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

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In the context of regime shifts, understanding the complex relationship between human societies and water resources utilization provides underlying supports to development in a coordinated way at a basin scale. However, there is still lacking of effective method to detect regime shifts of water utilization, with much fewer attempts to develop theoretical models to explain their transition phases as well. Here, by integrating three different dimensions of water utilization (stress, tendentiousness and pattern), we develop an Integrated Water Resources Utilization (IWRU) Index at a basin scale to detect regime shifts. By applying this index to the Yellow River Basin, China, we summarized a general transition framework of regimes, which gives a sketch of relationships between human societies and their water utilization. Based on the framework, transition phases within the three regimes and accompanying development traps can be well understood, as a useful guideline for the Yellow River to develop in a coordinated way.

Regime shifts | Human-water relationship | Water resource management | Water utilization | Sustainable development

Water, at the centre of the planetary drama of the Anthropocene, is not only essential for myriad Earth system processes, but also supporting development of human societies in various aspects (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 differ-


Significance Statement

Water, a key resource to support the sustainable development of human societies, whose natural cycle has been modified by growing socio-economic processes. We propose a new method with an integrated indicator to detect water utilization regimes and applying them on the Yellow River Basin, a typical overexploited basin in China. After sketching changes of relationships between development and water utilization within the Yellow River Basin, we summarized a general transition framework. By predicting widespread development traps, it can be a useful guideline for basins all around the world in their sustainable developing trajectories.

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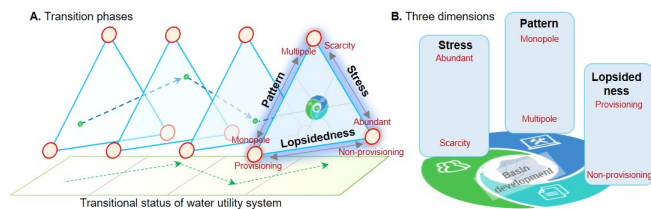
Fig. 1. A framework for understanding the changing relationship between watershed development and water resources.

ent 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
63 in highly water-stressed areas, where dominated sectors of
64 water utilization are various as well. (11, 12) In addition, human activities are still changing this pattern, since positive
66 impacts caused by human interventions mostly occur in up-
67 per regions whereas aggravated water resources downstream,
68 in many basins around the world. (13) Although existing re-
69 searches have evaluated the aspects of water resource utiliza-
70 tion from these different dimensions, we still cannot obtain a
71 coherent understanding of regime shifts regard to social devel-
72 opment and water utilization, without integrating them.

73 Here, by integrating three above mentioned dimensions of
74 water utilization, we develop an Integrated Water Resources
75 Utilization (IWRU) Index at a basin scale to give a sketch of
76 relationships between human societies and their water utiliza-
77 tion. Then, by applying this index to the Yellow River Basin,
78 China, we analysed water utilization regimes and their shifts
79 in this typical basin of anthropogenic impacts, with change
80 points detection and contribution decomposition methods fol-
81 lowing. In addition, combining data analysis, we identify
82 causes of the regime shifts. Finally, refer to the existing theo-
83 ries, we summarized a general transition framework of water
84 utilization regimes, which can be a useful guideline for basins
85 to predict development traps and to develop in a coordinated
86 way.

Results

88 **Detection of Water utilization regimes.** With two significant
89 points detected, the trend of IWRU index are split into three
90 periods, whose slopes are various and mainly contributed by
91 different dimensions (stress, tendentiousness or pattern of wa-
92 ter utilization, see Methods) (Figure 2). In the first period
93 (P1, 1965-1978), the IWRU index had a rapidly increasing
94 and the lightening of water stresses made the most striking
95 contribution (+0.722), while tendentiousness and pattern of
96 the water utilization had slight negative contribution (-0.048
97 and -0.09 respectively). In the second period (P2, 1979-1994),
98 the IWRU index experienced a slight drop, despite positive
99 contributions of tendentiousness and pattern of water utiliza-
100 tion (+0.352 and +0.279 respectively), because of increasing
101 stresses on water resource playing a larger negative role (-
102 0.636). However, as the further increasing of positive con-
103 tributions of water utilization tendentiousness (+0.485) and
104 pattern (+0.515), and decelerations of water stresses (-0.344,
105 46% less than P2) in the third period (P3, 1995-2013), a pos-
106 itive growth of the IWRU returned. As a result, each period
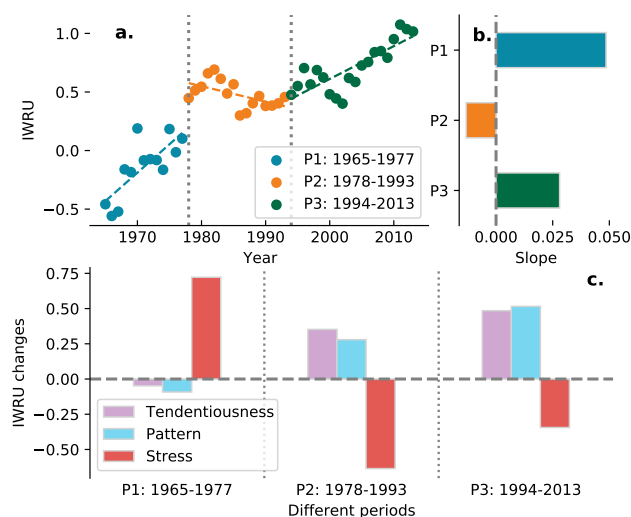
Fig. 2. Changes of the IWRU index. **A,** with two change points in 1978 and 1994, three periods were detected in trend of the IWRU. **B,** changes of IWRU in three periods have various slopes, while the second period have a negative growths rate. **C,** changes of the IWRU within three certain periods, which have different main contributors.

107 has a different most striking positive contributor to IWRU:
108 P1 is stress; P2 is tendentiousness; and P3 is pattern.

109 Combining these three dimensions' net contribution to
IWRU further, ratios of the contributions of the three dimen-
sions clustered clearly by different time periods, indicating 111
three regimes (Figure 3). At the very beginning (1965) and 112
throughout the whole P1, water utilization regime dominated 113
by high stress. After then, it experienced a shift to low stress 114
since 1978, with a change in the proportion of contributions 115
between tendentiousness and pattern, too. Finally, the three 116
dimensions' contribution were much similar in P3, making 117
the points highly concentrated at the centre of the ternary 118
diagram for that period. 119

Differences between water utilization regimes. The differ- 120
ences between the water utilization regimes are reflected in 121
changes of all three dimensions. Moving from the regime in 122
P1 to P2, the most striking change is the reversal of the trend 123
in water utilization stress, which is determined by a combi- 124
nation of scarcity, flexibility and variability (Figure 4A and 125
Figure 4D). In the P1, natural surface water resources were 126
rather abundant with lesser water consumptions (supplemen- 127
tary Fig. S1 and S3) and most of which were flexible water 128
utilization (supplementary Fig. S4). During the P1 and even 129
P2, however, water consumption increases rapidly and natural 130
surface water resources decreases at the same time, making 131
water increasingly scarce. Opposite effect to that, numerous 132
reservoirs built reduced the variability of water resources by 133
boosting storage capacities, but most of which built in P1 134
(supplementary Fig. S5 and supplementary Table S1). As a 135
result, water utilization stress decreases during P1, but begins 136
to rise rapidly in P2. 137

On the other hand, as the most positive contributors to 138
the IWRU index in P2 and P3 separately, tendentiousness 139
and patterns of water utilization were keeping to enlarge their 140
impacts (Figure 4B and Figure 4C). Representing tendentious- 141

Song *et al.*
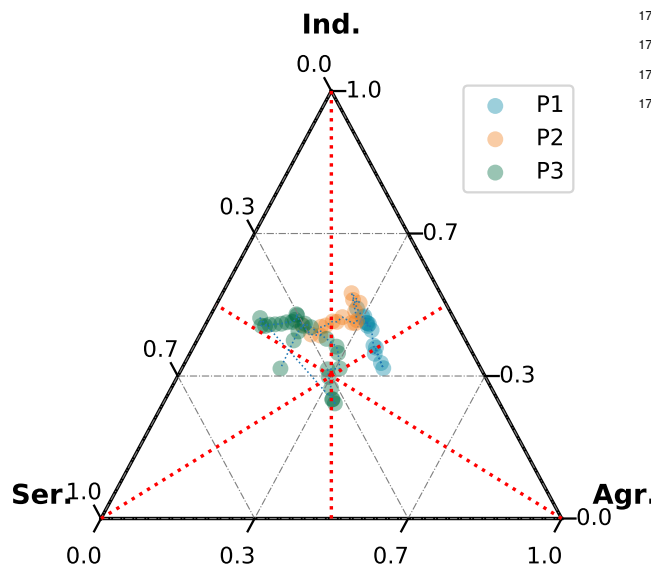
Fig. 3. Combination of three dimensions (S: stresses; T: tendentiousness; P: pattern) in different periods. Size of the points denoting average of absolute value of each indicator: the mean of the P1 phase is 0.10, while 0.14, 0.19 in P2 and P3. The red indicator line in this ternary plot denotes 1:1 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.

ness 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 4E). However, patterns
146 of water utilization, whose contributions to the IWRU are in-
147 creasing, were mainly benefited from decreasing disparities in
148 the amount of water resources used, both intersectoral and
149 regional (Figure 4F).

150 **Causes of water utilization regime changes.** Some main
151 drivers caused the above changes of water utilization regime.
152 (1) The expansion of irrigated area and the economic growth
153 of industry and services are keys to the changes in the ten-
154 dentiousness of water utilization between P1 and P2 (Figure5
155 A). During the P1, irrigated agricultural area in the Yellow
156 River basin expanded rapidly at a rate of $0.25 * 10^6/year$, and
157 irrigation water was the dominant utilization way (81.56% of
158 the total water use in 1965, and 83.17% in 1978). Entering
159 P2, however, while the expansion of irrigated area stalled, in-
160 dustry and services gradually took off and took up more water
161 resources (Figure5 B), leading to 8% reduction of proportion
162 of irrigation water.

163 (2) During the P3, irrigation, whose water consumptions
164 were still dominating, have noticeable changes in its efficiency,
165 however. Although irrigated agricultural area resumed expan-
166 sion, and both industry, urban services were boosting their
167 gross added values (GVA), water use density (WUI) experi-
168 enced significant declines and reached the lowest points (Fig-
169 ure5 A and B). It means, water utilization ways have changed,
170 along with technological solutions and a range of water con-
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-
voirs are built in regions with high water demands, as ratio of 177
regional water use and basinal water use for each new reser- 178
voir are significantly higher (Figure 5C). In the P2, on the 179
other hand, the number of new reservoirs decreases signifi- 180
cantly with little increment of total storage capacities (sup- 181
plementary Fig. S5). Entering the P3, however, the number 182
of new reservoirs are even much higher than that in the P1, 183
and most of them were built in regions with lower ratio of 184
regional water use and basinal water use (Figure 5C and sup- 185
plementary Fig. S5). 186

Discussion 187

Transition Framework. Widespread regime shifts in a human- 188
water system can be triggered by accumulation of gradual 189
changes, where increasing anthropogenic pressure are among 190
the most important drivers (4, 5). At the same time, human 191
society has become more and more dependent on water uti- 192
lization as it further develops, modifying natural water cycles 193
by socio-economic processes (1, 14). This social water cycle 194
has linked to the natural water cycle through water withdraw, 195
water utilization and drainage, forming a closed chain of in- 196
terdependence, interconnection and mutual influence, which 197
is consistent with nature-society dualistic water cycle theory 198
(15, 16). According to our results, regime shifts of water uti- 199
lization as transitional phases induced by developing, similar 200
in social-ecological system, is one of the most important char- 201
acteristics towards natural-social dualistic structure (2, 17). 202
As such, we summarized a transition framework of the water 203
utilization regimes here, which conceptualizes a general trajec- 204
tory towards a natural-social dualistic water cycle (Figure 6). 205

Throughout the above transition phases towards dualis- 206
tic water cycle, three dimensions of water utilization regime 207
are various in discipline of evolution, corresponding to typ- 208
ical changes within the Yellow River Basins as an example 209
(Figure 4). (1) Firstly, although stresses on water resources 210
increases by economic expansion boosting water demands, 211
socio-economic progress responding to resource scarcity by 212
better management and efficiency. Water resources were be- 213
coming more scarce in the Yellow River Basin from P1 to P3, 214
but the expansion of farmland, the construction of reservoirs, 215
and the increase in water use efficiency became responses 216
to different water utilization stresses in aspects (Figure 5). 217
Since the scarcity of water resources is directly perceptible 218
and sensitive for utilization, its stresses on societies is one 219
of the most striking drivers to regime shifts within human- 220
water systems (8). (2) Secondly, the non-provisioning part 221
of water demands growths with secondary and tertiary indus- 222
tries developing, leading tendentiousness of water utilization 223
continually tilted to the socio-economic part. As original re- 224
gion of Ancient Chinese Civilization, the Yellow River Basin 225
used to be dominated by agricultural but in its way to an 226
energy industry zone now (18). As a result, saving water 227
consumption in agriculture and making concessions for in- 228
dustry and energy is widely recognized as solutions for the 229
competing (19, 20). Anyhow, this changes of tendentiousness 230
reflect a truth that growing socio-economic parts are throw- 231
ing feedbacks to scarcity of water resources and contributing 232
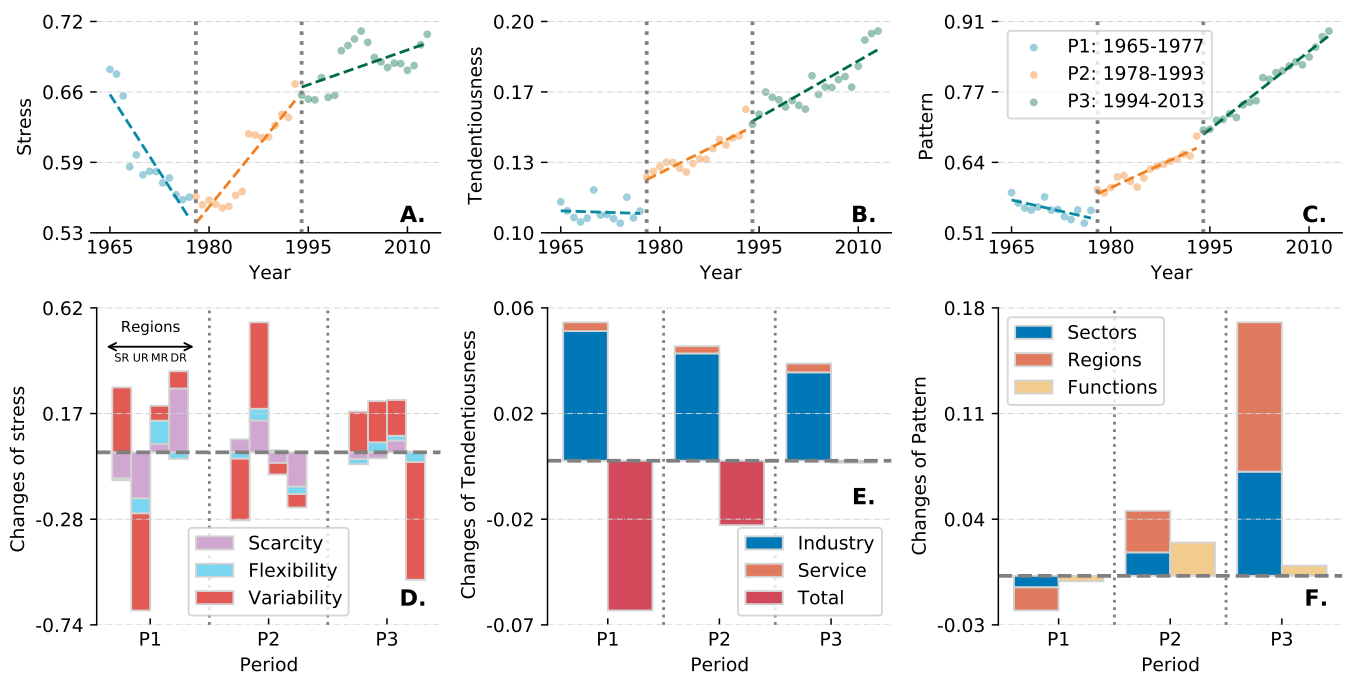
Fig. 4. Changes in different dimensions of water resources utilization regimes and their main contributors. **A,** changes of water utilization stress, indicated by unstandardized scarcity-flexibility-variability water stresses index (SFV-index). **B,** changes of water utilization tendentiousness, indicated by non-provisioning water shares. **C,** changes of water utilization pattern, indicated by unstandardized distribution information entropy index (see supplementary: Methods. S3 for details). **D,** Main impact factors to water utilization stresses in each period or region, and their contributions to changes of unstandardized SFV-index. **E,** Main impact water uses to water utilization tendentiousnesses, and their contributions to changes of non-provisioning water shares. **F,** Main impact factors to water utilization patterns, and their contributions to changes of related unstandardized distribution information entropy index (see supplementary: Methods. S3 for details).
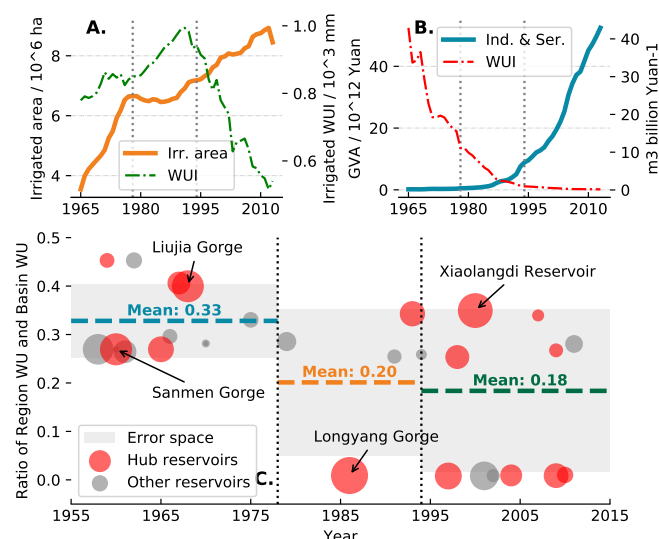

Fig. 5. Causes of water utilization regime shifts: economy growths, efficiency changes, and managements. **A.** Changes of total irrigated area and water consumption per unit of irrigated area. **B.** Changes of gross values added (GVA) of industry and services, and their water use density (WUI) respectively (see supplementary: Methods. S2 for details). **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.

to regime shifts. (3) Thirdly, with closer socio-economic ties and stiffer competition between regions and sectors, the geographic scope of water resource supply and demand allocation is expanding, leading to changing patterns of water utilization. In the Yellow River Basin, the gap in water consumptions between regions and sectors are narrowing, as the result of a carefully designed allocation (21). However, the allocation of water utilization is determined on the basis of regional and sectoral economic contexts and development trajectories(21). The changes in water utilization patterns along with regime shifts, therefore, are the outcomes of feedback loops within complex human-water systems.

By combining the above three dimensions, water utilization regimes reflect a tendency of transitional evolution thoroughly. In addition to the Yellow River Basin, which is the focus of this study, human-water relations in major river basins around the world can be explained by the framework. For examples, Indus River, Mississippi River, and Danube River, whose water utilizations have all gone through a relatively natural phases, rapid developments and integrated management regimes. (3, 22). In summary, our proposed transitional 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 7). 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
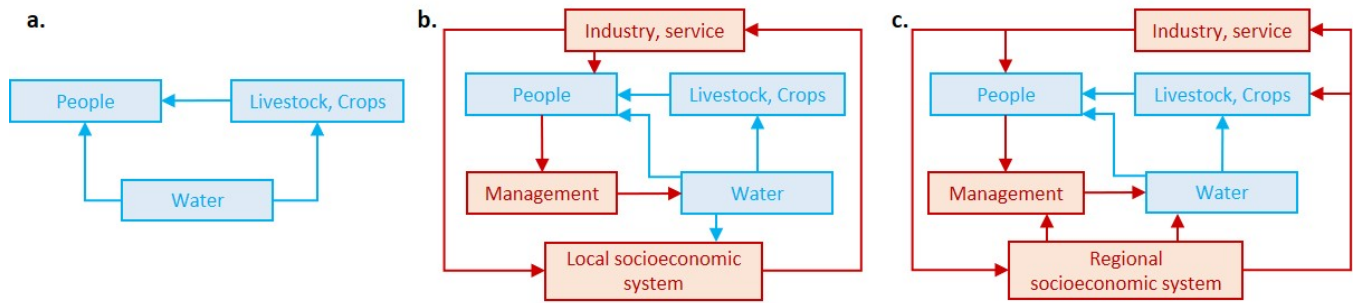
Fig. 6. Transition framework of the water utilization regime towards natural-social binary cycle. **A. Natural cycle:** As a kind of direct provisioning resource, the main functions of water resource is to support crop, livestocks and human-beings, which are the basic ecological services. **B. Regional 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.
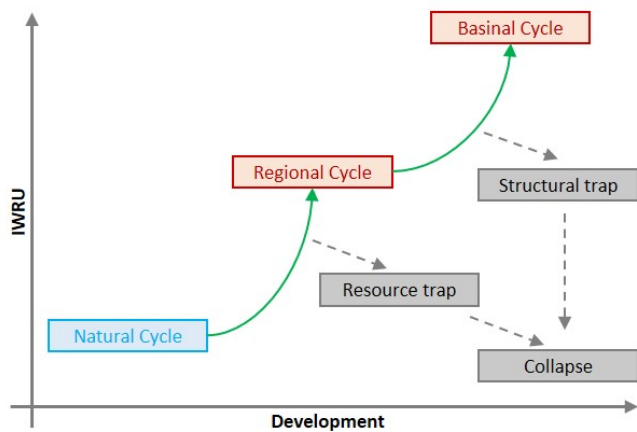
Fig. 7. Transition phases of water resources utilization regime and development traps. Green arrows indicate the trajectory without falling into any development trap, IWRU roughly follows a non-linear upward trend at the same time. However, overexploitation of water resources will leave the system in 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.

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 Yel-

low 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 4E) because of rigidify in the industrial structure. At the same time, the flexibility of water use is declining since domestic water use and thermal water use growth rapidly (supplementary Fig. S4). Typically, these may lead to a reduction in resilience of basins and leave highly coupled human-water systems facing greater vulnerability to collapse –as a structural trap (22). Therefore, based on the identification of current phases and development traps by the transition framework, further trans-

formative governance is still needed to achieve a high-quality sustainable development of the basin (26).

Materials and Methods

Here, we constructed the Integrated Water Resources Utilization (IWRU) Index which consists of three dimensions and identified the regime in the changes of the index over time by change points detection. Finally, the contribution to changes of IWRU index along with each main indicators were calculated separately for each regime (i.e. period).

Integrated Water Resources Utilization (IWRU) Index. The Integrated Water Resources Utilization (IWRU) Index consists of three dimensions (stresses, tendentiousnesses and patterns, denoted by sub-indicators correspondingly). Assuming they have equal weights, we log-transformed and standardized the three sub-indicators for elimination of differences between indicators. It means for each indicator I_{sub}, we performed:

$$I' = log(I_{sub})$$
$$I = (I' - I'_{min})/(I'_{max} - I'_{min})$$

where I is standardized series for I_{sub}. Then, since we assumed different relationships between development and sub-indicators, we added them together in equal weights:

$$IWRU = \sum_{i}^{3} I'_i$$

where i is stress, tendentiousness or pattern, and I'_i is standardized sub-indicator of them. A brief description of the sub-indicators used to measure each dimension follows (see SI Methods. S3 for more details).

Sub-indicator of Stresses. Humans use technology to continuously manage water resources, so a simple physical water scarcity index cannot reasonably assess water scarcity in the evolution and transition of socio-water systems. Therefore, we refer to the scarcity-flexibility-variability (SFV) water stress index proposed in Qin et al., 2019 to evaluate water scarcity in the basin. The index takes into account management measures (such as the construction of reservoirs) and the impact of changes in the industrial structure of water use on the evaluation of water scarcity (8).

To apply this method, we need to combine three metrics following:

First for scarcity, $A_{i,j}$ is the total water consumption as a proportion of regional multi-year average runoff volume, in year j and region i:

$$A_{i,j} = \frac{WU_{i,j}}{R_{i,avg}}$$

Second for flexibility, $B_{i,j}$ is the inflexible water use $WU_{inflexible}$ (i.e. for thermal power plants or humans and livestock) as a proportion of average multi-year runoff, in year i and region j:

$$B_{i,j} = \frac{WU_{inflexible}}{R_{i,avg}}$$

Finally for variability, the capacity of the reservoir and the positive effects of storage on natural runoff fluctuations are also considered.

$$C_i = C1_i * (1 - C2_i)$$
$$C1_{i,j} = \frac{R_{i,std}}{R_{i,avg}}$$
$$C2_i = \frac{RC_i}{R_{i,avg}}, \ if RC < R_{i,avg}$$
$$C2_i = 1, \ if RC >= R_{i,avg}$$

In all the equations above, $R_{i,avg}$ is the average runoff in region i, RC_i is the total storage capacities of reservoirs in the region i, $R_{i,std}$ is the standard deviation of runoff in the region i.

Finally, assuming three metrics (scarcity, flexibility and variability) have the same weights, we can calculate SFV index after normalizing them:

$$V = \frac{A_{normalize} + B_{normalize} + C_{normalize}}{3}$$

$$a = \frac{1}{V_{max} - V_{min}};$$
$$b = \frac{1}{V_{min} - V_{max}} * V_{min}$$
$$SFV = a * V + b$$

Sub-indicator of Tendentiousness. To tendentiousness, we use non-provisioning shares of water use as an indicator. While provisional water use (WU_{pro}) includes domestic, irrigated and livestock water uses, the non-provisioning water use ($WU_{non-pro}$) includes industrial and urban services water uses. Then, we can calculate the non-provisioning shares by:

$$NPS_{ij} = \frac{WU_{indirect,i,j}}{WU_{direct,i,j} + WU_{undirect,i,j}}$$

Sub-indicator of Patterns. To description of patterns between regions or sections, we designed an indicator by imitation of information entropy. Assuming the most egalitarian water allocation is assumed to be that each region or sectoral development utilizes the same proportion of water resources (the case of maximum entropy). The ratio between the actual water allocation entropy and this maximum entropy is the allocation entropy index.

$$ratio = \frac{Entropy}{Entropy_{max}}$$

where $Entropy$ and $Entropy_{max}$ are entropy and maximum entropy of water distributions, respectively. They can be calculated by:

$$Entropy = \sum_{i=1}^{n} \sum_{j=1}^{m} -log(p_{ij}) * p_{ij}$$

$$Entropy_{max} = n * \sum_{j=1}^{m} -\frac{p_j}{n} * log(\frac{p_j}{n})$$

where p_j and p_ij are proportions of water use in sector j and region i:

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

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

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

Change points detection. The method makes no assumptions about the distribution of the data and detects breakpoints based solely on the probability of the data coming from different distributions before and after the breakpoint. The approach after Pettitt (1979) is commonly applied to detect a single change-point in hydrological series or climate series with continuous data (30). It tests the $H0$: The variables follow one or more distributions that have the same location parameter (no change), against the alternative: a change point exists. The non-parametric statistic is defined as:

$$K_t = max|U_{t,T}|$$

where:

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} sgn(X_i - X_j)$$

The change-point of the series is located at K_T, provided that the statistic is significant. We use 0.001 as the threshold of p-value, which means the probability of a statistically significant change-point judgment being valid is more than 99.9%. Since this method only can return one significant change point, we repeat it Until all significant change points were detected.

Contribution decomposition. We have decomposed the amount of variation in each index at different stages in order to observe the contribution of each influencing factor to them. Use Integrated Water Resources Utilization (IWRU) Index as an example, which influenced by three dimensions: stress (S), tendentiousness (T) and pattern (P) (indicated by their own index respectively, see Water utilization regime index and supplementary Methods. S3):

$$IWRU = T * P * S^{-1}$$

Take the logarithm of both sides then, we get:

$$ln(IWRU) = ln(S) + ln(T) - ln(P)$$

Since the changes of IWRU $\Delta IWRU$ can be expressed as $\Delta IWRU = ln(IWRU_2) - ln(IWRU_1)$, where $IWRU_2$ and $IWRU_1$ are ending and beginning values of IWRU in a certain time period, combining the above equations we can get:

$$\Delta IWRU = ln(\frac{S_1}{S_2}) + ln(\frac{T_2}{T_1}) + ln(\frac{P_2}{P_1}) = -\Delta S + \Delta T + \Delta P$$

Then, we can calculate contributions C_F of a certain factor F in a certain period by:

$$C_F = \frac{|\Delta C_F|}{\Delta IWRU}$$

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).
30. AN Pettitt, A Non-Parametric Approach to the Change-Point Problem. *J. Royal Stat. Soc. Ser. C (Applied Stat.* **28**, 126–135 (1979).

Song *et al.*

PNAS | **September 21, 2020** | vol. XXX | no. XX | **7**