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 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 different 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 devel-

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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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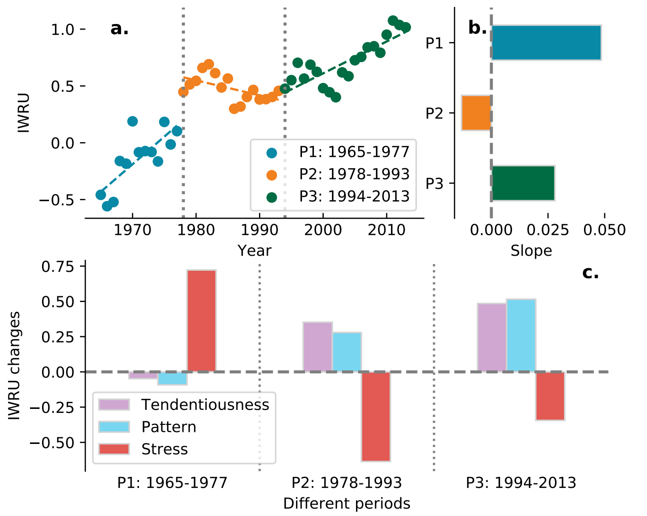

Fig. 1. Changes of the IWRU index. **A,** with two change points in 1978 and 1994, three periods were detected in trend of the IWRU. **B,** changes of IWRU in three periods have various slopes, while the second period have a negative growths rate. **C,** changes of the IWRU within three certain periods,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

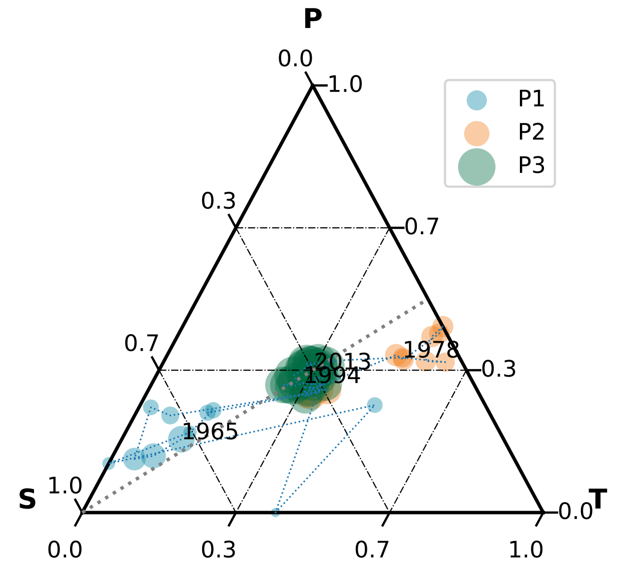

Fig. 2. Combination of three dimensions (S: stresses; T: tendentiousness; P: pattern) in different periods. Size of the points denoting values of the IWRU: the mean of the P1 phase is 0.10, while 0.14, 0.19 in P2 and P3. The red indicator line in this ternary plot denotes 1:1 contributions between tendentiousness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

opment 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 combination 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.

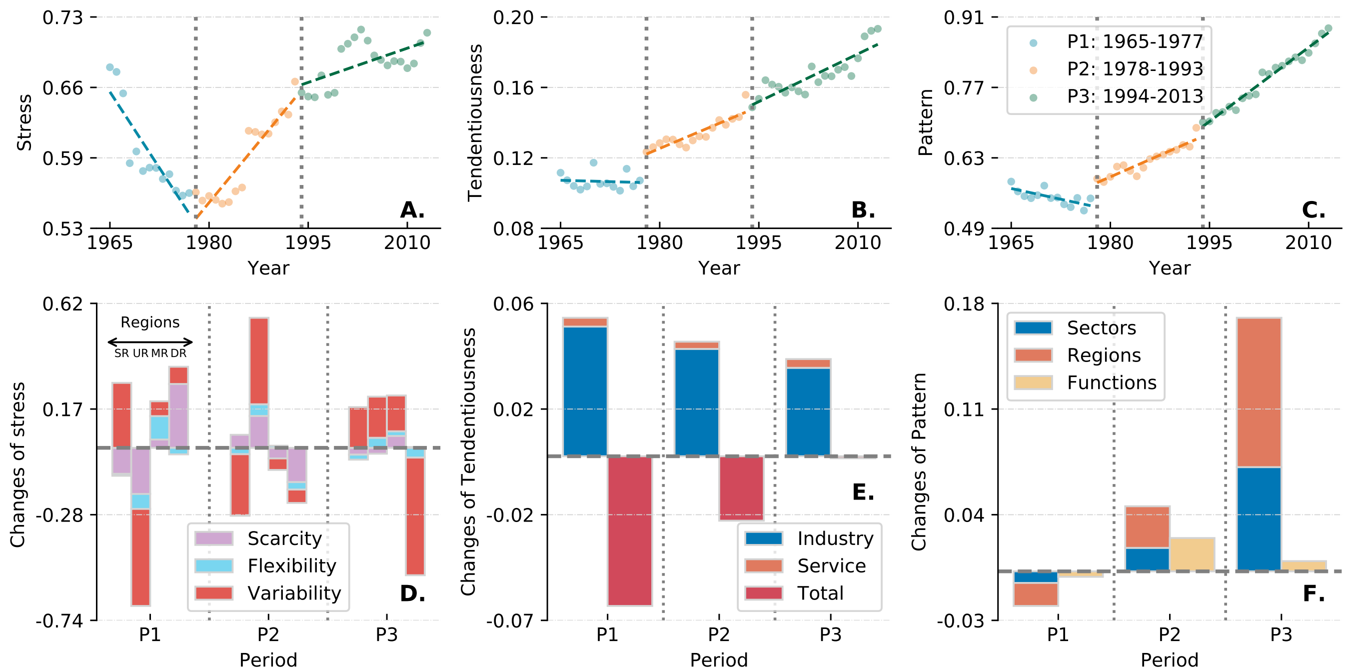

Fig. 3. Changes in different dimensions of water resources utilization regime. **A,** changes of scarcity-flexibility-variability water stresses index (SFV-index). **B,** changes of non-provisioning water share, indicating water utilization tendentiousness. **C,** changes of water utilization pattern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

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).

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 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 con-

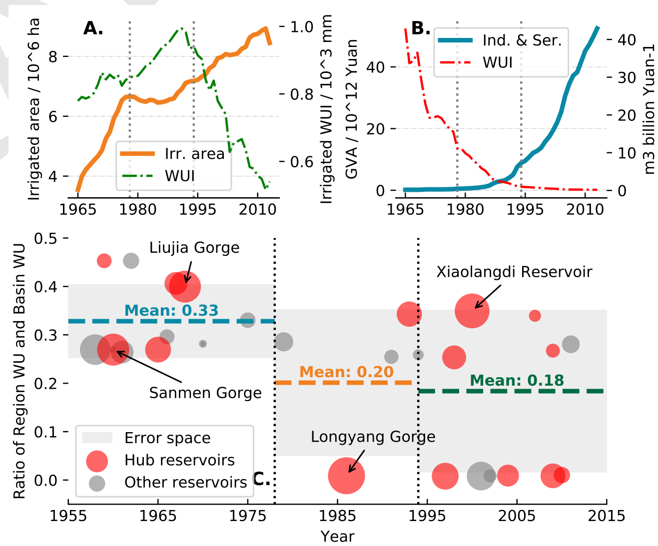

Fig. 4. Causes of water utilization regime shifts: economy growths, efficiency changes, and managements. **A.** Total irrigated area and water consumption per unit of irrigated area. **B.** Gross values added of industry and services, and their water use density (WUI) respectively. **C.** Constructions' 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.

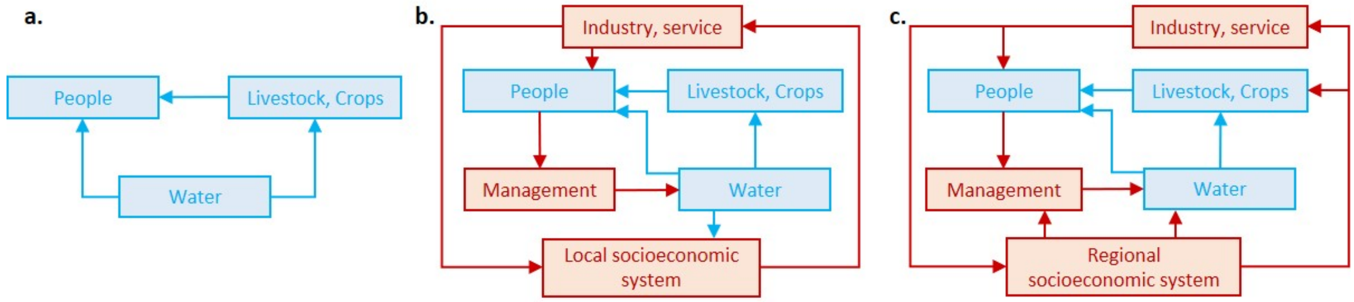

Fig. 5. Transition framework of the water utilization regime towards natural-social binary cycle. **A. Natural cycle:** As a kind of direct provisioning resource, the main functions of water resource is to support crop, livestocks and human-beings, which are the basic ecological services. **B. Regional 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.

servation 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 as transitional phases of water utilization regimes, 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).g

Towards natural-social binary cycle, there are two obvious features between different transition phases (figure 5). 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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