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

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The importance of water resources to human society, the impact of humans on water resources, the relationship between humans and... A complex human-water relationship is gradually being established between water resources. And resulted in water utilization regime. This helps to identify and understand the traps in the development of river basins, thus providing a theoretical basis for integrated water resources management and development in a coordinated way.

Water resource management | Human-water relationship | Water scarcity | Sustainable development

Water, at the centre of the planetary drama of the Anthropocene, is not only essential for myriad Earth system processes, but also a key resource supporting development of human societies in various aspects (1). At the same time, however, human's modification has profoundly influenced water processes and related changes may lead to adverse transitions in functions of human-water systems, along with various development traps. Facing major challenges of the Anthropocene, many of the world's big river basins are also centres of economy and civilization and urgently in need for integrated water resources management toward sustainability. (2) Therefore, understanding the complex relationship between human societies and water resources utilization provides underlying supports to development in a coordinated way, at a basin scale.

Regime is a general term of systems structure and function and one of the most explanatory perspectives when analysis interactions within a coupling system, like human and water. Since widespread fluctuating disturbances in social development and natural water resources were out of consideration, water utilization regime only will be driven shifting when reorganizations occurred and the tipping points reached. As many large river basins had all experienced phases of accelerated water exploitation, over-exploitation of water resource, and integrated water management, it is a reasonable assumption that existence of a transitional water utilization regime corresponds to development of societies. Understanding the transitional nature of water resource regimes, therefore, can help to diagnosis and predict development traps, which is crucial for integrated management and coordinated development at a basin scale regard to sustainability. Despite pervasive and important as it is, there is lacking of effective method to detect the water utilization regimes and their shifts, with much fewer attempts to develop formal models of its transitions as well.

The key to analysis water utilization regimes is to understand the interactions between human societies and water resources, which have been depicted from different dimensions, as an ancient but evergreen topic. Firstly, the most widespread concern is the rising stresses on human societies with regard to water resources. Even though the stocks of water in increasing artificial reservoirs are helpful to water resources availability, highly stressed basins still characterized by high water consumption intensities and a major constraint to socio-economic development, driven by a significant increase in water extractions and a larger share of inflexible water utilization during the last century. (3–5) 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 of the river basins, there are significant growths and preferential tendentiousness in the economy profits and water consumption regarding industry, leading a high potential for conflict between the industrial and agricultural sectors. (6, 7) Thirdly, since water availability and utilization are inherently regional 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 sections regarding water utilization are various. (8, 9) 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. (10) Although existing researches have evaluated the aspects of water resource utilization from these different dimensions, we still cannot obtain a coherent understanding of regime 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

Significance Statement

Authors must submit a 120-word maximum statement about the significance of their research paper written at a level understandable to an undergraduate educated scientist outside their field of speciality. The primary goal of the significance statement is to explain the relevance of the work in broad context to a broad readership. The significance statement appears in the paper itself and is required for all research papers.

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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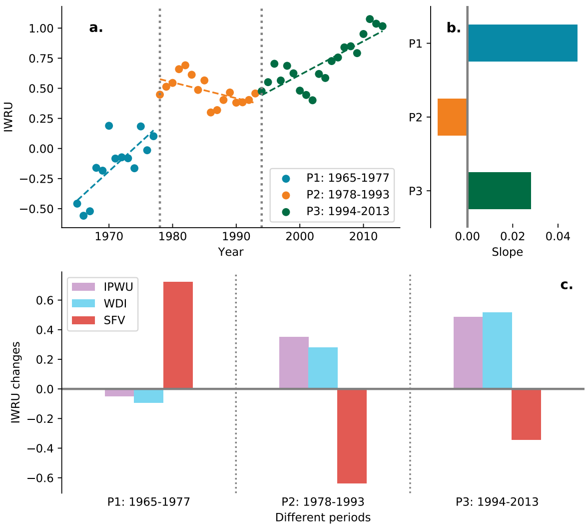

Fig. 1. Changes of the IWRU index. **A,** with two change points in 1978 and 1994, three periods were detected in trend of the IWRU. **B,** changes of IWRU in three periods have various slopes, while the second period have a negative growths rate. **C,** changes of the IWRU within three certain periods,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

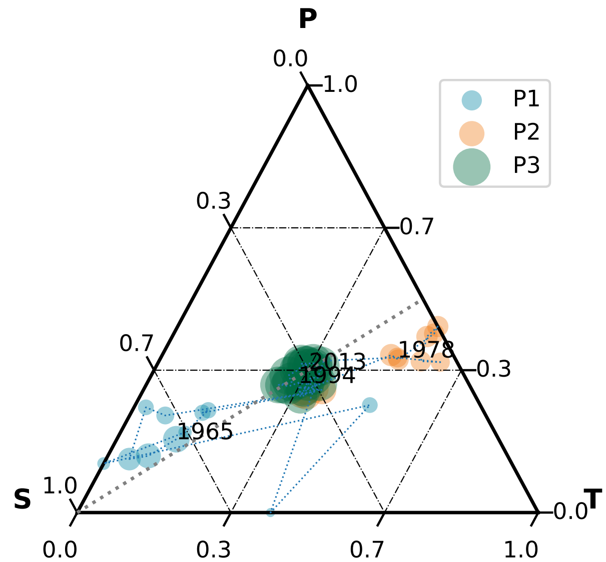

Fig. 2. Combination of three dimensions (S: stresses; T: tendentiousness; P: pattern) in different periods. Size of the points denoting values of the IWRU: the mean of the P1 phase is 0.10, while 0.14, 0.19 in P2 and P3. The red indicator line in this ternary plot denotes 1:1 contributions between tendentiousness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

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 model and data analysis, we further identify resource and development traps that have been exposed by regimes' shifting. 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

Division of Water utilization regimes. By the two significantly detected change points, the changes of IWRU index are split into three periods, whose slopes are various and mainly contributed by different factors (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 (124%), while tendentiousness and pattern of the water utilization had slight negative contribution. In the second period (P2, 1979-1994), the IWRU index experienced a slight drop, despite positive contributions of tendentiousness and pattern of water utilization, because of increasing stresses on water resource playing a larger negative role (-146%). However, as the further increasing of positive contributions of water utilization tendentiousness and pattern, and decelerations of water stresses in the third period (P3, 1995-2013), a positive growth of the IWRU returned. As a result, each period is various in the most striking positive contributors to IWRU, corresponding to different dimensions of water utilization.

Combining the three dimensions of water resources utilization, further more, sub-index regard to different water utilization dimensions were aggregative distinguishably in each same period, whose regimes show clear phase-characteristics (Figure 2). At the very beginning of research period (1965), high water stress domain the regime, while it experienced a large shift after entering P2 since 1978, with a change in the proportion of contributions between tendentiousness and pattern, too. In contrast, the three dimensions' contribution were similar from 1994 into P3 to 2013, making the points highly concentrated at the centre of the ternary diagram for that period. Taken all together, the three phases delineate distinct water resource utilization regimes, corresponding each period of.

Changes of water utilization between regimes. A comparison of the phases under different dimensions reveals notable differences regarding water utilization between each water use regime (Figure 3). Moving from the regime in P1 to P2, the most striking change is the reversal of the trend in water stresses (Figure 3A). The P1, when water resources were the most abundant period, also had the least water consumption, while most of which were flexible water utilization. Despite the rapid rise in water use during that period, numerous reservoirs were also built during this period, which increased storage capacities in each water-demand region to relief water resource stresses (SI). However, entering P2, although water consumptions continued to increase, the number of new reservoirs was significantly reduced and the total storage capacity of each region was hardly increasing any more. Coupled with declining natural water resources, the water stress index of the basin was rapidly increasing. 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 still enlarging their impacts (Figure 3B and C).

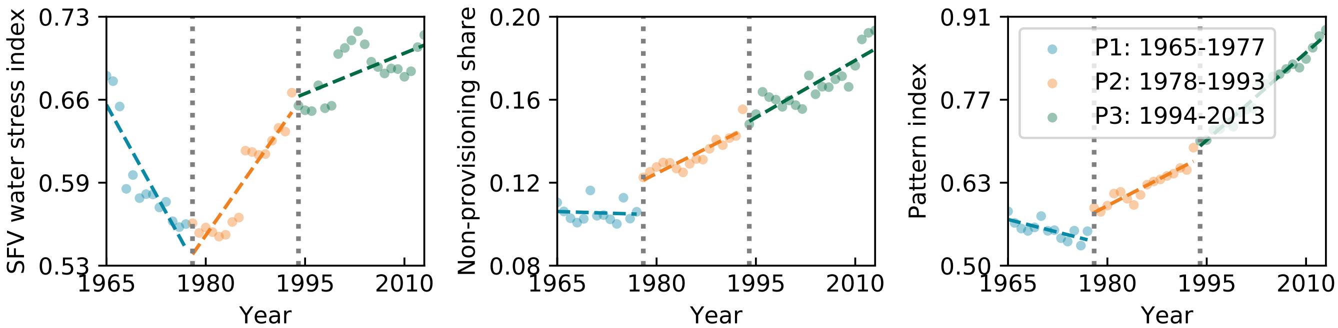

Fig. 3. Changes in different dimensions of water resources utilization regime. **A,** changes of scarcity-flexibility-variability water stresses index (SFV-index). **B,** changes of non-provisioning water share, indicating water utilization tendentiousness. **C,** changes of water utilization pattern index.

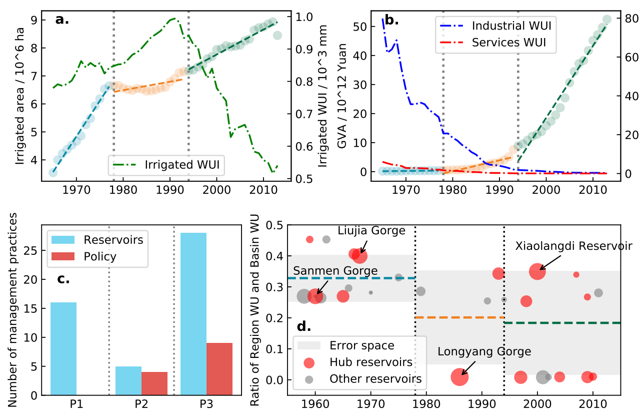

Fig. 4. Combination of three dimensions (S: stresses; T: tendentiousness; P: pattern) in different periods. Size of the points denoting values of the IWRU: the mean of the P1 phase is 0.10, while 0.14, 0.19 in P2 and P3. The red indicator line in this ternary plot denotes 1:1 contributions between tendentiousness (T) and patterns (P). Two key change points (1978, 1994), along with the beginning (1965) and the ending (2013) of research period, are labelled.

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 is waning. However, patterns of water utilization, with accelerating changes and larger contributions to the IWRU, were mainly benefited from the convergence of development paces between regions and the basin-wide intersectoral water balance. In summary, the changes in various aspects of the water use characteristics of the Yellow River Basin over the past 60 years are reflected in the changes in the corresponding indicators of the three dimensions.

Causes of water utilization regime changes. Some main drivers caused the changes of water utilization regime (Figure4). (1) The expansion of irrigated area and the economic growth of industry and services are key to the changes in the tendentiousness of water utilization in P1 and P2. During P1, irrigated agricultural area in the Yellow River basin expanded rapidly at a rate of xx/year, and agriculture was the dominant water use (xx % of the total). After entering P2, however, while the expansion of irrigated area stalled, industry and services gradually took off, which took up more water resources. (2) Efficiency of water use sparkly changed during the P3. Although both industrial services output and irrigated agricultural area resumed expansion in P3, both their output per unit and water consumption per unit area experienced significant declines. As a result, after the P3, the proportions of the different water-using sectors tend to average out while the total water consumption remains stable. (3) Changing water management practice contributed between different periods. In P1, most of the reservoirs are built in regions where water use is growing, and the trend of growth in storage capacity and growth in water demand remain relatively consistent regionally. In P2, on the other hand, the number of additional reservoirs decreases significantly. Within P3, the number of reservoirs increases significantly again, but the growth of storage capacity does not match the growth of water demand.

Discussion

Transition Framework. Widespread regime shift of coupled systems can be caused by gradual or abrupt changes, where anthropogenic stresses are among the most important drivers of. With the accumulation of human interventions, a natural-social binary structure of the water cycle has emerged, dominating the current feedbacks of the human-water systems. According to our results, regime shifts as transitional phases of water utilization regimes, similar to evolution of social-ecological system, is one of the most important characteristics towards natural-social binary structure. As such, we summarized a transition framework of the water utilization regimes, which conceptualizes a general trajectory towards a natural-social binary water cycle (figure 5).

Towards natural-social binary cycle, there are two obvious features between different transition phases. From the first phase (natural cycle) (Figure 5a), water is a kind of direct provisioning resources, mainly supporting to crop, livestocks or human-beings, as basic ecological services. However, to the second phase (local binary cycle) (Figure 5b), as local socio-economic systems developing, industry and services (secondary and tertiary-industry) calling for further water consumptions. However, since their services can only be generated through the circulation of socio-economic systems, water resources play a non-provisioning role in this cycle. What's more, better organized socio-economic system and developed technology gives humans the will and ability to better manage water resources and change, with intensive intervention in the natural water cycle. Entering the third phase (basin binary cycle) (Figure 5c), with further growth in more economically

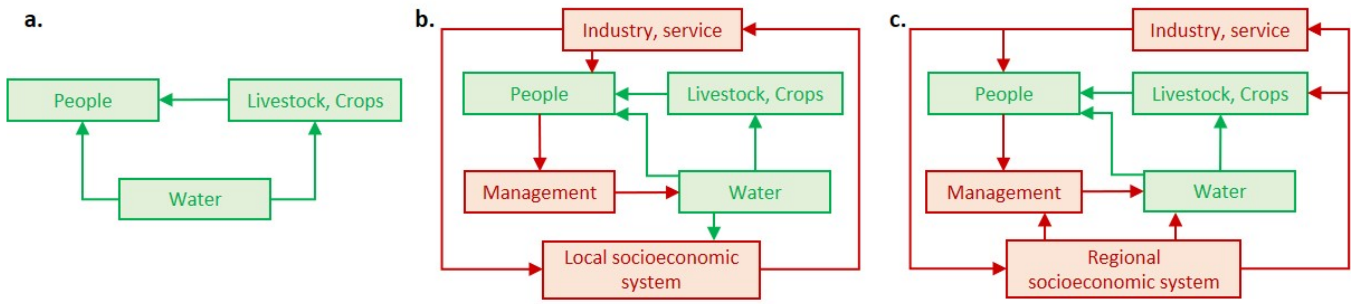

Fig. 5. Transition framework of the water utilization regime.

efficient industries and services, trade-off between whose water demands with provisioning demands should be based on the needs of regional socio-economic systems. What's more, Water withdrawals are no longer simply determined by local economic development, but more so by the socio-economic development needs of the entire basin, while water resource management are also more often considered on a basin-wide basis, correspondingly.

Throughout the above transition phases towards binary water cycle, three dimensions of water utilization regime are various, following three laws of evolution respectively. Firstly, although stresses on water resources increases by economic expansion boosting water demands, socio-economic progress responding to resource scarcity because of better management and increased water use efficiency. For Example... Secondly, the non-provisioning part of water demands further growths and tendentiousness of water utilization continually changes, as humans are more dependent on benefits from non-provisioning part of water supply. Thirdly, With closer socio-economic ties between regions and between regions and river basins, the geographic scope of resource supply and demand allocation is expanding, leading to changing patterns of water utilization. By combining the three dimensions, water utilization regimes have a tendency of transitional evolution.

For the Yellow River Basin, 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 phases of the transitional framework. For examples, ... In summary, our proposed transitional framework for the nature-society binary water cycle is general in nature.

Development Traps. Since each basin at different transition phase, they are facing different development traps regarding water utilization, leading an unsustainable trajectory. Like social-ecological systems and other complex systems, coupled human-water system disintegrate may occurred under the gradual pressure of rising resources, or collapse emerged because of structural mismatches. 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. Thus, it is crucial to distinguish major development traps based on the transition framework of water utilization regimes.

According to case studies from watersheds around the world, big river basins often face a resource trap at the beginning of their development, while highly developed ones often face a structural trap. For the Yellow River Basin, after the successive expansion of agriculture and industrial services during the P1 and P2 phases, the utilization rate of surface water resources has reached 80% of the natural runoff, far exceeding the internationally recognized threshold of 40%. Although water management measures in P1 (construction of numerous reservoirs) mitigated the pressure on water resources due to accelerated development, the pressure on water resources rebounded rapidly during P2, when the number of new reservoirs declined significantly. These have led to increasingly severe outages and groundwater depletion of the Yellow River from P2 onwards, and the Yellow River basin had been in a notable resource trap. In any case, the xxx and xxx basins have a development history similar to that of the Yellow River, suggesting that resource distress may be widespread in the early stages of the transition.

Faced with a clear resource trap, a clear transformation path towards integrated basin management was proposed that has contributed to the gradual escape of the Yellow River from the resource trap. ..... In short, these integrated management practices made the utilization of water resources into a regime of unified scheduling, in the Yellow River Basin to escape from the resource trap of economic expansion and accelerated resource depletion. Similarly, many of the world's major river basins have eventually moved towards a system of integrated management and integrated dispatch, especially the XXX and XXX basins, where water resources are extremely scarce.

However, Despite achieving integrated management and escaping through increased water efficiency, basins still face new structural traps and require further transformation. Firstly, in line with paradox of irrigation efficiency **??**, significant improvement in agricultural irrigation efficiency (or 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. As integrated basin allocation dominates water allocation, the propensity to allocate water between non-supply industries, such as industrial services, and agriculture is becoming fixed. At the same time, the flexibility of water use is declining since domestic water use and thermal water use growth rapidly. Typically, similar to other cases, these may lead to a reduction in watershed resilience and leave highly coupled human-water systems facing greater vulnerability to collapse – a typically structural trap. Therefore, based on the identification of the current basin transition stage and development dilemma, further transitional governance is still needed to achieve high-quality sustainable development of the basin.

Materials and Methods

Please describe your materials and methods here. This can be more than one paragraph, and may contain subsections and equations as required. Authors should include a statement in the methods section describing how readers will be able to access the data in the paper.

Water utilization regime index. Example text for subsection.

Stresses. Various metrics, therefore, proposed for water stress (e.g. water scarcity, water stresses index, scarcity-flexibility-variability index), where the dimensions of human impact are increasingly valued. Among of them, by taking changes of water flexibility and variability into account, the scarcity-flexibility-variability (SFV) index focus more on dynamic responses to water resources in developing perspective, which considered a valid indicator of temporal changes in water stresses.

Lopsidedness.

Patterns.

Change points detection.

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1. T Gleeson, et al., Illuminating water cycle modifications and Earth system resilience in the Anthropocene. *Water Resour. Res.* **56** (2020).
2. J Best, Anthropogenic stresses on the world's big rivers. *Nat. Geosci.* **12**, 7–21 (2019).
3. SL Postel, GC Daily, PR Ehrlich, Human Appropriation of Renewable Fresh Water. *Science* **271**, 785–788 (1996).
4. P Greve, et al., Global assessment of water challenges under uncertainty in water scarcity projections. *Nat. Sustain.* **1**, 486–494 (2018).
5. Y Qin, et al., Flexibility and intensity of global water use. *Nat. Sustain.* **2**, 515–523 (2019).
6. J Liu, et al., Water scarcity assessments in the past, present, and future. *Earth's Futur.* **5**, 545–559 (2017).
7. M Flörke, C Schneider, RI McDonald, Water competition between cities and agriculture driven by climate change and urban growth. *Nat. Sustain.* **1**, 51–58 (2018).
8. Y Wada, T Gleeson, L Esnault, Wedge approach to water stress. *Nat. Geosci.* **7**, 615–617 (2014).
9. T Oki, S Kanae, Global Hydrological Cycles and World Water Resources. *Science* **313**, 1068–1072 (2006).
10. T Veldkamp, et al., Water scarcity hotspots travel downstream due to human interventions in the 20th and 21st century. *Nat. Commun.* **8**, 15697 (2017).