Regime transition identification for water utilization of river basin

Shuang Song

Shuai Wang

Xutong Wu

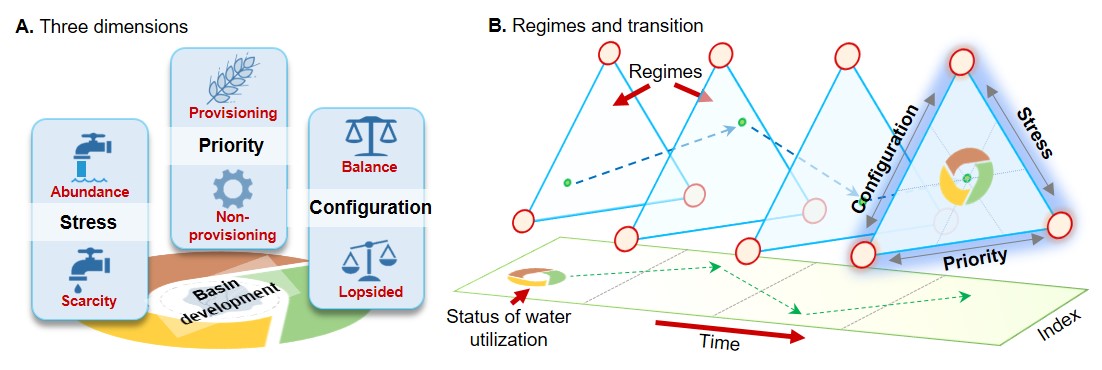
Bojie Fu

[introduction] ater, at “the centre of the planetary drama of the Anthropocene”, is not only essential for myriad Earth system processes, but also supporting development of human societies in various aspects. However, human’s modification has profoundly influenced the water cycle, which may lead adverse changes to functions of human-water systems, resulting in development dilemmas (Gleeson et al. 2020; Cumming and von Cramon-Taubadel 2018). Facing major challenges in the Anthropocene, many of the world’s big river basins, also hot spots of economy and civilization, urgently need integrated water resources management toward sustainability (Best 2019). Since it requires deep understanding of the complex relationships between human societies and water resources utilization, sketching their transitions provides underlying supports for developing in a coordinated and sustainable way at a basin scales.

Regime is a stable state of system’s 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 (Rocha et al. 2018; Scheffer and Carpenter 2003; Scheffer et al. 2001). Water have several key functions within a human-water system, the most important of which is sustaining the development of human societies through water utilization. However, interplayed human interference, such as water withdrawal, dam constructions and water managements have significantly changed water functions and induced changes in water use (Falkenmark, Wang-Erlandsson, and Rockström 2019). These gradual or abrupt changes triggered regime shifts as societies’ development strengthen their interlinks to water utilization with increased dependences. As a result, most large river basins had gone through phases of accelerated exploitation, over-exploitation, and integrated management, for which it is a reasonable assumption that there is a general transition pattern in water utilization. Identifying the regime shifts in water utilization and sketching a general pattern, therefore, can help to understand and predict developing trajectories of basins, which are crucial for integrated management and coordinated development towards sustainability.

Features of water utilization has been depicted and studied from various intertwined perspectives. Firstly, water stresses are of increasing importance and concerns. Greater water utilization stresses had become a major constraint to development, because of significant increment in water withdrawals and larger shares of inflexible water use, while store of water resource in reservoirs are helpful to relief of (Postel, Daily, and Ehrlich 1996; Greve et al. 2018; Qin et al. 2019). Secondly, as the priority of water utilization changed with the need of development. There are noticeable growths in economy profits of industry or services and their priority in water use, leading potential conflicts between different sectors (Liu et al. 2017; Flörke, Schneider, and McDonald 2018). Thirdly, since development are inherently regional concerns, where heterogeneous regions attempt to develop themselves by economically competitive sectors, configuration of water resources also plays as an important aspect. 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?”. However, these dimensions haven’t been well integrated by quantitative methods, and a coherent interpret of regime shifts regard to social development and water utilization is needed.

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 [[fig:framework]](#fig:framework)). Then, by applying this index to the Yellow River Basin, China, we analysed water utilization regimes shifts and their drivers in this typical basin of anthropogenic impacts. Finally, we proposed a transition phases framework of development echoing to the regime shifts, which can be a useful guideline for basins to predict dilemmas in water utilization and to develop in a coordinated way.



# Results

## Water utilization regimes

![Changes of the IWRU index. A, Change points detection. With change points in 1978 and 1994, the IWRU have three periods in changing trend. B, Changing slopes of each period. C, Contributions of each dimension to the changes of IWRU within three periods. Stress, priority and configuration are the main positive contributor of P1, P2 and P3, respectively. ](data:application/pdf;base64,)

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With two significant points, the changing trend of IWRU index are detected into three periods (Figure [1](#fig:IWRU)A). Not only the slope of changes are various within each period, changes are also mainly contributed by different dimensions (Figure [1](#fig:IWRU)B and Figure [1](#fig:IWRU)C). In the first period (P1, 1965-1978), the IWRU index had a rapidly increasing and the lightening of water stresses made the most striking positive contribution (131%), while priority and configuration of the water utilization had slight negative contribution (-11% and -20%). In the second period (P2, 1979-1994), though contributions of priority and configuration turned into positive, the IWRU index experienced a drop because of stresses on water resource playing a larger negative role (-188% dropped than P1). However, as the further increasing of positive contributions of priority (75%) and configuration (84%), and decreases of water stresses in negative contribution (-59%) in the third period (P3, 1995-2013), a positive growth of the IWRU returned.

![Combination of contributions regards three dimensions in different periods (S: stresses; P: priority; C: configuration). The closer a point to an angle of the triangle, greater the proportion of the contribution of this dimension. The red indicator line in this ternary plot denotes 1:1 contributions between priority (P) and configuration (C). When the points are bellow this line, the contribution ratio of configuration is lower than that of priority, and vice versa.](data:application/pdf;base64,)

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Taken together, each period has the unique most striking positive contributor to IWRU, and overall features of three dimensions in different periods are shown in Figure [2](#fig:phases). At the very beginning (1965) and throughout the whole P1, water utilization regime dominated by high stresses. After then, it experienced a shift to low stresses since 1978, with a change in the proportion of contributions between priority and configuration, too. Finally, the contribution of three dimensions were much similar in P3 (32.91%, 31.87% and 35.21% for priority, configuration and stress respectively), making the points highly concentrated at the centre of the ternary diagram in that period.

## Drivers of water utilization regime shifts

![ 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. Completed time of each new reservoir and their located regions’ water use percentages in basin’s total water use (WU), at that time. Red ones denote hub reservoirs in the basin, which plays a role in basinal integrated water management. Size of the points indicates their magnitude of water storage capacities. Some important or special reservoirs’ name denoted: (1) Xiaolangdi reservoir and Sanmen Reservoir were constructed mainly responsible for managing sediments of the Yellow River. (2) Liujia Gorge, Longyang Gorge, were constructed mainly responsible for managing water flood discharge and storage. These marked reservoirs, therefore are significant for the entire basin, far crucial than regional development. ](data:application/pdf;base64,)

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.** Completed time of each new reservoir and their located regions’ water use percentages in basin’s total water use (WU), at that time. Red ones denote hub reservoirs in the basin, which plays a role in basinal integrated water management. Size of the points indicates their magnitude of water storage capacities. Some important or special reservoirs’ name denoted: (1) Xiaolangdi reservoir and Sanmen Reservoir were constructed mainly responsible for managing sediments of the Yellow River. (2) Liujia Gorge, Longyang Gorge, were constructed mainly responsible for managing water flood discharge and storage. These marked reservoirs, therefore are significant for the entire basin, far crucial than regional development.

Various main drivers caused the above changes of water utilization regime. Firstly, 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 (Figure[3](#fig:Causes)A). During the P1, irrigated agricultural area in the Yellow River basin expanded rapidly at a rate of , and irrigation water was the dominant utilization way ( of the total water use in 1965, and in 1978, see *SI Appendix* Fig. S7). Entering P2, however, while the expansion of irrigated area stalled, industry and services gradually took off and took up more water resources (Figure[3](#fig:Causes) B), leading to reduction of proportion of irrigation water (*SI Appendix* S7).

Secondly, efficiency of water utilization changed from the P2 to the P3. While irrigated area resumed expansion again in the P3 whose water consumptions were still dominant (Figure[3](#fig:Causes)A), both industry, urban services were boosting their gross added values (GVA) (Figure [3](#fig:Causes)B). However, the water use density (WUI) of them experienced significant declines and reached the lowest points (Figure [3](#fig:Causes)A and Figure [3](#fig:Causes)B). It means, water utilization ways have changed, along with technological solutions and a range of water conservation practices (*SI Appendix* Fig. S8). As a result, the differences between the sectors of water use reduced while the total water consumption remains stable, during the P3 (*SI Appendix* Fig. S7).

Finally, changing water management practice contributed throughout all three periods. According to the location, we calculate the ratios of regional and basinal water use for each reservoir. In the P1, most of the reservoirs are built in regions with high water demands, as ratios are significantly higher (Figure [3](#fig:Causes)C, p<0.01). In the P2, the number of new reservoirs decreases significantly with little increment of total storage capacities (*SI Appendix* Fig. S6). Entering the P3, however, the number of new reservoirs are even much higher than that in the P1, and most of them were built in regions with lower ratio of regional water use (Figure [3](#fig:Causes)C and *SI Appendix* Fig. S6).

# Discussion

## Shifted water utilization regimes with the development of society

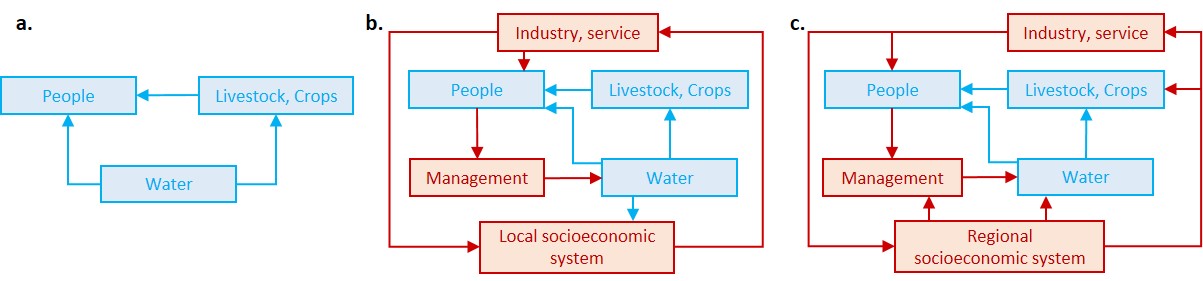
The IWRU index captures the complex human-water feedbacks that links social development and water resources utilization from three dimensions (stress, priority and configuration). Our results show that three distinct regimes of water utilization within YRB, which have been driven by different causes regarding the three above dimensions. At the beginning of P1, the contribution of agriculture in the YRB to GDP was nearly a half (46% in 1965), much higher than that of industry or services (33% and 26% in 1965, respectively see *SI Appendix* fig. S9). Given that downstream industrial water had not depended on Yellow River yet, and the provincial estimates are exaggerated in industrial or services GDP (*SI Appendix* Methods S3), this figure still greatly understates the dependence on agriculture for social development. At that time, one of the main tasks of the Yellow River Conservancy Commission (YRCC), therefore, was to set up agencies for water infrastructure (Archives 2004), and the new reservoirs were mostly distributed in regions with high water demands (Figure [3](#fig:Causes) C). As a result, this regime is characterized by a rapid expansion of irrigation water to support development of agriculture.

The regime 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. As the most obvious performance, the Yellow River was dried up for several times since 1972 (*SI Appendix* Fig. S10). During 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 (Figure [3](#fig:Causes)A), while the importance of industry began to increase with the Reform and Opening-up policy. In addition, most laws and regulations have been successively implemented (*SI Appendix* Table 2). For an example, the far-reaching “87 Water Diversion Scheme”, which was put forward in 1987, limited the amount of water withdraw for each province as a constant in the YRB.

The next regime shift was not occurred until a significant increase in water use efficiency since about 1993. After more than a decade of development, the focus of economy had shifted to industry and services whose contribution of GDP in YRB are 45% and 31%, while agriculture accounting for only 23% (*SI Appendix* Fig. S9). A rapid increase in industrial demand for water has been accompanied by economic growth, which had led to water-saving reforms in inefficient agriculture. As a result, water use efficiency improved significantly in both agriculture and industry during the third regime (Figure [3](#fig:Causes)A and Figure [3](#fig:Causes)B), 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 [3](#fig:Causes)A).

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

## Transition framework in water utilization



The links between the above transition process and the regime shifts of water utilization may be pervasive as socio-economic processes are gradually dominating human-water systems in most river basins. As such, we summarized a transition framework, which conceptualizes a general trajectory towards regional socio-economic dominating water utilization stage by stage (Figure [[fig:summary]](#fig:summary)).

Three dimensions of water utilization are various throughout the transition. Firstly, while stresses on water resources increases when economic expansion boosting water demands, socio-economic progress can respond to resource scarcity by better management or efficiency. Water resources were becoming more scarce in the YRB from P1 to P3 (*SI Appendix* Fig. S3). However, water utilization stresses changes a lot rather than always increasing, because constructions of reservoir and the increased water use efficiency were all played roles (Figure [3](#fig:Causes)). 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 (Qin et al. 2019). 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 converted to an energy industry zone now (“Will Energy Bases Drain the Yellow River?” n.d.). As a result, saving water consumption in agriculture and making concessions for industry and energy is widely recognized as solutions for the competing (Xiang, Svensson, and Jia 2016; Bebb 2011). 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. Last, with tighter socio-economic links and comparative advantages between regions and sectors, the geographic scope of water resource supply and demand allocation is expanding, leading to changing configurations of water utilization. In the Yellow River Basin, the gap of water consumptions between regions and sectors are narrowing, as the result of a carefully designed configuration.

By combining the above three dimensions, these changes gradually transformed water utilization regimes in a “natural phase” (Figure [[fig:summary]](#fig:summary)A) to one in local or regional phase (Figure [[fig:summary]](#fig:summary)B and Figure [[fig:summary]](#fig:summary)C), with socio-economic processes dominated step by step. In addition to the YRB, human-water relations in major river basins around the world can be explained by the framework. For examples, Indus River, Mississippi River, and Danube River, whose water utilizations have all gone through a relatively natural regime, rapid developments and integrated management regimes. (Best 2019; Cumming 2011). In summary, some similar pattern of water utilization can be revealed by the transition framework with basins development.

# Dilemmas and future directions

Not only the index helps to identify regime shifts of water utilization, our transition framework also helps in predicting possible dilemmas with the development of society. According to cases all around the world, big river basins often face resource dilemmas after resources-dependent developments, while highly developed ones need to resolve structural problems more often (*SI Appendix* Fig. S11). After the successive exploitation of agriculture, industry and services (refers from natural phase to a local phase in the framework, Figure [[fig:summary]](#fig:summary)), it is easy for basins to get into a resource dilemma. As an example, the YRB proposed a clear transformation towards integrated basin management to get rid of the severe resource dilemma, with several management practices. The most important of these is the “87 Water Allocation Scheme”, which adopts a top-down approach in allocating water resources to all regions and sectors. Since then, the scheme has been revised and refined, and a comprehensive water resources utilization system has gradually formed. These integrated management practices made the utilization of water resources into a regime of unified scheduling since the P3 in the Yellow River Basin, to escape from the resource dilemma. Accelerated development has been followed by severe water scarcity and a series of ecological problems, similar dilemmas are pervasive in basins highly dependent on water resources, where in need of moving towards integrated governance as well (Best 2019; Cumming 2011; UNEP-DHI, UNEP, and UNEP 2016).

In addition, further dilemmas occurred as basins developments tighter interlinked to the ecosystems after integrated management and move to a regional phase (refers from a local phase to a regional phase in the framework, Figure [[fig:summary]](#fig:summary)). Firstly, significant improvement in agricultural irrigation efficiency has been accompanied by re-expansion in irrigated area, resulting in a usually unabated trend of water resources stress which is known as paradox of efficiency (Grafton et al. 2018). Secondly, the changing priority between non-provisioning (i.e. industry or services) and provisioning (i.e. domestic and irrigation water use) may lead the water utilization more inflexible and damage to resilience of the basin (Qin et al. 2019). Take the YRB as an example again, after getting rid of the resource dilemma, the stresses on water resources were still growing, while inflexible water use (domestic and thermal uses) growth most strikingly (supplementary Fig. S4). It can be a warning to river basins around the world in comprehensive developments, since these may lead to a reduction in resilience of basins and leave highly coupled human-water systems facing greater vulnerability to collapse –as a structural dilemma (Cumming 2011).

Taken together, based on the identification of current phases and development dilemmas by the transition framework, further transformative governance is still needed to achieve a high-quality sustainable development of the basin, because development is not a panacea for every dilemma (Scoones et al. 2020).

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