with. Despite a major water utilization of agricultural irrigation dominating most river basins, there are noticeable growths and preferential tendentiousness in the economy profits and water consumption regarding industry or services, leading potential conflicts between differ-

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 indicator to detect water utilization regimes and applying them on the Yellow River Basin, a typical overexploited basin in China. After sketching changes of relationships between development and water utilization within the Yellow River Basin, we summarized a general transition framework. By predicting widespread development traps, 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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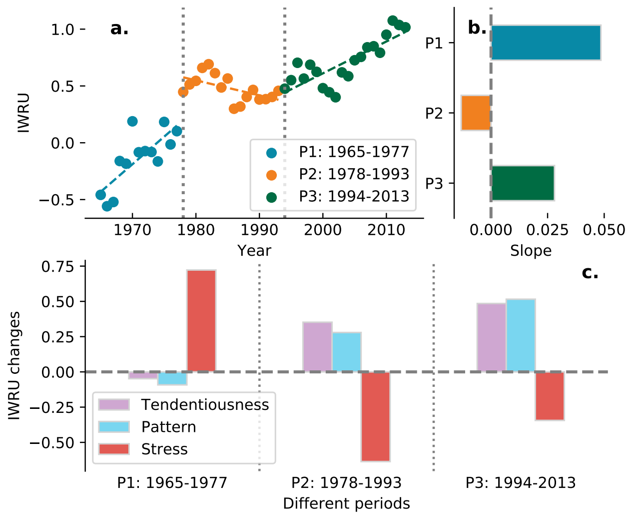

Fig. 1. Changes of the IWRU index. **A,** with two change points in 1978 and 1994, three periods were detected in trend of the IWRU. **B,** changes of IWRU in three periods have various slopes, while the second period have a negative growths rate. **C,** changes of the IWRU within three certain periods, which have different main contributors.

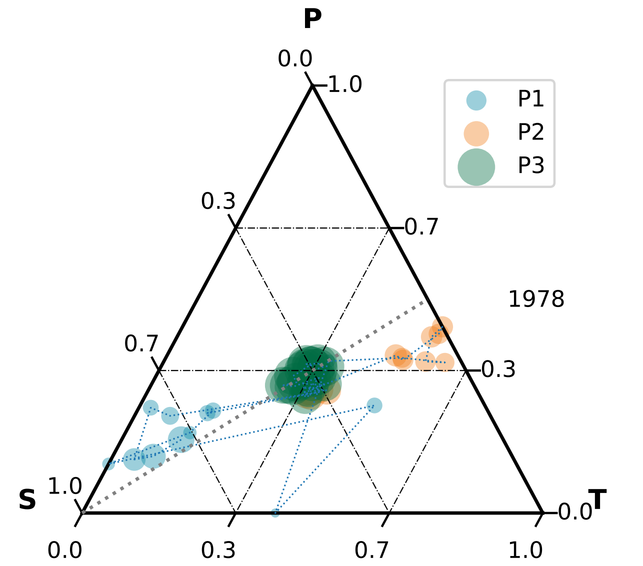

Fig. 2. Combination of three dimensions (S: stresses; T: tendentiousness; P: pattern) in different periods. Size of the points denoting average of absolute value of each indicator: the mean of the P1 phase is 0.10, while 0.14, 0.19 in P2 and P3. The red indicator line in this ternary plot denotes 1:1 contributions between tendentiousness (T) and patterns (P). Two key change points (1978, 1994), along with the beginning (1965) and the ending (2013) of research period, are labelled.

ent sectors. (9, 10) Thirdly, since water distribution and utilization are inherently basinal concerns, patterns of also play an important role. Although only 10% of available water is withdrawn on global average, about 30% of population live in highly water-stressed areas, where dominated sectors of water utilization are various as well. (11, 12) In addition, human activities are still changing this pattern, since positive impacts caused by human interventions mostly occur in upper regions whereas aggravated water resources downstream, in many basins around the world. (13) Although existing researches have evaluated the aspects of water resource utilization from these different dimensions, we still cannot obtain a coherent understanding of regime shifts regard to social development and water utilization, without integrating them.

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. Then, by applying this index to the Yellow River Basin, China, we analysed water utilization regimes and their shifts in this typical basin of anthropogenic impacts, with change points detection and contribution decomposition methods following. In addition, combining data analysis, we identify causes of the regime shifts. Finally, refer to the existing theories, we summarized a general transition framework of water utilization regimes, which can be a useful guideline for basins to predict development traps and to develop in a coordinated way.

Results

Detection of Water utilization regimes. With two significant points detected, the trend of IWRU index are split into three periods, whose slopes are various and mainly contributed by different dimensions (stress, tendentiousness or pattern of water utilization, see Methods) (Figure 1). In the first period (P1, 1965-1978), the IWRU index had a rapidly increasing and the lightening of water stresses made the most striking contribution (+0.722), while tendentiousness and pattern of the water utilization had slight negative contribution (-0.048 and -0.09 respectively). In the second period (P2, 1979-1994), the IWRU index experienced a slight drop, despite positive contributions of tendentiousness and pattern of water utilization (+0.352 and +0.279 respectively), because of increasing stresses on water resource playing a larger negative role (-0.636). However, as the further increasing of positive contributions of water utilization tendentiousness (+0.485) and pattern (+0.515), and decelerations of water stresses (-0.344, 46% less than P2) 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; P2 is tendentiousness; and P3 is pattern.

Combining these three dimensions' net contribution to IWRU further, ratios of the contributions of the three dimensions clustered clearly by different time periods, indicating three regimes (Figure 2). At the very beginning (1965) and throughout the whole P1, water utilization regime dominated by high stress. After then, it experienced a shift to low stress since 1978, with a change in the proportion of contributions between tendentiousness and pattern, too. Finally, the three dimensions' contribution were much similar in P3, making the points highly concentrated at the centre of the ternary diagram for that period.

Differences between water utilization regimes. The differences between the water utilization regimes are reflected in changes of all three dimensions. Moving from the regime in P1 to P2, the most striking change is the reversal of the trend in water utilization stress, which is determined by a combi-

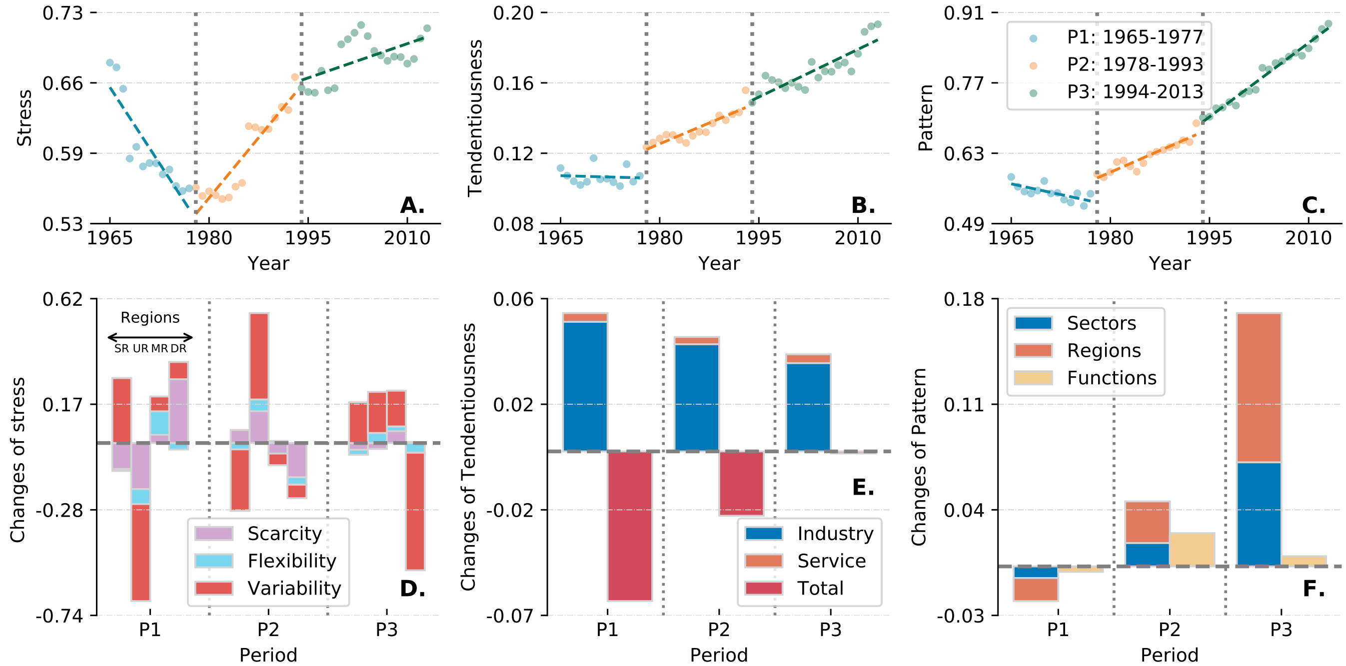

Fig. 3. Changes in different dimensions of water resources utilization regimes and their main contributors. **A,** changes of water utilization stress, indicated by unstandardized scarcity-flexibility-variability water stresses index (SFV-index). **B,** changes of water utilization tendentiousness, indicated by non-provisioning water shares. **C,** changes of water utilization pattern, indicated by unstandardized distribution information entropy index (see supplementary: Methods. S3 for details). **D,** Main impact factors to water utilization stresses in each period or region, and their contributions to changes of unstandardized SFV-index. **E,** Main impact water uses to water utilization tendentiousnesses, and their contributions to changes of non-provisioning water shares. **F,** Main impact factors to water utilization patterns, and their contributions to changes of related unstandardized distribution information entropy index (see supplementary: Methods. S3 for details).

nation of scarcity, flexibility and variability (Figure 3A and Figure 3D). In the P1, natural surface water resources were rather abundant with lesser water consumptions (supplementary Fig. S1 and S3) and most of which were flexible water utilization (supplementary Fig. S4). During the P1 and even P2, however, water consumption increases rapidly and natural surface water resources decreases at the same time, making water increasingly scarce. Opposite effect to that, numerous reservoirs built reduced the variability of water resources by boosting storage capacities, but most of which built in P1 (supplementary Fig. S5 and supplementary Table S1). As a result, water utilization stress decreases during P1, but begins to rise rapidly in P2.

On the other hand, as the most positive contributors to the IWRU index in P2 and P3 separately, tendentiousness and patterns of water utilization were keeping to enlarge their impacts (Figure 3B and Figure 3C). Representing tendentiousness of water utilization, increasing non-provisioning share of water utilization were mainly contributed by larger industrial water consumptions and minor total water uses, while the influence of both are weakening (Figure 3E). However, patterns of water utilization, whose contributions to the IWRU are increasing, were mainly benefited from decreasing disparities in the amount of water resources used, both intersectoral and regional (Figure 3F).

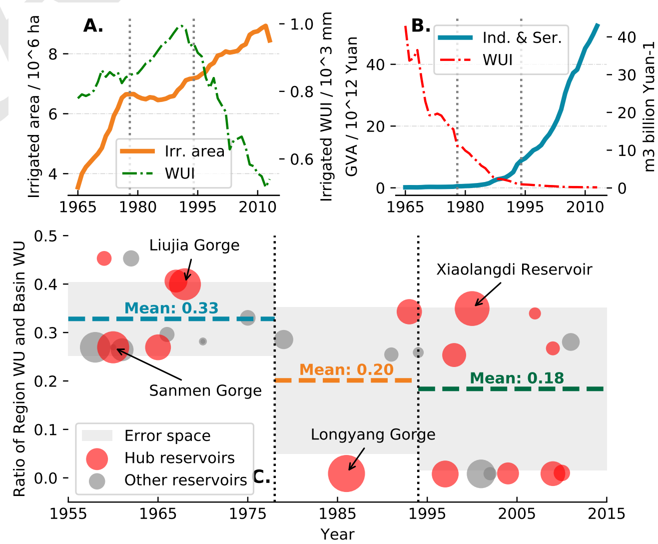

Fig. 4. Causes of water utilization regime shifts: economy growths, efficiency changes, and managements. **A.** Changes of total irrigated area and water consumption per unit of irrigated area. **B.** Changes of gross values added (GVA) of industry and services, and their water use density (WUI) respectively (see supplementary: Methods. S2 for details). **C.** Constructions' finished time of each new reservoir and their located regions' water use percentages in basin's total water use, at that time. Red ones denote hub reservoirs in the basin, which plays a role in integrated water management. Size of the points indicates their magnitude of water storage capacities. Some important or special reservoirs' name are 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. Therefore, these marked reservoirs are significant for the entire basin, far crucial than regional development.

Causes of water utilization regime changes. 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 tendentiousness of water utilization between P1 and P2 (Figure4

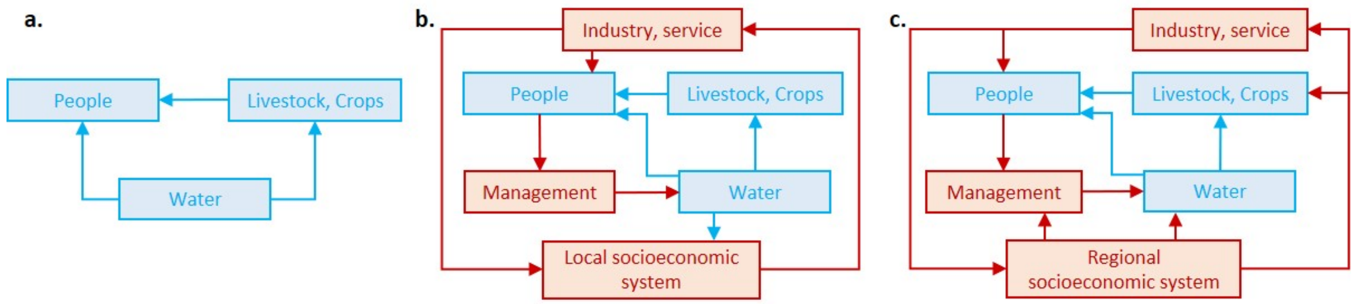

Fig. 5. Transition framework of the water utilization regime towards natural-social binary cycle. **A. Natural cycle:** As a kind of direct provisioning resource, the main functions of water resource is to support crop, livestocks and human-beings, which are the basic ecological services. **B. Regional cycle:** 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 cycle, water resources play a non-provisioning role. What's more, better organized socio-economic system and developed technology gives humans the will and ability to better manage water resources and change since this phase, with intensive intervention in the natural water cycle. **C. Basinal cycle:** Entering this phase, with further developing in more 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.

A). During the P1, irrigated agricultural area in the Yellow River basin expanded rapidly at a rate of $0.25*10^6/year$, and irrigation water was the dominant utilization way (81.56% of the total water use in 1965, and 83.17% in 1978). 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.

(2) During the P3, irrigation, whose water consumptions were still dominating, have noticeable changes in its efficiency, however. Although irrigated agricultural 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 (Figure4 A and B). It means, water utilization ways have changed, along with technological solutions and a range of water conservation practices (supplementary Fig. S6). As a result, the proportions of water use between the different sectors tend to average out while the total water consumption remains stable, after the P3 (supplementary 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). In the P2, on the other hand, the number of new reservoirs decreases significantly with little increment of total storage capacities (supplementary Fig. S5). 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 supplementary Fig. S5).

Discussion

Transition Framework. Widespread regime shifts in a human-water system can be triggered by accumulation of gradual changes, where increasing anthropogenic pressure are among the most important drivers (4, 5). At the same time, human society has become more and more dependent on water utilization as it further develops, modifying natural water cycles by socio-economic processes (1, 14). This social water cycle has linked to the natural water cycle through water withdraw, water utilization and drainage, forming a closed chain of interdependence, interconnection and mutual influence, which is consistent with nature-society dualistic water cycle theory (15, 16). According to our results, regime shifts of water utilization as transitional phases induced by developing, similar in social-ecological system, is one of the most important characteristics towards natural-social dualistic structure (2, 17). As such, we summarized a transition framework of the water utilization regimes here, which conceptualizes a general trajectory towards a natural-social dualistic water cycle (Figure 5).

Throughout the above transition phases towards dualistic water cycle, three dimensions of water utilization regime are various in discipline of evolution, corresponding to typical changes within the Yellow River Basins as an example (Figure 3). (1) Firstly, although stresses on water resources increases by economic expansion boosting water demands, socio-economic progress responding to resource scarcity by better management and efficiency. Water resources were becoming more scarce in the Yellow River Basin from P1 to P3, but the expansion of farmland, the construction of reservoirs, and the increase in water use efficiency became responses to different water utilization stresses in aspects (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 (8). (2) Secondly, the non-provisioning part of water demands growths with secondary and tertiary industries developing, leading tendentiousness 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 (18). As a result, saving water consumption in agriculture and making concessions for industry and energy is widely recognized as solutions for the competing (19, 20). Anyhow, this changes of tendentiousness reflect a truth that growing socio-economic parts are throwing feedbacks to scarcity of water resources and contributing to regime shifts. (3) Thirdly, with closer socio-economic ties and stiffer competition between regions and sectors, the geographic scope of water resource supply and demand allocation is expanding, leading to changing patterns of water utilization. In the Yellow River Basin, the gap in water consumptions be-

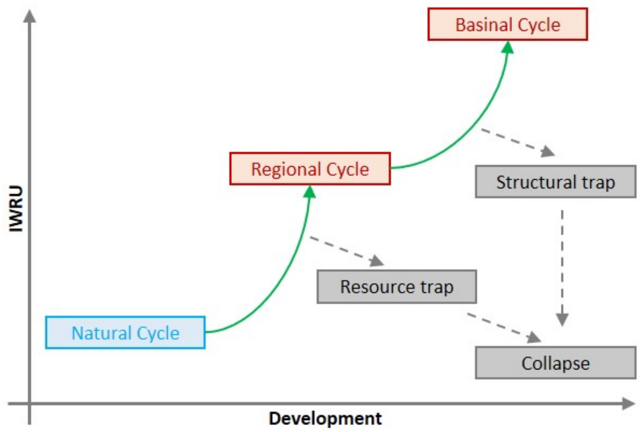

Fig. 6. Transition phases of water resources utilization regime and development traps. Green arrows indicate the trajectory without falling into any development trap, IWRU roughly follows a non-linear upward trend at the same time. However, overexploitation of water resources will leave the system in a resource trap, without moving to regional coordinated cycle. And even if one enters a regional cycle, it can still fall into a structural trap when water utilization fails to adapt to the complex changes within human-water systems.

tween regions and sectors are narrowing, as the result of a carefully designed allocation (21). However, the allocation of water utilization is determined on the basis of regional and sectoral economic contexts and development trajectories(21). The changes in water utilization patterns along with regime shifts, therefore, are the outcomes of feedback loops within complex human-water systems.

By combining the above three dimensions, water utilization regimes reflect a tendency of transitional evolution thoroughly. In addition to the Yellow River Basin, which is the focus of this study, 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 phases, rapid developments and integrated management regimes. (3, 22). In summary, our proposed transitional framework for the nature-society dualistic water cycle is universal, for identify regime shifts of water utilization.

Development Traps. At different transition phases, basins may face to various development traps in water utilization, leading an unsustainable trajectory (Figure 6). Like social-ecological systems and other complex systems, coupled human-water system may collapse under the gradual pressure on resources or because of structural mismatches (23–25). A number of studies have identified transformation as an important way out of unsustainable trajectory, and different types of transformation are required according to dominating phases and traps of systems (26, 27). Thus, our transition framework can identify regime shifts of water utilization, which can help to predict possible development traps.

According to case studies around the world, big river basins often face resource traps at the beginning of their developments, while highly developed ones often face structural traps. During P1 and P2 (refers from natural cycle to the regional cycle) in the Yellow River Basin, after the successive exploitation of agriculture, industry and services, the Water resource extraction rate has reached 79%, far exceeding the internationally recognized warning threshold of 40%. Although water management practices in P1 (construction of numerous reservoirs) mitigated the stress on water resources from accelerated development, it became scarce rapidly throughout and water utilization stresses rebounded in the P2 along with a regime shift. The resource trap is revealed at this point, with severe runoff outages and groundwater depletion of the Yellow River from P2 onwards (supplementary Fig. S8). Since similar phenomena occurred in Mississippi and Indus River Basins, the fact that the accelerated development has been followed by water scarcity and a series of ecological problems shows that the resource traps is pervasive in the transition trajectory, especially from natural cycle to regional cycle (3, 22).

To get rid of the resource trap, a clear transformation towards integrated basin management was proposed, with several management practices (supplementary Methods S4 and Fig. S9). 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 (21). 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 (21). 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 trap. Similarly, many of the world's major river basins have eventually moved towards a system of integrated governance, especially for trans-boundary rivers (e.g. Danube and Mekong River), where water resources are in need of collaborative governance (28).

However, in the regional cycle regime of water utilization, the Yellow River Basins still faces structural traps and require further transformation according to changes within the human-water system. Firstly, in line with paradox of irrigation efficiency, significant improvement in agricultural irrigation efficiency (i.e. decline in water use intensity) has been accompanied by a resurgence in irrigated area, resulting in an unabated and weak upward trend in water stress (29). Secondly, the changing tendentiousness between non-provisioning (i.e. industry and urban services) and provisioning (i.e. domestic and irrigation water use) is stagnating (see Figure 3E) because of rigidify in the industrial structure. At the same time, the flexibility of water use is declining since domestic water use and thermal water use growth rapidly (supplementary Fig. S4). Typically, 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 trap (22). Therefore, based on the identification of current phases and development traps by the transition framework, further transformative governance is still needed to achieve a high-quality sustainable development of the basin (26).

Materials and Methods

Here, we constructed the Integrated Water Resources Utilization (IWRU) Index which consists of three dimensions and identified the regime in the changes of the index over time by change points detection. Finally, the contribution to changes of IWRU index along with each main indicators were calculated separately for each regime (i.e. period).

Integrated Water Resources Utilization (IWRU) Index. The Integrated Water Resources Utilization (IWRU) Index consists of three dimensions (stresses, tendentiousnesses and patterns, denoted by sub-indicators correspondingly). Assuming they have equal weights, we log-transformed and standardized the three sub-indicators for elimination of differences between indicators. It means for each indicator I_{sub}, we performed:

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

where I is standardized series for I_{sub}. Then, since we assumed different relationships between development and sub-indicators, we added them together in equal weights:

$$IWRU = \sum_{i}^{3} I'_i$$

where i is stress, tendentiousness or pattern, and I'_i is standardized sub-indicator of them. A brief description of the sub-indicators used to measure each dimension follows (see SI Methods. S3 for more details).

Sub-indicator of Stresses. Humans use technology to continuously manage water resources, so a simple physical water scarcity index cannot reasonably assess water scarcity in the evolution and transition of socio-water systems. Therefore, we refer to the scarcity-flexibility-variability (SFV) water stress index proposed in Qin et al., 2019 to evaluate water scarcity in the basin. 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 (8).

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.

$$C_i = C1_i * (1 - C2_i)$$
$$C1_{i,j} = \frac{R_{i,std}}{R_{i,avg}}$$
$$C2_i = \frac{RC_i}{R_{i,avg}},\ ifRC < R_{i,avg}$$
$$C2_i = 1,\ ifRC >= R_{i,avg}$$

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:

$$V = \frac{A_{normalize} + B_{normalize} + C_{normalize}}{3}$$
$$a = \frac{1}{V_{max} - V_{min}};$$
$$b = \frac{1}{V_{min} - V_{max}} * V_{min}$$
$$SFV = a * V + b$$

Sub-indicator of Tendentiousness. To tendentiousness, we use non-provisioning shares 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:

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

Sub-indicator of Patterns. To description of patterns between regions or sections, we designed an indicator by imitation of information entropy. Assuming the most egalitarian water allocation is assumed to be that each region or sectoral development utilizes the same proportion of water resources (the case of maximum entropy). The ratio between the actual water allocation entropy and this maximum entropy is the allocation entropy index.

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

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:

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

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).

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 (30). 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 (S), tendentiousness (T) and pattern (P) (indicated by their own index respectively, see Water utilization regime index and supplementary Methods. S3):

$$IWRU = T * P * S^{-1}$$

Take the logarithm of both sides then, we get:

$$ln(IWRU) = ln(S) + ln(T) - ln(P)$$

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

$$\Delta IWRU = ln(\frac{S_1}{S_2}) + ln(\frac{T_2}{T_1}) + ln(\frac{P_2}{P_1}) = -\Delta S + \Delta T + \Delta P$$

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

$$C_F = \frac{|\Delta C_F|}{\Delta IWRU}$$

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