# Universal regime transition for water resources utilization in developing river basins

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**From agrarian to industrial societies, humans have harnessed ecosystems over rivers basins around the world, while using water resources as blood that sustains social developments. Although relations between societies and water resources keep changing throughout, there is still lacking effective methods to detect related regimes of water resources utilization, with much fewer attempts to develop theoretical framework to explain their transitions as well. Here, by integrating 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 three water utilization regimes in developing over half a century, whose shifts led by various but pervasive causes. Based on that, we summarized a universal transition framework which gives a sketch of relationships between human societies and their water utilization, as 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 various 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 water utilization regimes of accelerated exploitation, over-exploitation, and integrated management, for which it is a reasonable assumption that there is a general transition pattern. Sketching the transition of water utilization regimes, therefore, can help to understand and predict developing trajectories of basins, which are crucial for integrated management and coordinated development towards sustainability. Despite pervasiveness, there is still lacking of effective method to distinguish the water utilization regimes and detect regime shifts, with much fewer attempts to develop theoretical models to explain their transitions 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, features of water utilization has been depicted and studied from different perspectives. 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 during the last century, while store of water resource in reservoirs are helpful to relief of (8–10). Secondly, as the need of industry, services and ecology developments, priority of water utilization changed with. Despite a major water utilization of agricultural irrigation dominating most river basins, there are noticeable growths in economy profits of industry or services and their priority in water consumption, leading potential conflicts between different sectors (11, 12). Thirdly, since water distribution and utilization are inherently regional concerns where all regions attempt to develop themselves by economi-

## 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 universal 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.

The authors declare no competing interests.

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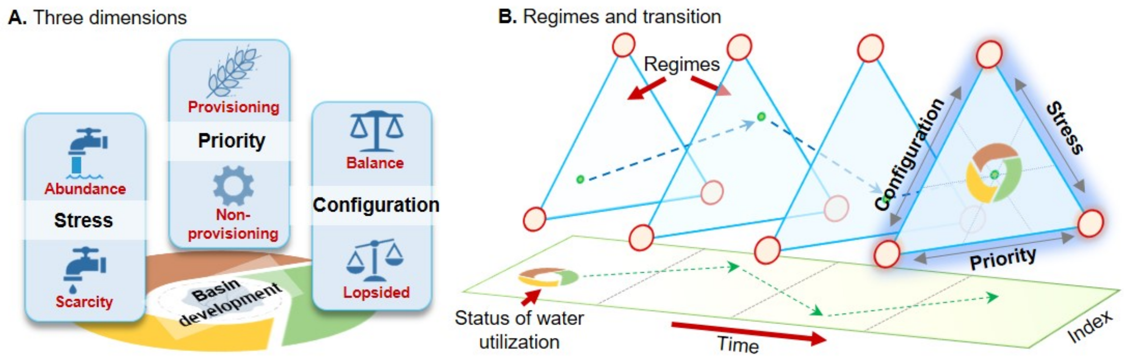


**Fig. 1.** A framework for understanding the changing relationship between watershed development and water resources. **A,** three dimensions (stress, priority and configuration) of water resources utilization. Each dimension has two poles (denoted in red) which indicates the two potential directions 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.



cally competitive sectors, configuration also plays as an important aspect. While only 10% of available water is withdrawn on global average, about 30% of population settles in highly water-stressed regions with vary dominated water demands (13, 14). Human activities further affect this configuration, as positive impacts mostly occur in upper regions whereas aggravated downstream, though most governments are trying to control this situation. (15). 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 coherent 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 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 drivers of the regime shifts. Finally, refer to the existing theories, we summarized a universal transition framework of water utilization regimes, which can be a useful guideline for basins to predict development dilemmas and to develop in a coordinated way.

## Results

**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*) (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 contribution (+0.722 change contribution and 83.7% net contribution),

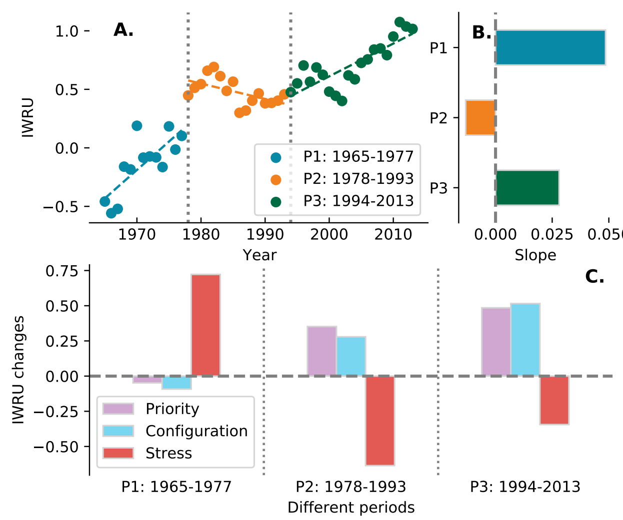


**Fig. 2.** Changes of the IWRU index. **A,** two change points in 1978 and 1994, three periods were detected in changing trend of the IWRU. **B,** changes of IWRU in three periods have various slopes, while the second period have a negative growths rate. **C,** changes of the IWRU within three certain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

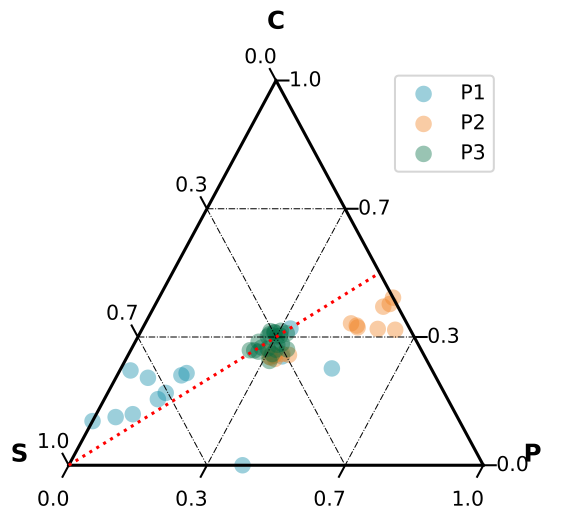


**Fig. 3.** Combination of net contributions regards three dimensions in different periods (S: stresses; P: priority; C: configuration). The closer a point to an angle of the triangle, greater the proportion of the net contribution of this dimension. The red indicator line in this ternary plot denotes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

while priority and configuration of the water utilization had slight negative contribution (-0.048 and -0.09 in change contributions, 5.6% and 10.7% in net contributions, respectively). In the second period (P2, 1979-1994), the IWRU index experienced a slight drop, despite positive contributions of priority and configuration of water utilization (+0.352 and +0.279 in change contributions, 22.0% and 27.8% in net contributions respectively), because of increasing stresses on water resource playing a larger negative role (-0.636 change contribution and 50.2% net contribution). However, as the further increasing of positive contributions of water utilization priority (+0.485 change contribution and 36.1% net contribution) and configuration (+0.515 and 38.3%, corresponding), and decelerations of water stresses (-0.344 change contribution, 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 priority; and P3 is configuration.

Combining these three dimensions' net contribution (differ from change contributions, see *Methods*) to IWRU further, ratios of the contributions of the three dimensions 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 net contributions between priority and configuration, too. Finally, the net 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.

**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(Figure 4A), which is determined by a combination of scarcity, flexibility and variability (Figure 4D and *SI Appendix* Method S4). In the P1, natural surface water resources were rather abundant with fewer water consumptions (*SI Appendix* Fig. S3) and most of which were flexible water utilization (*SI Appendix* 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 there are much fewer reservoirs built in P2 (*SI Appendix* Fig. S5). 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, priority (Figure 4B) and configuration (Figure 4C) of water utilization were keeping to enlarge their impacts. Representing priority of water utilization, increasing non-provisioning share of water utilization were mainly contributed by larger industrial water consumptions and minor total water uses, while their influences are weakening (Figure 4E). However, configuration of water utilization, whose contributions to the IWRU are increasing, were mainly benefited from decreasing differences in the amount of water resources used, both intersectoral and regional (Figure 4F).

**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 water utilization between P1 and P2 (Figure5A). 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. S6). Entering P2, however, while the expansion of irrigated area stalled, industry and services gradually took off and took up more water resources (Figure5 B), leading to 8% reduction of proportion of irrigation water (*SI Appendix*).

(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 (Figure5A and Figure 5B). It means, water utilization ways have changed, along with technological solutions and a range of water conservation practices. 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. S6).

(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 5C, 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. S5). Entering the P3, however, the number of new reservoirs are even much higher than that in the P1,

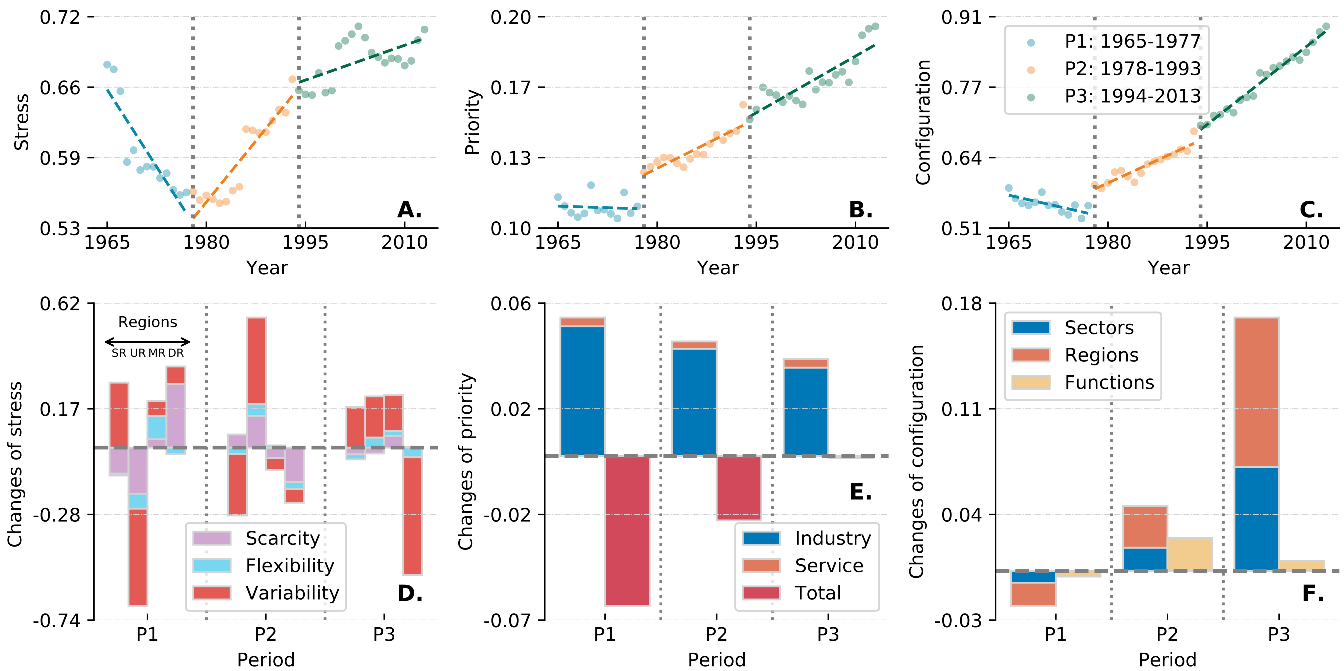


**Fig. 4.** Changes in different dimensions of water resources utilization regimes and their main contributors. **A,** changes of water utilization stress, indicated by unstandardized scarcity-flexibility-variability water stresses index (SFV-index, see *Methods* and *SI Appendix* Method S4). **B,** 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).

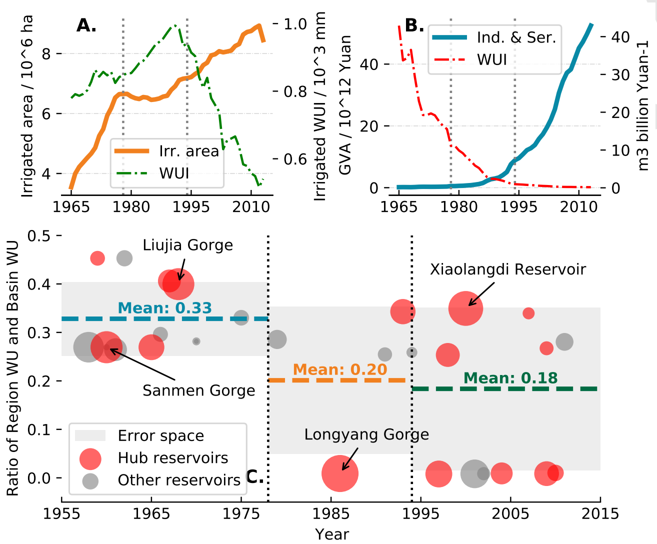


**Fig. 5.** Drivers of water utilization regime shifts: economy growths, efficiency changes, and management practices. **A.** Changes of total irrigated area, and water consumptions in per unit of area (*SI Method* S2). **B.** Changes of gross values added (GVA) of industry and services, and their water 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 bainsal 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.

and most of them were built in regions with lower ratio of regional water use and basinal water use (Figure 5C and *SI Appendix* Fig. S5).

## Discussion

**Interpret of regime shifts within YRB.** 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. S8). 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 5 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 cut off for the first time with a length of

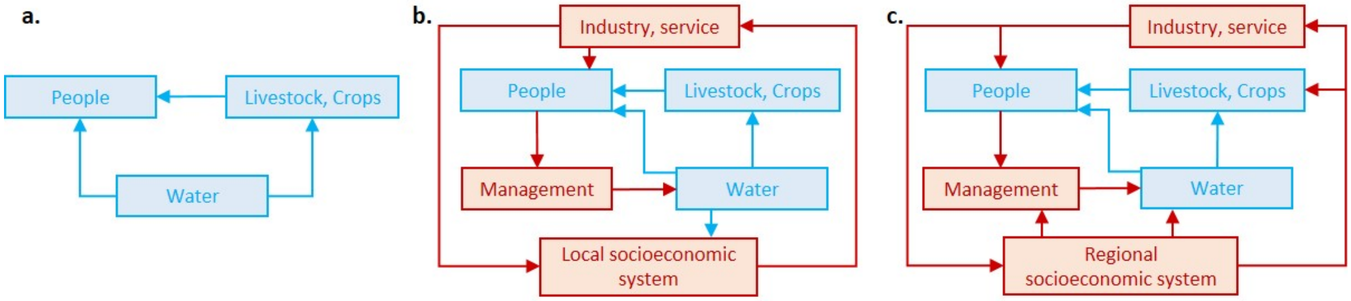


**Fig. 6.** Transition framework of the water utilization regime towards nature-society dualistic water cycle. **A. Natural cycle:** As an indispensable provisioning resource, the main functions of water resource is to support crop, livestocks and human-beings, which are the basic ecological services. **B. Local 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 resource plays a non-provisioning role. 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 cycle:** Entering this 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.

310 km for 19 days, and continued to be cut off for many years since then (*SI Appendix* Fig. S9). Came to the 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 5A), 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 3). 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.S8). 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 5A and Figure 5B), 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 5A).

In short, agricultural expansion, industrial services expansion, water resources management, as well as scientific and technological progress and water use efficiency improvement, have driven the YRB to change regimes twice between 1965 and 2013, which had been along with social development in different aspects and can be interpreted by a transition process.

**Transition framework of water utilization.** 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, 7). 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, 16). 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 (17, 18). According to our results, regime shifts of water utilization, as transition phases in three related dimensions induced by social development, are of the most important characteristics towards natural-social dualistic cycle (2, 19). As such, we summarized a universal transition framework of the water utilization regimes here, which conceptualizes a general trajectory towards a natural-social dualistic water cycle (Figure 6).

Throughout the above transition phases towards dualistic water cycle, three dimensions of water utilization regime are various in discipline of evolution. (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 5). 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 (20). As a result, saving water consumption in agriculture and making concessions for industry and energy is widely recognized as solutions for the competing (21, 22). 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 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 configurations of water utilization. In the Yellow River Basin, the gap in water consumptions be-

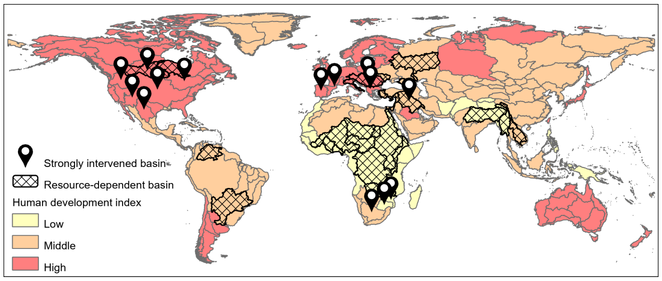


**Fig. 7. The Human Development Index of the world's great river basins, and the major problems facing some basins.** Overdependence on water resources for economic development in some basins, and high levels of human modification in others that have disrupted ecosystem structure. Data resources: Human Development Index in each basin refers from (30), 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 (31).

tween regions and sectors are narrowing, as the result of a carefully designed allocation (23). However, the allocation of water utilization is determined on the basis of regional and sectoral economic contexts and development trajectories(23). The changes in water utilization configurations along with regime shifts, therefore, are the outcomes of feedback loops within complex human-water systems.

By combining the above three dimensions, these changes gradually transformed water utilization regimes in a natural cycle (Figure 6A) to one in local or regional cycle (Figure 6 B and C), towards dualistic water cycle. 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, 24). In summary, our proposed transitional framework for the nature-society dualistic water cycle is universal, for identify regime shifts of water utilization.

**Dilemmas and future directions.** For sustainability scientists, recognizing that different regimes of water utilization regarding different water utilization regimes has important implications for social development and river basin management. At different transition phases, however, basins may face to various development dilemmas in water utilization, leading an unsustainable trajectory. Like social-ecological systems and other complex systems, coupled human-water system may collapse under the stresses reached the tipping point or structural mismatches (25–27). 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 regimes and dilemmas of (28, 29). Since our transition framework can identify regime shifts of water utilization, it may help to predict possible dilemmas in development.

According to case studies 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 (Figure 7). In the Yellow River Basin, after the successive exploitation of agriculture (from P1 to P2, refers from natural cycle to a local cycle), industry and services, the water resource extraction rate has reached 79%, far exceeding the internationally recognized warning threshold of 40%. The resource dilemma revealed after the regime shift, with severe runoff outages and groundwater depletion of the Yellow River (*SI Appendix* Fig. S8). To get rid of the resource dilemma, a clear transformation towards integrated basin management proposed, with several management practices (*SI Appendix* Methods S5). 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.

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 (23). 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 (23).

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 dilemmas is pervasive in the transition trajectory, especially from natural cycle to regional cycle (3, 24). 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 (32).

However, basins still face structural dilemmas and require further transformation according to changes within the regional cycle of water utilization. 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 (33). Secondly, the changing priority between non-provisioning (i.e. industry and urban services) and provisioning (i.e. domestic and irrigation water use) is stagnating (see Figure 4E) 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 dilemma (24). Therefore, 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 (28).

## 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, priority and configurations, 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, priority or configuration, 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 (10).

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 priority.*** To priority, 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 configurations.*** To description of configurations between regions or sections, we designed an indicator by imitation of information entropy (Allocational Entropy Metric, see supplementary document: Methods S4). 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 $p_i j$ are proportions of water use in sector $j$ and region $i$:

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

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

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

**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 (34). 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.**

***Change contributions.*** 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 ($S$), priority ($T$) and configuration ($P$) (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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