Identifying regime transitions for water governance at a basin scale

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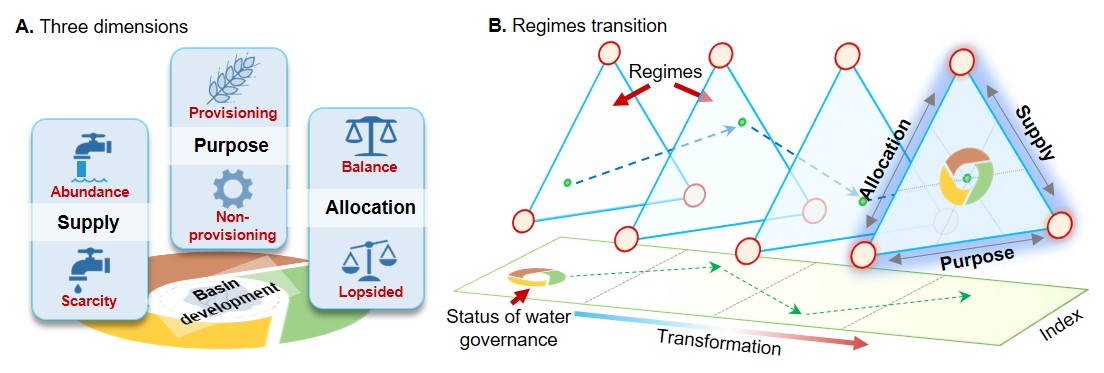
[introduction-section-1] ater has been described as being “at the centre of the planetary drama of the Anthropocene” (Gleeson et al. 2020). It is essential, not only for earth system processes but also in supporting the economic development and continued wellbeing of human societies. Human activities stemming from our reliance on water have profoundly modified the natural water cycle, moving rivers along a trajectory towards a hydrosocial water cycle (Gleeson et al. 2020; Sivapalan, Savenije, and Blöschl 2012; Qin et al. 2014; Abbott et al. 2019; Levia et al. 2020), in which social and power relations dominate the nature of hydrological cycles. Facing this major transformation, many of the world’s big river basins (which are hot spots of civilization and economic growth) are urgently in need of new models of water governance for sustainability (**???**; Falkenmark, Wang-Erlandsson, and Rockström 2019; Di Baldassarre et al. 2019). As an integral part of a proposed earth system governance framework, sustainable water governance requires a deep understanding of the complex relationships between people and water (Biermann et al. 2012; Steffen et al. 2020; Di Baldassarre et al. 2019).

[introduction-section-2] For water resources in populated areas, missing governance means missing sustainability (UNDP Water Governance Facility, Tropp, and Jiménez 2015). A first important step in identifying transitions towards a hydrosocial water cycle is to identify the different regimes under which it occurs. According to the United Nations Development Programme (UNDP), three key dimensions of water use are decided by the water governance regime directly: “How much water can be used?” (supply), “How can different services provided by water be balanced?” (purpose), and “How can water be allocated equally and efficiently?” (allocation) (UNDP Water Governance Facility et al. 2013; UNDP Water Governance Facility, Tropp, and Jiménez 2015; UNDP Water Governance Facility 2016). A regime is defined as a locally stable state of a system’s structure, function, and dominant controls (Carpenter et al. 2011). Large and persistent changes in key system properties may lead to a loss of local stability, potentially resulting in a regime shift with impacts on system outcomes and widespread cascading effects (Rocha et al. 2018; Gregr et al. 2020). Regime shifts are both consequences and signals of substantive changes in water governance, and may lead to new challenges to sustainability (Steffen et al. 2020).

In addition to being caused by changes in key environmental, economic, social and political variables, regime shifts in water governance can be triggered through changes in each of the three key dimensions of governance (supply, purpose, and allocation; (UNDP Water Governance Facility et al. 2013; UNDP Water Governance Facility, Tropp, and Jiménez 2015; UNDP Water Governance Facility 2016)). First, the supply of water depends not only on weather (with worrying long-term trends in many regions, such as the loss of glaciers) but also on the demands of economic activities such as irrigation and industry; water storage can resolve some but not all of these issues (Greve et al. 2018; Wada et al. 2017; Qin et al. 2019). Second, the purposes for which water is used are balanced between consumptive uses (e.g., drinking and food production) and non-consumptive uses (e.g., energy production or fisheries); water may also provide a range of different non-consumptive regulating and cultural services, such as waste disposal or scenic values (Liu et al. 2017; Flörke, Schneider, and McDonald 2018; Kleemann et al. 2020). Water governance can be viewed as the process of assigning weights to each of these different purposes and enforcing the resulting rules. Third, the allocation of water across the whole basin is influenced not only by regional environmental context but also by local socio-economic trends and regions’ comparative economic advantages, which can be altered by changing social and political drivers (Roobavannan et al. 2017; Speed, Li, and Quesne 2013). Despite the obvious relevance of substantive changes in any of the three dimensions of water governance, the lack of a simple but comprehensive method for identifying changes in water governance regimes makes it difficult to achieve water governance for sustainability (Figure [[fig:framework]](#fig:framework)).

[introduction-section-3] As an informative example, we focus on the Yellow River Basin (YRB, see *Appendix* Methods S1 and Figure S1 for details). The YRB has experienced some of the most intense water use and dramatic regime shifts of any large river basin in China, giving rise to long-standing challenges for its governance. From about 550BC until half a century ago, flooding and the huge sediment loads of the Yellow River brought frequent human disasters and the constant shifts in the river’s channel made it difficult for people to use its waters (Song et al. 2020; C. Li et al. 2020). Since the 1960s, the implementation of conservation measures, regulation reservoirs, and levee constructions have contained the issues caused by high-sediment loads (Wang et al. 2016; Wu et al. 2020). However, water over-use has led to drying up of the Yellow River, creating new governance challenges that have been addressed through a range of related policies (e.g., regulating water use and limiting water withdrawals) (Xia and Pahl-Wostl 2012). Today, given that it is still difficult to completely meet water demands and various trade-offs must be negotiated between regions and sectors, there is still a long way to go towards successful water governance (Wang et al. 2019; Wohlfart et al. 2016). All in all, therefore, the YRB has been among the most rapidly-changing large river basins in the world, with myriad responses to the endless governance challenges induced by environmental, economic, social and political factors. Identifying regime shifts in water governance within the YRB can thus provide crucial insights into the world’s rapidly-changing big river basins and the ways in which governance may respond to meeting challenges to their sustainability.

[introduction-section-3] We first use the three key dimensions (supply, purpose and allocation) of water governance to develop an Integrated Water Governance Index (IWGI) that can detect and describe changes in water governance at a basin scale (Figure [[fig:framework]](#fig:framework)). Then, by applying the index to a typical rapid-changing big river basin (the YRB), we show how the index can be used to analyse the complicated regimes of water governance and their main causes in a comprehensive but simple way. Then, by applying the index to a typical rapid-changing big river basin (the YRB), we show how the index can be used to analyse the complicated regimes of water governance and their main causes in a comprehensive but simple way.



# Results

## Water governance regimes

![Changes in the IWGI index. A, Change points detection. With significant change points in 1978 and 1994, the IWGI has three different periods. B, Contributions of each dimension to the changes of IWGI within each of the three periods. Supply, purpose and allocation were respectively the main positive contributors to P1, P2 and P3. ](data:application/pdf;base64,)

Changes in the IWGI index. **A,** Change points detection. With significant change points in 1978 and 1994, the IWGI has three different periods. **B,** Contributions of each dimension to the changes of IWGI within each of the three periods. Supply, purpose and allocation were respectively the main positive contributors to P1, P2 and P3.

With two significant breakpoints, the changes in the IWGI are divided into three periods (Figure [1](#fig:IWGI)A) with different slopes. The changes are contributed by different water governance dimensions (Figure [1](#fig:IWGI)B). In the first period (P1, 1965-1978), the IWGI increased rapidly. Water supply made the most striking positive contribution (131%), while purpose and allocation had a slight negative contribution (-11% and -20%). In the second period (P2, 1979-1994), the contributions of purpose and allocation became positive and the IWGI experienced a drop because steeply declining supply capacity played a larger negative role (dropping to -188% lower than P1). In the third period (P3, 1995-2013), as positive contributions from purpose (75%) and allocation (84%) increased further and the negative contribution of water supply lessened (-59%), positive growth of the IWGI returned.

![Combination of contributions across three dimensions in different periods (S: supply; P: purpose; A: allocation). The closer a point is to an angle of the outside triangle, the greater the proportion of the contribution of this dimension. The red indicator line in this plot denotes a 1:1 contributions between purpose (P) and allocation (A). When the points are below this line, the contribution ratio of allocation is lower than that of function, and vice versa.](data:application/pdf;base64,)

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Each period has a unique most striking positive contributor to IWGI. Overall features of the three dimensions in different periods are shown in Figure [2](#fig:phases). Throughout P1, the water governance regime was dominated by increasing supply capacities. It then experienced a shift, slowing down in increasing supply during P2, with an accompanying reverse in the contributed proportion between purpose and allocation. Finally, the contribution of all three dimensions was similar in P3 (32.91%, 31.87% and 35.21% for purpose, allocation and supply respectively), making the points cluster at the centre of the diagram. The three different periods corresponded to three distinct water governance regimes: a massive supply regime (P1: 1965-1978), a purpose-focused regime (P2: 1979-1993), and a many-sided governance regime (P3: 1994-2013).

## Causes of water governance regime shifts

![ Causes of water governance regime shifts in the Yellow River Basin: environmental change, economic growth and efficiency changes, social transformation, and water governance policies. A. Changes in total irrigated area (orange line), and water uses in per unit of area (WU/A, green dot line, see SI Appendix Methods S2). B. Changes in gross values added (GVA) of industry and services (blue line), and their water use for unit production (WU/GVA, red dot line) respectively (SI Appendix Methods S2). C. Completed time of each new reservoir and their surrounding region’s water use percentages as a proportion of the basin’s total water use (WU) at that time. Red circles denote hub reservoirs in the basin, which play a role in integrated basin water management. The size of each circle indicates the magnitude of its water storage capacity. Some important reservoirs include: (1) Xiaolangdi reservoir and Sanmen Reservoir, which were constructed mainly for managing sediments; and (2) Impoundments at Liujia Gorge, Longyang Gorge, which were constructed mainly for managing flood water discharge and water supply. The named reservoirs are significant for the entire basin, not only for regional development. D. Social transformations and national-level policies related to water governance (see SI Appendix Methods S1 and Table S2). In order, the four transformations are “ethos of conquer nature (since 1958)”, “reform and opening-up (since 1978)”, “the 87 Water Diversion Scheme (since 1987)”, “environmental regulation (since 2003)” in order (see SI Appendix Methods S1). ](data:application/pdf;base64,)

Causes of water governance regime shifts in the Yellow River Basin: environmental change, economic growth and efficiency changes, social transformation, and water governance policies. **A.** Changes in total irrigated area (orange line), and water uses in per unit of area (WU/A, green dot line, see *SI Appendix* Methods S2). **B.** Changes in gross values added (GVA) of industry and services (blue line), and their water use for unit production (WU/GVA, red dot line) respectively (*SI Appendix* Methods S2). **C.** Completed time of each new reservoir and their surrounding region’s water use percentages as a proportion of the basin’s total water use (WU) at that time. Red circles denote hub reservoirs in the basin, which play a role in integrated basin water management. The size of each circle indicates the magnitude of its water storage capacity. Some important reservoirs include: (1) Xiaolangdi reservoir and Sanmen Reservoir, which were constructed mainly for managing sediments; and (2) Impoundments at Liujia Gorge, Longyang Gorge, which were constructed mainly for managing flood water discharge and water supply. The named reservoirs are significant for the entire basin, not only for regional development. **D.** Social transformations and national-level policies related to water governance (see *SI Appendix* Methods S1 and Table S2). In order, the four transformations are “ethos of conquer nature (since 1958)”, “reform and opening-up (since 1978)”, “the 87 Water Diversion Scheme (since 1987)”, “environmental regulation (since 2003)” in order (see *SI Appendix* Methods S1).

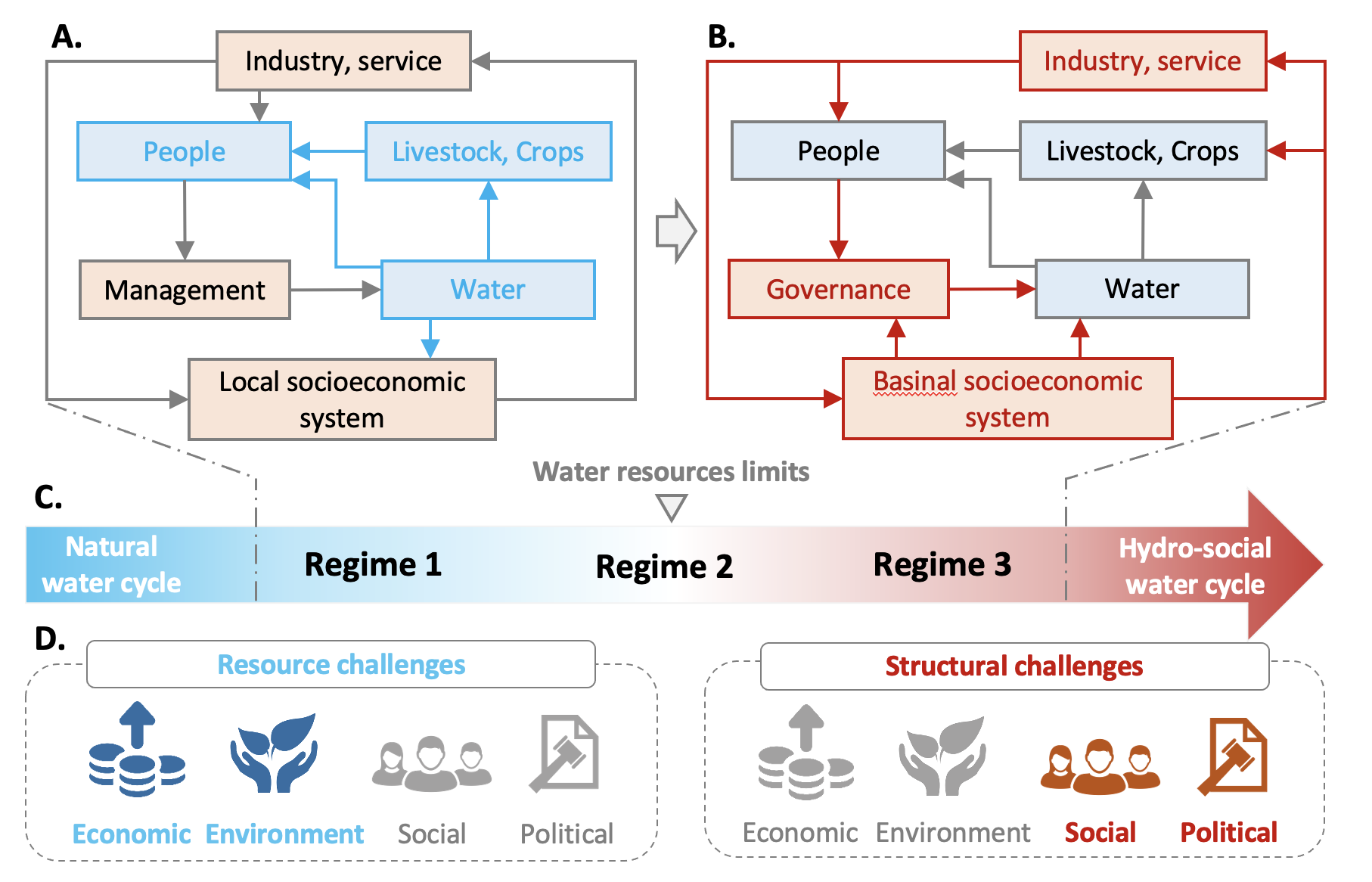
Digging more deeply into the underlying causes of changes in the IWGI, the expansion of irrigated area and the economic growth of industry and services were key to the change in purpose between P1 and P2. During P1, the area of irrigated agriculture in the Yellow River Basin expanded rapidly at a rate of (Figure[3](#fig:Causes) A), and irrigation water was the dominant water use ( of the total water use in 1965, and in 1978 *SI Appendix* Fig. S3). Entering P2, however, the expansion of irrigated area stalled and industry and services gradually took off, with more water demands (Figure[3](#fig:Causes) B), leading to a reduction in the proportion of irrigation water use (*SI Appendix* S3).

The efficiency of water use changed from P2 to P3. While irrigated area resumed its expansion again in P3 (Figure[3](#fig:Causes)A), industry and urban services assumed a stronger economic role (represented by Gross Added Values, GVA) (Figure [3](#fig:Causes)B). However, because of more efficient technology and better water conservation practices (*SI Appendix* Fig. S4), However, because of more efficient technology and better water conservation practices (Figure [3](#fig:Causes)A and Figure [3](#fig:Causes)B). As a result, the differences between sectors of water use were reduced while the total water consumption remained stable during P3 (*SI Appendix* Fig. S3).

Finally, environmental context, social transformation and water governance policies played roles in all three regimes. We calculated the ratios of regional and basinal water use for each reservoir (R/B ratio), with a higher ratio representing a potential role for supply rather than regulation (Figure [3](#fig:Causes)C). Under the guiding ethos of “conquering nature”, most of the reservoirs were built in regions with high water demands during P1, when natural water resources were relatively abundant (*SI Appendix* Fig. S5), and R/B ratios were significantly higher (Figure [3](#fig:Causes)C, p<0.01). In P2, the number of new reservoirs decreased significantly and allocation of water was rigorously controlled by “the 87 Water Diversion Scheme”, with little increase in total water storage capacity (*SI Appendix* Fig. S6). Entering P3, myriad national-level water governance policies were proposed under the guide of “environmental regulation” (Figure [3](#fig:Causes)D), and the number of new reservoirs was even higher for facilitating and regulating objectives. Most of these were built in regions with lower R/B ratios (Figure [3](#fig:Causes)C and *SI Appendix* Fig. S6).

# Discussion

## Water governance challenges along transition regimes



Our results show that there have been three distinct but sequential governance regimes within the YRB (Figure [2](#fig:phases)): a massive supply regime (1965-1978), a purpose-focused regime (1979-1993) and a many-sided governance regime (1994-2013). Shifts between these regimes were caused by different environmental, economic, social or political drivers (Figure [3](#fig:Causes)). It is important to note that each regime occurred gradually, with multifaceted causes, as the basin moves towards a hydrosocial water cycle. The challenges were primarily economic and environmental at the beginning of the YRB’s water governance trajectory and social and policy-related towards the end (Figure [[fig:summary]](#fig:summary)).

During the massive supply regime (1965-1978), the basin economy was mainly dependent on the agriculture and natural water resources were relatively abundant (*SI Appendix* Figure S5); water governance thus tended to supply more resources for agriculture (e.g. by construction of reservoirs and channels). Due to the limited effects of socio-economic feedbacks on this regime, water governance had few protective policies, assumed an unlimited water supply, and took little consideration of the impacts of water use on social equity and the environment (Zhou et al. 2020). Since nearly 80% of surface water was used (mainly for provisioning purposes), the Yellow River dried up during the second half of the regime (*SI Appendix* Figure S7). Ecological issues, such as wetlands shrinkage and declines in biodiversity, emerged as the drying up became more and more serious, leading a huge social-ecological crisis and a significant challenge to existing modes of water governance rigorously (Wohlfart et al. 2016).

The start of the purpose-focused regime (1978) coincided with Chinese “reform and opening-up”. This huge social transformation led to the emergence of industry and services, broke the dominance of agriculture, and resulted in higher competition for water use (Figure [3](#fig:Causes) and *SI Appendix* Fig. S8). In the face of ongoing environmental challenges and new economic challenges, the Yellow River Conservancy Commission (*SI Appendix* Methods S1) underwent a reorganization and received instructions from the Ministry of Water Resources (then called the Ministry of Water Resources and Electric Power) to resume and strengthen work on hydrology and basin management in the YRB (Archives 2004). As a result, new policies and regulations (e.g., “the 87 Water Diversion Scheme”) were introduced in the YRB ahead of the rest of the country to allocate water and successfully stop the expansion of irrigated water consumption (Wang et al. 2018).

The next shift, to the many-sided governance regime, did not occur until a significant increase in water use efficiency in about 1993, overcame some resource limits (Liu et al. 2013). Since socio-economic trade-offs between water-dependent regions and sectors played a more important role at this regime, water governance had to achieve efficient water allocation while balancing different purposes in the face of limited water supply (Dalin et al. 2015). For example, the water rights conversion project that has been popularized during this regime may even save regional agricultural water for industrial developments in other regions, and water transfer has been another huge project to meet water demands within the YRB (Barnett et al. 2015; Yunpeng and Liangzhi 2010). On the other hand, the old water policy (e.g., “The 87 Water Diversion Scheme”), which once helped the YRB resolve its environmental crisis, limited social equity and coordinated allocation under the new regime because of path dependence (Wang et al. 2018). Many national-level water policies were proposed or adjusted under this regime, as the absence of such policies and social injustice in water use became new structural challenges for governance (Konar et al. 2019).

In general, shifts between the three governance regimes occurred sequentially during a transformation towards the hydrosocial cycle. Transition from biophysical control to social and political control of ecosystem dynamics may become increasingly widespread in social-ecological systems as increasing anthropogenic impacts gradually change the world (Best and Darby 2020; Cumming and von Cramon-Taubadel 2018; Cumming et al. 2014). Some of the implications of this kind of change, when accompanied by engineering solutions, have been explored in the Millennium Assessment’s ‘Technogarden’ scenario ((Program) 2005). The transition regimes identified here echo the two kinds of major water governance challenges globally (resource challenges and structural challenges, Figure [[fig:summary]](#fig:summary) and *SI Appendix* Fig. S9) (Singh, Saha, and Tyagi 2019; Porcher and SAUSSIER 2019). Resource challenges, represented as water shortage and water supplying difficulties, are mainly faced by undeveloped and developing basins and are highly related to economic and environmental changes (Allan et al. 2019; Flörke, Schneider, and McDonald 2018; Liu and Yang 2012). Alternatively, highly-controlled and developed basins (especially for transboundary rivers) must mainly resolve structural challenges, such as water disputes or lack of equity, and may be in urgent need of novel flexible, efficient sociopolitical governance structures (Kitroeff 2020; Roobavannan et al. 2017; UNEP-DHI, UNEP, and UNEP 2016). It is typical that resource challenges and structural challenges have occurred sequentially during the transition of water governance within the YRB. Our analysis thus suggests that the initial phase of transition often leads to resource-focused challenges that result from economic, demographic and environmental change; while later phases are dominated by structural challenges relating to social and political aspects of governance. From the perspective of the core dimensions emphasized by the UNDP for water governance, our proposed schema connects governance challenges and the transformation of large river basins towards a hydrosocial water cycle.

Additional challenges are raised by the process of upscaling that occurs as river basins transition between regimes. Under the influence of economic forces, water use gradually changes from being a primarily local concern to becoming a national or international concern, with large river basins being critical sources of ecosystem services, economic development, and human wellbeing. For example, the requirement in the ecological system management of water and sediment diversion in the Xiaolangdi reservoir of the Yellow River leads to rapid cutting of the downstream river, which makes it impossible for farmers to get irrigation water resources for a long time. Successful navigation of water regime transitions through an upscaling process requires a corresponding upscaling in the governance regime and the creation of higher-level institutions that can regulate and manage cross-scale effects.

## Implications and future directions

The IWGI index captures the transitional regimes of water governance in a relatively simple but comprehensive way. It is important for scientists and decision makers to recognize the changing governance challenges, because development is not a panacea for all basin issues regarding sustainability (Cumming and von Cramon-Taubadel 2018; Reyers et al. 2018). Models and approaches developed under one regime are not necessarily useful under a different regime. For today’s world, water-related challenges remains one of the major gaps in our progress towards sustainability, while development-first strategies are still a dominant guideline in many places and may be in opposition to improving governance (Xu et al. 2020; Liu et al. 2017; Greve et al. 2018). Although most large river basins have shown improvements in water management technologies and water use efficiency along with development, freshwater use is still considered to be approaching planetary boundaries where human-water systems may collapse (M. Li et al. 2020; de Graaf et al. 2019; Huggins et al. 2020). Overall, there are probably two main reasons for this apparent failure of governance. First, significant improvement in agricultural irrigation efficiency is usually accompanied by a re-expansion of irrigated area, resulting in an unabated trend of water resources stress (the paradox of efficiency) (Grafton et al. 2018). Second, without successful governance, complicated governance structures dominated by hydrosocial water cycles may result in less flexible water use and undermine the resilience of social-ecological systems at a basin scale (Qin et al. 2019; Levia et al. 2020; Grill et al. 2019). From these perspectives, we need better and more comprehensive strategies to address governance challenges because the core problems are complex and difficult to manage (Steffen et al. 2020; Muneepeerakul and Anderies 2020; **???**; Biermann et al. 2012). A deeper understanding of governance that incorporates ideas of non-liner change, regimes, and transitions should help to shift the focus of governance towards maintaining the resilience of the basin’s social-ecological system and improving its sustainability.

Abbott, Benjamin W., Kevin Bishop, Jay P. Zarnetske, David M. Hannah, Rebecca J. Frei, Camille Minaudo, F.Stuart Chapin, et al. 2019. “A Water Cycle for the Anthropocene.” *Hydrological Processes* 33 (23): 3046–52. <https://doi.org/10.1002/hyp.13544>.

Allan, J. R., N. Levin, K. R. Jones, S. Abdullah, J. Hongoh, V. Hermoso, and S. Kark. 2019. “Navigating the Complexities of Coordinated Conservation Along the River Nile.” *Science Advances* 5 (4): eaau7668. <https://doi.org/10.1126/sciadv.aau7668>.

Archives, Yellow River. 2004. *Organizational History of the Yellow River Conservancy Commission*. Yellow River Water Conservancy Press.

Barnett, Jon, Sarah Rogers, Michael Webber, Brian Finlayson, and Mark Wang. 2015. “Sustainability: Transfer Project Cannot Meet China’s Water Needs.” *Nature News* 527 (7578): 295. <https://doi.org/10.1038/527295a>.

Best, Jim, and Stephen E. Darby. 2020. “The Pace of Human-Induced Change in Large Rivers: Stresses, Resilience, and Vulnerability to Extreme Events.” *One Earth* 2 (6): 510–14. <https://doi.org/10.1016/j.oneear.2020.05.021>.

Biermann, F., K. Abbott, S. Andresen, K. Bäckstrand, S. Bernstein, M. M. Betsill, H. Bulkeley, et al. 2012. “Navigating the Anthropocene: Improving Earth System Governance.” *Science* 335 (6074): 1306–7. <https://doi.org/10.1126/science.1217255>.

Carpenter, S. R., J. J. Cole, M. L. Pace, R. Batt, W. A. Brock, T. Cline, J. Coloso, et al. 2011. “Early Warnings of Regime Shifts: A Whole-Ecosystem Experiment.” *Science* 332 (6033): 1079–82. <https://doi.org/10.1126/science.1203672>.

Cumming, Graeme S., Andreas Buerkert, Ellen M. Hoffmann, Eva Schlecht, Stephan von Cramon-Taubadel, and Teja Tscharntke. 2014. “Implications of Agricultural Transitions and Urbanization for Ecosystem Services.” *Nature* 515 (7525): 50–57. <https://doi.org/10.1038/nature13945>.

Cumming, Graeme S., and Stephan von Cramon-Taubadel. 2018. “Linking Economic Growth Pathways and Environmental Sustainability by Understanding Development as Alternate Socialecological Regimes.” *Proceedings of the National Academy of Sciences* 115 (38): 9533–8. <https://doi.org/10.1073/pnas.1807026115>.

Dalin, Carole, Huanguang Qiu, Naota Hanasaki, Denise L. Mauzerall, and Ignacio Rodriguez-Iturbe. 2015. “Balancing Water Resource Conservation and Food Security in China.” *Proceedings of the National Academy of Sciences* 112 (15): 4588–93. <https://doi.org/10.1073/pnas.1504345112>.

de Graaf, Inge E. M., Tom Gleeson, L. P. H. (Rens) van Beek, Edwin H. Sutanudjaja, and Marc F. P. Bierkens. 2019. “Environmental Flow Limits to Global Groundwater Pumping.” *Nature* 574 (7776): 90–94. <https://doi.org/10.1038/s41586-019-1594-4>.

Di Baldassarre, Giuliano, Murugesu Sivapalan, Maria Rusca, Christophe Cudennec, Margaret Garcia, Heidi Kreibich, Megan Konar, et al. 2019. “Sociohydrology: Scientific Challenges in Addressing the Sustainable Development Goals.” *Water Resources Research* 55 (8): 6327–55. <https://doi.org/10.1029/2018WR023901>.

Falkenmark, Malin, Lan Wang-Erlandsson, and Johan Rockström. 2019. “Understanding of Water Resilience in the Anthropocene.” *Journal of Hydrology X* 2 (January): 100009. <https://doi.org/10.1016/j.hydroa.2018.100009>.

Flörke, Martina, Christof Schneider, and Robert I. McDonald. 2018. “Water Competition Between Cities and Agriculture Driven by Climate Change and Urban Growth.” *Nature Sustainability* 1 (1): 51–58. <https://doi.org/10.1038/s41893-017-0006-8>.

Gleeson, Tom, Lan Wang-Erlandsson, Miina Porkka, Samuel C. Zipper, Fernando Jaramillo, Dieter Gerten, Ingo Fetzer, et al. 2020. “Illuminating Water Cycle Modifications and Earth System Resilience in the Anthropocene.” *Water Resources Research* 56 (4). <https://doi.org/10.1029/2019WR024957>.

Grafton, R. Q., J. Williams, C. J. Perry, F. Molle, C. Ringler, P. Steduto, B. Udall, et al. 2018. “The Paradox of Irrigation Efficiency.” *Science* 361 (6404): 748–50. <https://doi.org/10.1126/science.aat9314>.

Gregr, Edward J., Villy Christensen, Linda Nichol, Rebecca G. Martone, Russell W. Markel, Jane C. Watson, Christopher D. G. Harley, Evgeny A. Pakhomov, Jonathan B. Shurin, and Kai M. A. Chan. 2020. “Cascading Social-Ecological Costs and Benefits Triggered by a Recovering Keystone Predator.” *Science*. <https://doi.org/10.1126/science.aay5342>.

Greve, P., T. Kahil, J. Mochizuki, T. Schinko, Y. Satoh, P. Burek, G. Fischer, et al. 2018. “Global Assessment of Water Challenges Under Uncertainty in Water Scarcity Projections.” *Nature Sustainability* 1 (9): 486–94. <https://doi.org/10.1038/s41893-018-0134-9>.

Grill, G., B. Lehner, M. Thieme, B. Geenen, D. Tickner, F. Antonelli, S. Babu, et al. 2019. “Mapping the World’s Free-Flowing Rivers.” *Nature* 569 (7755): 215–21. <https://doi.org/10.1038/s41586-019-1111-9>.

Huggins, Xander, Tom Gleeson, Matti Kummu, Samuel C Zipper, Tara Troy, Yoshihide Wada, and Jay Famiglietti. 2020. “The Social-Ecological Dimensions of Changing Global Freshwater Availability.” Preprint. EarthArXiv. <https://doi.org/10.31223/osf.io/j97ud>.

Kitroeff, Natalie. 2020. “‘This Is a War’: Cross-Border Fight over Water Erupts in Mexico.” *The New York Times*, October.

Kleemann, Janina, Matthias Schröter, Kenneth J. Bagstad, Christian Kuhlicke, Thomas Kastner, Dor Fridman, Catharina J. E. Schulp, et al. 2020. “Quantifying Interregional Flows of Multiple Ecosystem Services A Case Study for Germany.” *Global Environmental Change* 61 (March): 102051. <https://doi.org/10.1016/j.gloenvcha.2020.102051>.

Konar, Megan, Margaret Garcia, Matthew R. Sanderson, David J. Yu, and Murugesu Sivapalan. 2019. “Expanding the Scope and Foundation of Sociohydrology as the Science of Coupled Human-Water Systems.” *Water Resources Research* 55 (2): 874–87. <https://doi.org/10.1029/2018WR024088>.

Levia, Delphis F., Irena F. Creed, David M. Hannah, Kazuki Nanko, Elizabeth W. Boyer, Darryl E. Carlyle-Moses, Nick van de Giesen, et al. 2020. “Homogenization of the Terrestrial Water Cycle.” *Nature Geoscience* 13 (10): 656–58. <https://doi.org/10.1038/s41561-020-0641-y>.

Li, Congcong, Yongqiang Zhang, Yanjun Shen, and Qiang Yu. 2020. “Decadal Water Storage Decrease Driven by Vegetation Changes in the Yellow River Basin.” *Science Bulletin*, July. <https://doi.org/10.1016/j.scib.2020.07.020>.

Li, Mo, Thomas Wiedmann, Junguo Liu, Yafei Wang, Yuanchao Hu, Zongyong Zhang, and Michalis Hadjikakou. 2020. “Exploring Consumption-Based Planetary Boundary Indicators: An Absolute Water Footprinting Assessment of Chinese Provinces and Cities.” *Water Research* 184 (October): 116163. <https://doi.org/10.1016/j.watres.2020.116163>.

Liu, Jianguo, and Wu Yang. 2012. “Water Sustainability for China and Beyond.” *Science* 337 (6095): 649–50. <https://doi.org/10.1126/science.1219471>.

Liu, Junguo, Hong Yang, Simon N. Gosling, Matti Kummu, Martina Flörke, Stephan Pfister, Naota Hanasaki, et al. 2017. “Water Scarcity Assessments in the Past, Present, and Future.” *Earth’s Future* 5 (6): 545–59. <https://doi.org/10.1002/2016EF000518>.

Liu, Junguo, Chuanfu Zang, Shiying Tian, Jianguo Liu, Hong Yang, Shaofeng Jia, Liangzhi You, Bo Liu, and Miao Zhang. 2013. “Water Conservancy Projects in China: Achievements, Challenges and Way Forward.” *Global Environmental Change* 23 (3): 633–43. <https://doi.org/10.1016/j.gloenvcha.2013.02.002>.

Muneepeerakul, Rachata, and John M. Anderies. 2020. “The Emergence and Resilience of Self-Organized Governance in Coupled Infrastructure Systems.” *Proceedings of the National Academy of Sciences* 117 (9): 4617–22. <https://doi.org/10.1073/pnas.1916169117>.

Porcher, Simon, and Stéphane SAUSSIER, eds. 2019. *Facing the Challenges of Water Governance*. Palgrave Studies in Water Governance: Policy and Practice. Palgrave Macmillan. <https://doi.org/10.1007/978-3-319-98515-2>.

(Program), Millennium Ecosystem Assessment, ed. 2005. *Ecosystems and Human Well-Being: Synthesis*. Washington, DC: Island Press.

Qin, Dayong, Chuiyu Lu, Jiahong Liu, Hao Wang, Jianhua Wang, Haihong Li, Junyin Chu, and Genfa Chen. 2014. “Theoretical Framework of Dualistic NatureSocial Water Cycle.” *Chinese Science Bulletin* 59 (8): 810–20. <https://doi.org/10.1007/s11434-013-0096-2>.

Qin, Yue, Nathaniel D. Mueller, Stefan Siebert, Robert B. Jackson, Amir AghaKouchak, Julie B. Zimmerman, Dan Tong, Chaopeng Hong, and Steven J. Davis. 2019. “Flexibility and Intensity of Global Water Use.” *Nature Sustainability* 2 (6): 515–23. <https://doi.org/10.1038/s41893-019-0294-2>.

Reyers, Belinda, Carl Folke, Michele-Lee Moore, Reinette Biggs, and Victor Galaz. 2018. “Social-Ecological Systems Insights for Navigating the Dynamics of the Anthropocene.” *Annual Review of Environment and Resources* 43 (1): 267–89. <https://doi.org/10.1146/annurev-environ-110615-085349>.

Rocha, Juan C., Garry Peterson, Örjan Bodin, and Simon Levin. 2018. “Cascading Regime Shifts Within and Across Scales.” *Science* 362 (6421): 1379–83. <https://doi.org/10.1126/science.aat7850>.

Roobavannan, M., J. Kandasamy, S. Pande, S. Vigneswaran, and M. Sivapalan. 2017. “Role of Sectoral Transformation in the Evolution of Water Management Norms in Agricultural Catchments: A Sociohydrologic Modeling Analysis: ECONOMIC DIVERSIFICATION IN WATER USEAGE.” *Water Resources Research* 53 (10): 8344–65. <https://doi.org/10.1002/2017WR020671>.

Singh, Amarjit, Dipankar Saha, and Avinash Chand Tyagi, eds. 2019. *Water Governance: Challenges and Prospects*. Springer Water. Springer Singapore. <https://doi.org/10.1007/978-981-13-2700-1>.

Sivapalan, Murugesu, Hubert H. G. Savenije, and Günter Blöschl. 2012. “Socio-Hydrology: A New Science of People and Water: INVITED COMMENTARY.” *Hydrological Processes* 26 (8): 1270–6. <https://doi.org/10.1002/hyp.8426>.

Song, Shuang, Shuai Wang, Bojie Fu, Yanxu Liu, Kevin Wang, Yikai Li, and Yaping Wang. 2020. “Sediment Transport Under Increasing Anthropogenic Stress: Regime Shifts Within the Yellow River, China.” *Ambio* 1 (June). <https://doi.org/10.1007/s13280-020-01350-8>.

Speed, Robert, Yuanyuan Li, and Tom Le Quesne. 2013. *Basin Water Allocation Planning: Principles, Procedures and Approaches for Basin Allocation Planning*. Asian Development Bank.

Steffen, Will, Katherine Richardson, Johan Rockström, Hans Joachim Schellnhuber, Opha Pauline Dube, Sébastien Dutreuil, Timothy M. Lenton, and Jane Lubchenco. 2020. “The Emergence and Evolution of Earth System Science.” *Nature Reviews Earth & Environment* 1 (1): 54–63. <https://doi.org/10.1038/s43017-019-0005-6>.

UNDP Water Governance Facility. 2016. “Water Governance: Issue Sheet.”

UNDP Water Governance Facility, Ingvild Oia, Paavani Reddy, Håkan Tropp, and Håkan Tropp. 2013. *User’s Guide on Assessing Water Governance*. United Nations Development Programme.

UNDP Water Governance Facility, Dr Håkan Tropp, and Dr Alejandro Jiménez. 2015. “Water Governance in Perspective: Water Governance Facility 10 Years 2005-2015.” Water Governance Facility.

UNEP-DHI, UNEP, and UNEP. 2016. *Transboundary River Basins: Status and Trends*.

Wada, Yoshihide, Marc F P Bierkens, Megan Konar, Junguo Liu, Hannes Müller Schmied, Taikan Oki, Yadu Pokhrel, Murugesu Sivapalan, and Tara J Troy. 2017. “HumanWater Interface in Hydrological Modelling: Current Status and Future Directions.” *Hydrol. Earth Syst. Sci.*, 26.

Wang, Shuai, Bojie Fu, Shilong Piao, Yihe Lü, Philippe Ciais, Xiaoming Feng, and Yafeng Wang. 2016. “Reduced Sediment Transport in the Yellow River Due to Anthropogenic Changes.” *Nature Geoscience* 9 (1): 38–41. <https://doi.org/10.1038/ngeo2602>.

Wang, Yaping, Wenwu Zhao, Shuai Wang, Xiaoming Feng, and Yanxu Liu. 2019. “Yellow River Water Rebalanced by Human Regulation.” *Scientific Reports* 9 (1): 9707. <https://doi.org/10.1038/s41598-019-46063-5>.

Wang, Yu, Shaoming Peng, Guiqin Jiang, and Hongbin Fang. 2018. “Thirty Years of the Yellow River Water Allocation Scheme and Future Prospect.” *MATEC Web of Conferences* 246: 01083. <https://doi.org/10.1051/matecconf/201824601083>.

Wohlfart, Christian, Claudia Kuenzer, Cui Chen, and Gaohuan Liu. 2016. “SocialEcological Challenges in the Yellow River Basin (China): A Review.” *Environmental Earth Sciences* 75 (13): 1066. <https://doi.org/10.1007/s12665-016-5864-2>.

Wu, Xutong, Yongping Wei, Bojie Fu, Shuai Wang, Yan Zhao, and Emilio F. Moran. 2020. “Evolution and Effects of the Social-Ecological System over a Millennium in China’s Loess Plateau.” *Science Advances* 6 (41): eabc0276. <https://doi.org/10.1126/sciadv.abc0276>.

Xia, Chun, and Claudia Pahl-Wostl. 2012. “The Development of Water Allocation Management in the Yellow River Basin.” *Water Resources Management* 26 (12): 3395–3414. <https://doi.org/10.1007/s11269-012-0078-1>.

Xu, Zhenci, Sophia N. Chau, Xiuzhi Chen, Jian Zhang, Yingjie Li, Thomas Dietz, Jinyan Wang, et al. 2020. “Assessing Progress Towards Sustainable Development over Space and Time.” *Nature* 577 (7788): 74–78. <https://doi.org/10.1038/s41586-019-1846-3>.

Yunpeng, Xue, and You Liangzhi. 2010. “Water Right Transfer Experiment and the Impact on the Water Resources Management Policy in China: An Overview.” *Business and Public Administration Studies* 5 (3): 52–52.

Zhou, Feng, Yan Bo, Philippe Ciais, Patrice Dumas, Qiuhong Tang, Xuhui Wang, Junguo Liu, et al. 2020. “Deceleration of China’s Human Water Use and Its Key Drivers.” *Proceedings of the National Academy of Sciences*, March, 201909902. <https://doi.org/10.1073/pnas.1909902117>.