

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

Shuang Song<sup>a, b</sup>, Shuai Wang<sup>a, b, 1</sup>, Bojie Fu<sup>a, b</sup>, and Xutong Wu<sup>c, d</sup>

<sup>a</sup> State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, P.R. China ; <sup>b</sup> Institute of Land Surface System and Sustainability, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, P.R. China ; <sup>c</sup> College of Urban and Environmental Sciences, Peking University, Beijing 100871, P.R. China ; <sup>d</sup> State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, P.R. China

This manuscript was compiled on August 23, 2020

**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-

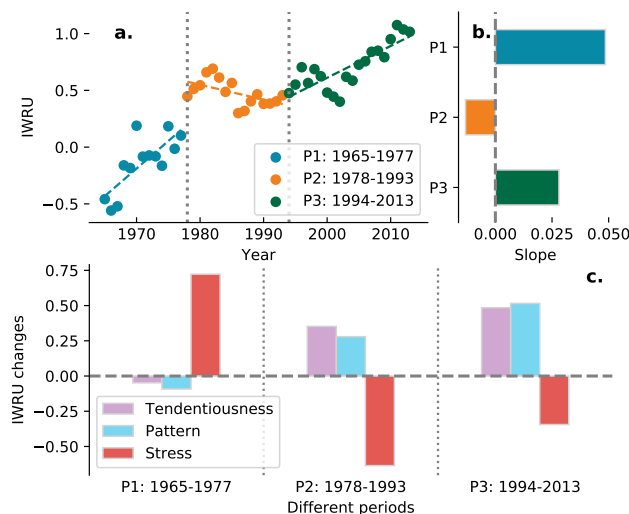
## Significance Statement

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.

<sup>1</sup> To whom correspondence should be addressed. E-mail: shuaiwang@bnu.edu.cn



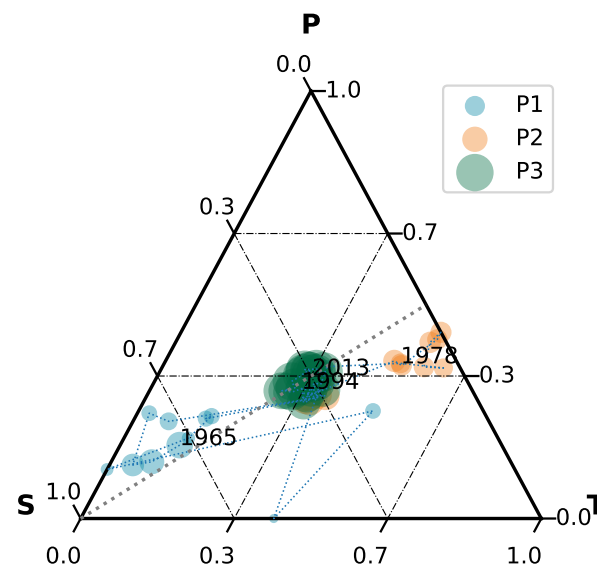
**Fig. 1.** Changes of the IWRU index. **A**, with two change points in 1978 and 1994, three periods were detected in trend of the IWRU. **B**, changes of IWRU in three periods have various slopes, while the second period have a negative growths rate. **C**, changes of the IWRU within three certain periods,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

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

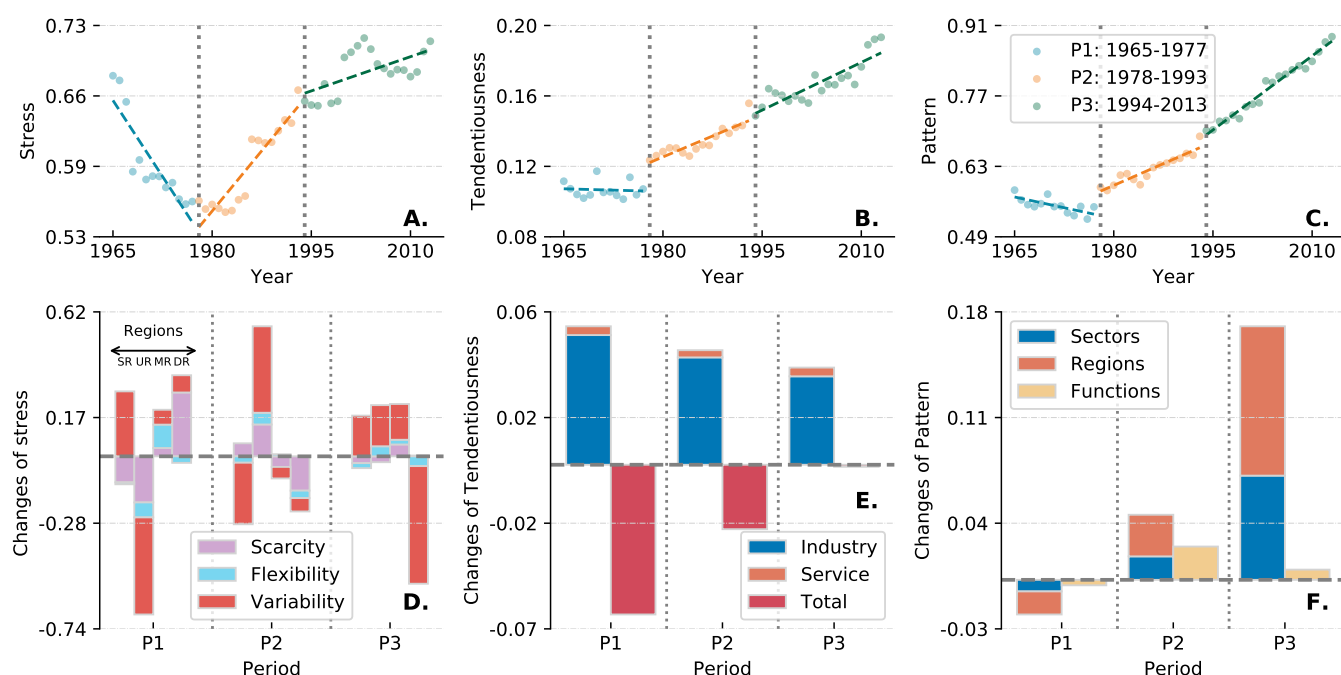


**Fig. 2.** Combination of three dimensions (S: stresses; T: tendentiousness; P: pattern) in different periods. Size of the points denoting values of the IWRU: the mean of the P1 phase is 0.10, while 0.14, 0.19 in P2 and P3. The red indicator line in this ternary plot denotes 1:1 contributions between 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.

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.

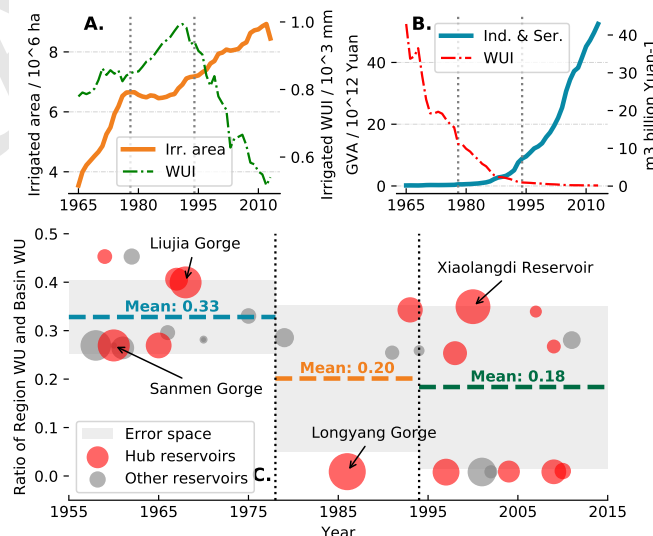


**Fig. 3.** Changes in different dimensions of water resources utilization regime. **A**, changes of scarcity-flexibility-variability water stresses index (SFV-index). **B**, changes of non-provisioning water share, indicating water utilization tendentiousness. **C**, changes of water utilization pattern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

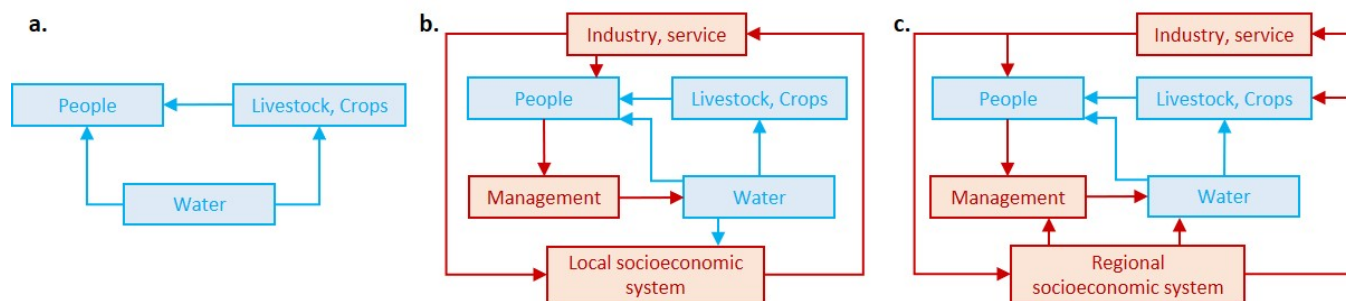
On the other hand, as the most positive contributors to the IWRU index in P2 and P3 separately, tendentiousness and patterns of water utilization were keeping to enlarge their impacts (Figure 3B and Figure 3C). Representing tendentiousness of water utilization, increasing non-provisioning share of water 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 (Figure 4A). During the P1, irrigated agricultural area in the Yellow River basin expanded rapidly at a rate of  $0.25 \times 10^6$ /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 (Figure 4B), 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 (Figure 4A 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**, Constructors' 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, livestock 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.

171 servation practices (supplementary Fig. S6). As a result, the  
172 proportions of water use between the different sectors tend to  
173 average out while the total water consumption remains stable,  
174 after the P3 (supplementary Fig. S7).

175 (3) Changing water management practice contributed  
176 throughout all three periods. In the P1, most of the reser-  
177 vairs are built in regions with high water demands, as ratio of  
178 regional water use and basinal water use for each new reser-  
179 vour are significantly higher (Figure 4C). In the P2, on the  
180 other hand, the number of new reservoirs decreases signifi-  
181 cantly with little increment of total storage capacities (sup-  
182 plementary Fig. S5). Entering the P3, however, the number  
183 of new reservoirs are even much higher than that in the P1,  
184 and most of them were built in regions with lower ratio of  
185 regional water use and basinal water use (Figure 4C and sup-  
186 plementary Fig. S5).

## 187 Discussion

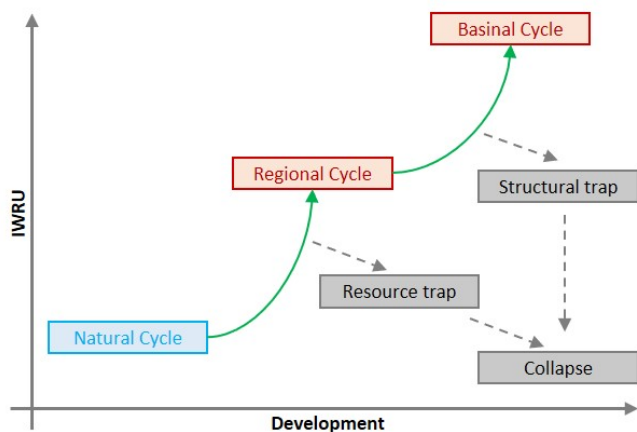
188 **Transition Framework.** Widespread regime shifts in a human-  
189 water system can be triggered by accumulation of gradual  
190 changes, where increasing anthropogenic pressure are among  
191 the most important drivers (4, 5). At the same time, human  
192 society has become more and more dependent on water uti-  
193 lization as it further develops, modifying natural water cycles  
194 by socio-economic processes (1, 14). This social water cycle  
195 has linked to the natural water cycle through water withdraw,  
196 water utilization and drainage, forming a closed chain of in-  
197 terdependence, interconnection and mutual influence, which  
198 is consistent with nature-society dualistic water cycle theory  
199 (15, 16). According to our results, regime shifts of water uti-  
200 lization as transitional phases induced by developing, similar  
201 in social-ecological system, is one of the most important char-  
202 acteristics towards natural-social dualistic structure (2, 17).  
203 As such, we summarized a transition framework of the water  
204 utilization regimes here, which conceptualizes a general trajec-  
205 tory towards a natural-social dualistic water cycle (Figure 5).

206 Throughout the above transition phases towards dualistic  
207 water cycle, three dimensions of water utilization regime  
208 are various in discipline of evolution, corresponding to typ-  
209 ical changes within the Yellow River Basins as an example  
210 (Figure 3). (1) Firstly, although stresses on water resources  
211 increases by economic expansion boosting water demands,

212 socio-economic progress responding to resource scarcity by  
213 better management and efficiency. Water resources were be-  
214 coming more scarce in the Yellow River Basin from P1 to P3,  
215 but the expansion of farmland, the construction of reservoirs,  
216 and the increase in water use efficiency became responses  
217 to different water utilization stresses in aspects (Figure 4).  
218 Since the scarcity of water resources is directly perceptible  
219 and sensitive for utilization, its stresses on societies is one  
220 of the most striking drivers to regime shifts within human-  
221 water systems (8). (2) Secondly, the non-provisioning part  
222 of water demands growths with secondary and tertiary indus-  
223 tries developing, leading tendentiousness of water utilization  
224 continually tilted to the socio-economic part. As original re-  
225 gion of Ancient Chinese Civilization, the Yellow River Basin  
226 used to be dominated by agricultural but in its way to an  
227 energy industry zone now (18). As a result, saving water  
228 consumption in agriculture and making concessions for indus-  
229 try and energy is widely recognized as solutions for the  
230 competing (19, 20). Anyhow, this changes of tendentiousness  
231 reflect a truth that growing socio-economic parts are throw-  
232 ing feedbacks to scarcity of water resources and contributing  
233 to regime shifts. (3) Thirdly, with closer socio-economic ties  
234 and stiffer competition between regions and sectors, the geo-  
235 graphic scope of water resource supply and demand allocation  
236 is expanding, leading to changing patterns of water utilization.  
237 In the Yellow River Basin, the gap in water consumptions be-  
238 tween regions and sectors are narrowing, as the result of a  
239 carefully designed allocation (21). However, the allocation of  
240 water utilization is determined on the basis of regional and  
241 sectoral economic contexts and development trajectories(21).  
242 The changes in water utilization patterns along with regime  
243 shifts, therefore, are the outcomes of feedback loops within  
244 complex human-water systems.

245 By combining the above three dimensions, water utiliza-  
246 tion regimes reflect a tendency of transitional evolution thor-  
247 oughly. In addition to the Yellow River Basin, which is the fo-  
248 cus of this study, human-water relations in major river basins  
249 around the world can be explained by the framework. For  
250 examples, Indus River, Mississippi River, and Danube River,  
251 whose water utilizations have all gone through a relatively  
252 natural phases, rapid developments and integrated manage-  
253 ment regimes. (3, 22). In summary, our proposed transitional





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

framework for the nature-society dualistic water cycle is universal, for identify regime shifts of water utilization.

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

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

To get rid of the resource trap, a clear transformation towards integrated basin management was proposed, with several management practices (supplementary Methods S4 and

Fig. S9). The most important of these is the 87 Water Allocation Scheme, which adopts a top-down approach in allocating water resources to all regions and sectors (21). Since then, the scheme has been revised and refined, and a comprehensive water resources utilization system has gradually been formed that takes the basin scale into account (21). These integrated management practices made the utilization of water resources into a regime of unified scheduling since the P3 in the Yellow River Basin, to escape from the resource trap. Similarly, many of the world's major river basins have eventually moved towards a system of integrated governance, especially for trans-boundary rivers (e.g. Danube and Mekong River), where water resources are in need of collaborative governance (28).

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

## Materials and Methods

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.**

**ACKNOWLEDGMENTS.** Please include your acknowledgments here, set in a single paragraph. Please do not include any acknowledgments in the Supporting Information, or anywhere else in the manuscript.

1. T Gleeson, et al., Illuminating water cycle modifications and Earth system resilience in the Anthropocene. *Water Resour. Res.* **56** (2020).
2. GS Cumming, S von Cramon-Taubadel, Linking economic growth pathways and environmental sustainability by understanding development as alternate social–ecological regimes. *Proc. Natl. Acad. Sci.* **115**, 9533–9538 (2018).
3. J Best, Anthropogenic stresses on the world's big rivers. *Nat. Geosci.* **12**, 7–21 (2019).
4. JC Rocha, G Peterson, Ö Bodin, S Levin, Cascading regime shifts within and across scales. *Science*, 6 (2018).
5. M Falkenmark, L Wang-Erlandsson, J Rockström, Understanding of water resilience in the Anthropocene. *J. Hydrol. X* **2**, 100009 (2019).
6. SL Postel, GC Daily, PR Ehrlich, Human Appropriation of Renewable Fresh Water. *Science* **271**, 785–788 (1996).
7. P Greve, et al., Global assessment of water challenges under uncertainty in water scarcity projections. *Nat. Sustain.* **1**, 486–494 (2018).
8. Y Qin, et al., Flexibility and intensity of global water use. *Nat. Sustain.* **2**, 515–523 (2019).
9. J Liu, et al., Water scarcity assessments in the past, present, and future. *Earth's Futur.* **5**, 545–559 (2017).
10. 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).
11. Y Wada, T Gleeson, L Esnault, Wedge approach to water stress. *Nat. Geosci.* **7**, 615–617 (2014).
12. T Oki, S Kanae, Global Hydrological Cycles and World Water Resources. *Science* **313**, 1068–1072 (2006).
13. T Veldkamp, et al., Water scarcity hotspots travel downstream due to human interventions in the 20th and 21st century. *Nat. Commun.* **8**, 15697 (2017).
14. G Di Baldassarre, et al., Sociohydrology: Scientific Challenges in Addressing the Sustainable Development Goals. *Water Resour. Res.* **55**, 6327–6355 (2019).
15. D Qin, et al., Theoretical framework of dualistic nature–social water cycle. *Chin. Sci. Bull.* **59**, 810–820 (2014).
16. J Liu, D Qin, H Wang, M Wang, Z Yang, Dualistic water cycle pattern and its evolution in Haihe River basin. *Chin. Sci. Bull.* **55**, 1688–1697 (2010).
17. GS Cumming, et al., Implications of agricultural transitions and urbanization for ecosystem services. *Nature* **515**, 50–57 (2014).
18. Will Energy Bases Drain the Yellow River? (year?).
19. X Xiang, J Svensson, S Jia, Will the energy industry drain the water used for agricultural irrigation in the Yellow River basin? *Int. J. Water Resour. Dev.* (2016).
20. C Bebb, Water Rights Transfers and High-Tech Power Plants Hold off Energy-Water Clash in Northern China (2011).
21. Y Wang, S Peng, G Jiang, H Fang, Thirty Years of the Yellow River Water Allocation Scheme and future Prospect. *MATEC Web Conf.* **246**, 01083 (2018).
22. GS Cumming, The resilience of big river basins. *Water Int.* **36**, 63–95 (2011).
23. B Reyers, C Folke, ML Moore, R Biggs, V Galaz, Social-Ecological Systems Insights for Navigating the Dynamics of the Anthropocene. *Annu. Rev. Environ. Resour.* **43**, 267–289 (2018).
24. GS Cumming, KA Dobbs, Quantifying Social-Ecological Scale Mismatches Suggests People Should Be Managed at Broader Scales Than Ecosystems. *One Earth*, S2590332220303511 (2020).
25. S Wang, S Song, J Zhang, B Fu, COSUST\_ms0530 (under review). (year?).
26. I Scoones, et al., Transformations to sustainability: Combining structural, systemic and enabling approaches. *Curr. Opin. Environ. Sustain.*, S1877343519300909 (2020).
27. W Steffen, et al., Trajectories of the Earth System in the Anthropocene. *Proc. Natl. Acad. Sci.* **115**, 8252–8259 (2018).
28. Ö Bodin, Collaborative environmental governance: Achieving collective action in social-ecological systems. *Science* **357**, eaan1114 (2017).
29. RQ Grafton, et al., The paradox of irrigation efficiency. *Science* **361**, 748–750 (2018).