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Article

Alignment of social and ecological structures increased the ability of river management

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ABSTRACT

Large hydrologic basins involve multiple stakeholders, and coupled dynamic social and ecological processes. Managing such basins has long been a challenge. Balancing the demand for water from nature against that from humans is always difficult, particularly in arid watersheds. Here, we analyze potential institutional causes of ecological degradation and how it can be reversed by introducing new forms of governance. The framework and assumptions are illustrated using China's second-largest endorheic basin, where empirical evidence shows that the introduction of a new governing authority connecting midstream and downstream actors facilitated the establishment of a new governance regime that is better aligned with the biophysical scales of the watershed. A trans-regional water allocation project initiated by the new higher-level authority successfully rescued downstream oases and restored a dried terminal lake. These outcomes suggest that when social and ecological structures are better aligned our ability to manage the interplay between social and ecological processes increases. However, the lack of direct connection between the actors of the middle and lower reaches resulted in the paradox of an increase in water demand. We therefore suggest that measures to stimulate the emergence of horizontal social ties linking different critical groups of actors across the watershed could further the alignment of the institutional and biophysical structures—without these changes sustainable management of river basins and other common pool resources will remain problematic.

1. Introduction

In ancient China (651 BCE), seven states located near the Yellow River formed the famous "Kwai Qiu League" in order to co-manage their common river. The objective was to avoid the influence of political boundaries on the integrity of the basin and thus to secure smoothness and prevent disaster. This kind of institutional (or socio-ecological) fit, includes horizontal fit, i.e., alignment of social and ecological connectivity, and vertical fit, i.e., alignment of connections linking actors and ecological resources with social and ecological connectivity [1,2]. Such thinking has resonated all over the world, and, crucially, is at the heart of research into socio-ecological systems [3]. Some advanced methods, like socio–ecological network analysis, have been developed to advance institutional fit analysis by explicitly considering collaborations among local and regional organizations [4]. However, more empirical inquiries into how and whether the alignment of social and ecological connectivity would lead to more desirable ecological outcomes are needed.

Ecosystems comprise a complex mix of interdependent components spanning geographical and temporal scales, but typically not well aligned with various human-made governance structures [1,5]. A mismatch of an ecosystem with the relevant structures of governance is usually referred to as a scale mismatch [4]. Such mismatches include: spatial-scale mismatch, temporal mismatch and functional mismatch; here we mainly focus on spatial-scale mismatch. Scale mismatches always compromise ecological connectivity and threaten the ability of ecosystems to provide the ecosystem services that societies rely on Refs. [6–8]. River ecosystems typically transcend political and jurisdictional boundaries, which results in interdependent ecological and/or hydrological components of the same watershed being managed by different actors [9]. These different actors often fail to look beyond the boundaries defining their own part of the watershed [10] resulting in the lack of coordinated management activities, possibly leading

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to mismanagement of their common river, involving free-riding on other's efforts and the "tragedy of the commons" [11]. Further, this institutional fragmentation makes it more challenging for the different actors to act together to maintain ecosystem integrity and resilience at the watershed level, and to negotiate and reconcile different interests striking a favorable balance between natural and human water use [12]. Case studies of fishery and forest conservation projects have empirically tested the presumed relationships between conservation outcomes and certain patterns of alignment of socio-ecological interdependences [2]. However, if and to what extent horizontal and vertical alignments (fit) of governing institutions affect socio-ecological outcomes, and in which contexts, is still an area where substantial knowledge gaps remain, and where empirical evidence is very scarce [1].

Water is a multifunctional and critical resource for ecosystems and societies that tends to transgress different socially defined boundaries [13]. Hence we argue it serves as an excellent topic to study the furthering of understanding on how the alignment of social and ecological structures and processes affects societies' abilities to manage common pool resources sustainably. Here we develop an alignment framework and test the framework using a large-scale watershed with a specific focus on the possible pros and cons of enhancing socio-ecological alignment through the application of a coordinating higher-level actor, and/or through the establishment of direct horizontal social ties between upstream and downstream actors.

2. Materials and methods

2.1. Alignment framework

Here, we build on the new integrated framework of metacoupling (human-nature interactions across space – within a coupled human and natural system or socio-ecological system, and between adjacent and distant systems [14]). We use a minimal social-ecological system (building blocks) (Fig. 1) to show the alignment of social and ecological structures [1,2]. Cross-boundary governance involves at least two adjacent or distant systems (e.g., downstream and midstream in a river basin). Lines represent the linkages between ecological components and communication or collaboration between actors in adjacent or distant systems through flows of water, information, people, energy, and capital. Access to most common pool resources is highly competitive, but it is difficult to exclude other users [15]. It is commonly argued that social and ecological processes need to be aligned in space and time; otherwise, such scale mismatches will make governance inherently difficult because of externality, and result in resource extraction [16]. These assumptions can be captured by two different kinds of fit. Horizontal fit represents the situation of actors (red) managing separate but interconnected ecological components (green). They may be collaborating (Fig. 1c), or not collaborating (Fig. 1a). Vertical fit crosses different network layers as in Fig. 1b and c, where a higher administrative level (orange) operating as a mediating actor indirectly connects the actors at a lower level. We hypothesize that social connectivity is a prerequisite for the alignment of social and ecological structures [1]: it results in a tendency to collaborate and is associated with better preservation of ecological resources and more effective management.

2.2. Study area

To test the alignment framework, we analyzed data from a large river basin. The Heihe River Basin (HRB) is the second-largest endorheic (closed or inward flowing) basin in the arid region of northwestern China, with a total area of approximately 143×10^3 km^2 [17]. Its special geomorphic structure determines the hydrologic characteristics of the basin [18]. The river originates in the ice-covered Qilian Mountains, and then flows across the province of Gansu and the Inner Mongolia Autonomous Region. It then flows northward to disappear in terminal lakes in the Gobi Desert (see caption to Fig. 2a). In the past few decades, HRB has experienced some important transitions, such as agricultural expansion,

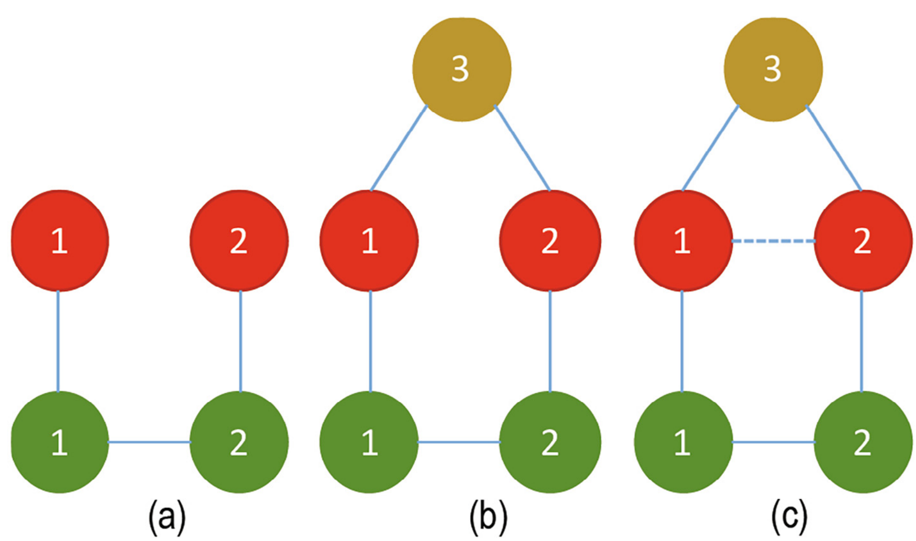

Fig. 1. Diagram showing the alignment of social and ecological structures. (a) A metacoupled human and natural system consists of two socio-ecological systems (e.g., middle and downstream sections of the Heihe River Basin separately managed by Gansu Province and Inner Mongolia of China, Fig. 2). Nodes represent actors (red circles) and ecological components (green circles). Nodes with the same number are of the same socio-ecological system. Lines refer to the connections between ecological components, and communication or collaboration between actors in different systems through flows of water, information, people, capital, and goods. (b) Addition of a higher-level authority (yellow circle) to Fig. 1(a) allows coordination of activities in the socio-ecological systems at the lower level. Our example is the Heihe River Bureau established by the central government of China that indirectly connects Gansu Province and Inner Mongolia through facilitating the implementation of the Ecological Water Diversion Project. (c) Addition of horizontal interactions between actors in the socio-ecological systems (dotted lines) to Fig. 1(b). The lack of direct contact between the actors representing different socio-ecological systems (e.g., Gansu Province and Inner Mongolia) hypothetically leads to the water allocation paradox. By strengthening the direct ties between the actors (dotted line), we hypothesize the allocation paradox could be reconciled.

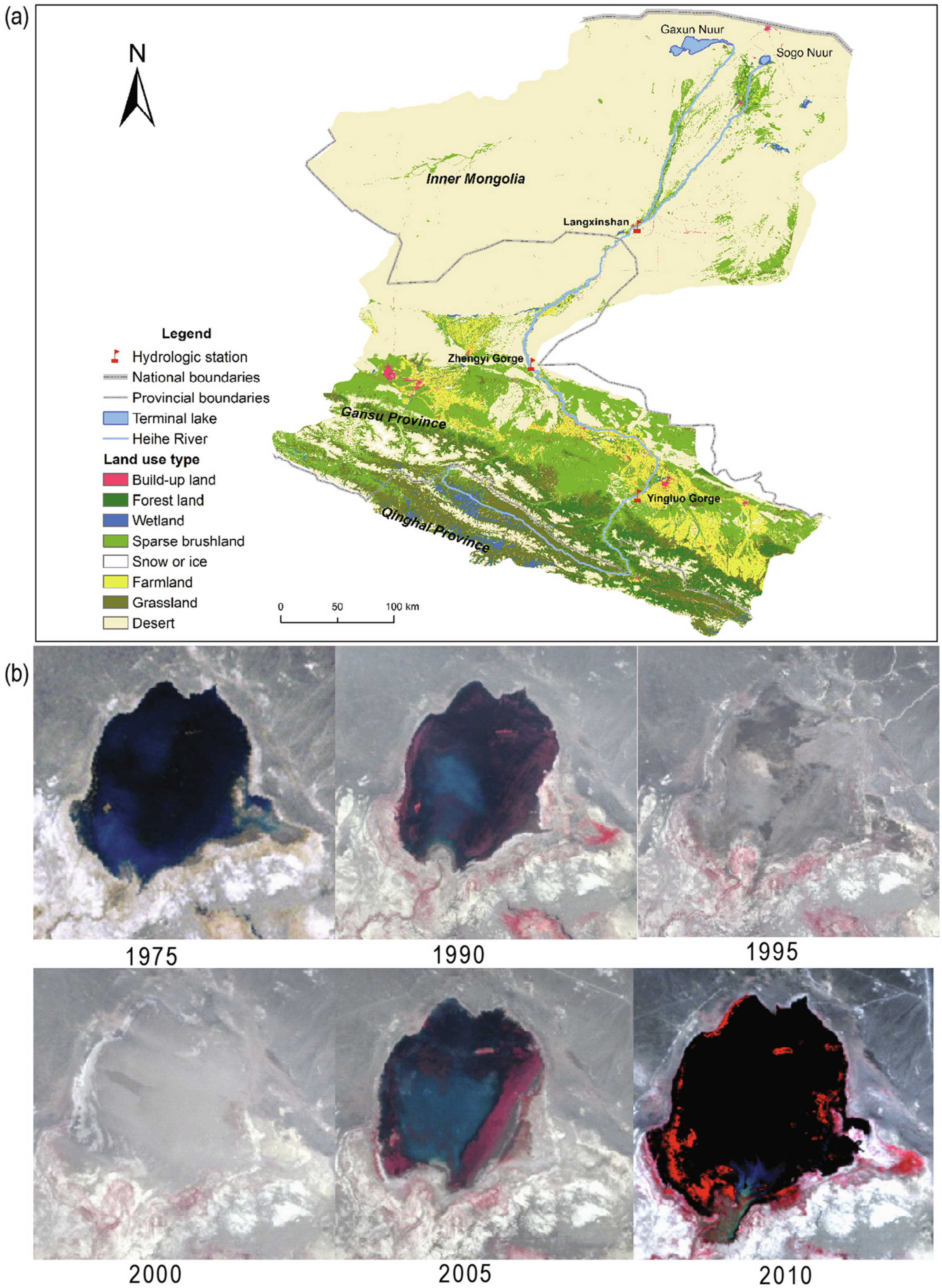

Fig. 2. Location of the Heihe River Basin (HRB) and the degradation and recovery processes of its terminal lake, Sogo Nuur. (a) The Yingluo Gorge station and Zhengyi Gorge station divide the river into distinct upstream, midstream and downstream basin areas. The greater part of the downstream basin area is situated in the Inner Mongolia Autonomous Region, whereas the upstream and midstream areas are in Gansu Province. (b) Landsat satellite images demonstrate the mismatch between the administrative and natural river structures which led to the gradual degradation of downstream ecosystems, the major feature of this is the gradual drying up of the terminal lake, Sogo Nuur (black color refers to water bodies and yellow refers to desert). Since 2000, the Ecological Water Diversion Project (EWDP) has successfully reversed the decline of this lake and the lake area is now stable.

downstream ecological degradation, and the Ecological Water Diversion Project (EWDP) [11] (Fig. 2b). The midstream area is located in the between the gauging stations at Yingluo Gorge and Zhengyi Gorge. It contains a large area of irrigated agriculture [19]. Because this diverse landscape contains many representative ecosystems the HRB has been used as an experimental river basin to pursue integrated water-ecosystem-economic studies over the past three decades [20]. The HRB is thus one of the most instrumented and well-studied river basins in China and abundant data are available [21]. The socio-ecological system in the HRB has changed drastically in the past few decades, giving us the opportunity to analyze the effects of implementing changes in governance and the effectiveness of socio-ecological fit over time. The various governance challenges revealed through these analyses, and the suggestions on how to potentially do better in addressing these challenges, should be useful for the management of other endorheic river basins or common pool resources. Here, we mainly analyze potential institutional causes of the degradation of the river basin's ecosystems, and evaluate the effectiveness of basin ecohydrological conditions and processes, as well as the problems which arise and their possible institutional solutions.

2.3. Data and methods

Data used in this study included hydrological observations, land use and Normalized Difference Vegetation Index (NDVI) datasets, and socioeconomic statistics. The hydrological data were collected from the Heihe River Bureau, including the Yingluo Gorge and the Zhengyi Gorge stations. Groundwater data were collected at long term groundwater monitoring wells in the middle and lower regions. Socioeconomic data were obtained from the regional statistical yearbook, annual reports, and through years of fieldwork in the watershed. The fieldwork involved regular interactions with various different actors and agencies operating in different areas of the watershed. The geographic data, including the locations of hydrologic stations, the basin boundary, river, and lake datasets were downloaded from the Cold and Arid Regions Science Data Center at Lanzhou (http://westdc.westgis.ac.cn/).

Land-use maps were derived from Landsat remote sensing images and the Chinese Huan Jing (HJ) satellite with a ground resolution of 30 m. Thematic mapper (TM) images stemming from the US Geological Survey TM/Enhanced TM dataset were used as a reference for the geometric correction of HJ imagery. The Mean Growing Season Normalized Difference Vegetation Index (MGSNDVI) was used as an indicator of vegetation cover (MGSNDVI > 0.1) in the study area. MGSNDVI is defined as the mean of the NDVIs in the seven-month growing season (April–October) for each pixel. And the least-squares regression approach was used to quantify the multi-annual MGSNDVI trends over the 2000–2010 periods for each pixel. The slope of the trend indicated the magnitude of the change, with positive and negative values of the slope denoting an increasing or decreasing trend, respectively. In this study, an increasing trend was considered to represent vegetation recovery, whereas vegetation degradation was indicated by a decreasing trend. The larger the absolute value of the slope, the more rapid the vegetation change. The trend was considered to be statistically significant at the $P < 0.05$ level. The variations of the annual mean groundwater level were used to reflect the effect of EWDP on groundwater in the middle and lower regions, and the annual mean groundwater level was calculated using regional spatial interpolation (see Supplementary Information online).

3. Results

3.1. Administrative mismatch and ecological degradation

The mid and downstream areas of the HRB are located in Gansu Province and Inner Mongolia respectively (Fig. 2a). Two separate administrative agencies therefore manage sub-regions of the river basin, each with the objective of maximizing their own interests. Neither organization looks at the river and its catchment as an integrated whole (Fig. 1a). This management structure represents a prototypical case of socio-ecological misalignment. The middle reach has long been an important grain-producing area [22]. However, as technology, socioeconomic development and population have increased, so the area of farmland has continuously expanded. For example, from 1990 to 2000, the area of farmland expanded by 686 km^2 (13.9%) in the midstream area (Fig. 3a). Because of the lack of rain in this area, this expansion was mainly as irrigated agriculture, with water being taken from the HRB. This water extraction has led to less water flowing through the Zhengyi Gorge station (Fig. 3a). Since the 1970s there has been an increasing trend in incoming water upstream of Yingluo Gorge station, at a rate of 0.09×10^8 m^3 a^{-2} (Fig. 3b) as a result of the climate change [23]. However, from 1970 to 2000, the water extracted upstream of Zhengyi Gorge station decreased from 71% during the 1970s to 47% during the 1990s (Fig. 3b). The consequent reduction in flow resulted in the drying up of the two terminal lakes, the Sogo Nuur and Gaxun Nuur (Fig. 2b), and the dieback of *Populus euphratica* forests growing as groundwater-fed oases in the downstream basin. This ecological degradation of the downstream basin is serious and the area has become a major source of dust storms [24]. The local social structure and economy nearly collapsed as a result of this degradation. These changes demonstrate the problems that can occur when interconnected components of a river basin are managed by separate organizations that do not collaborate nor adopt a basin-wide perspective in their management activities.

3.2. Aligning social and ecological objectives transforms the ecohydrological regime

In an attempt to remedy this unfavorable situation, the central government of China established the Heihe River Bureau in 1999. This whole-basin, administrative authority was charged with mediating between and coordinating the other sub-basin organizations through the establishment of cross-level ties between actors in Gansu Province and Inner Mongolia. Through these ties, the Bureau could establish itself as the focal point of communication spanning the whole watershed (Fig. 1b). In the year 2000, they also implemented the EWDP [25].

Following the initiation of the EWDP, the annual river flow at Zhengyi Gorge station, as a percentage of the water that flowed through the Yingluo Gorge station, increased by 10% (2000–2010) compared with the period of 1990–2000 (Fig. 3b). In 2002, the terminal lake Sogo Nuur re-appeared. The maximum surface area of the lake has expanded from 27.9 km^2 in 2002 to 61.1 km^2 in 2009 (Fig. S1 online) and it has tended to be stable (Fig. 3c). The ecosystems in downstream areas of the basin have also been considerably restored, with 12% of the downstream area showing a significant increasing trend in Mean Growing Season Normalized Difference Vegetation Index (MGSNDVI) for the period of 2000–2010 (Fig. S2 online). Large areas of *Populus euphratica* forest in the downstream area also recovered (Fig. 3d).

3.3. Water allocation also results in a paradox

Through the executive orders of the central Government, the Heihe River Bureau implemented trans-provincial water allocation and successfully restored the dried lakes and degraded ecosystems. However, some problems have also arisen. One of the most striking problems is the decline of groundwater levels in the middle part of the basin. This has resulted from the continuous expansion of cultivated land even after the EWDP (Fig. 4a). HRB is an integrated river-aquifer system, with many interactions between surface water and groundwater. The increased volume of groundwater extracted in the middle mainstream is almost equal to the increase in the flow which has been allocated to the downstream reaches

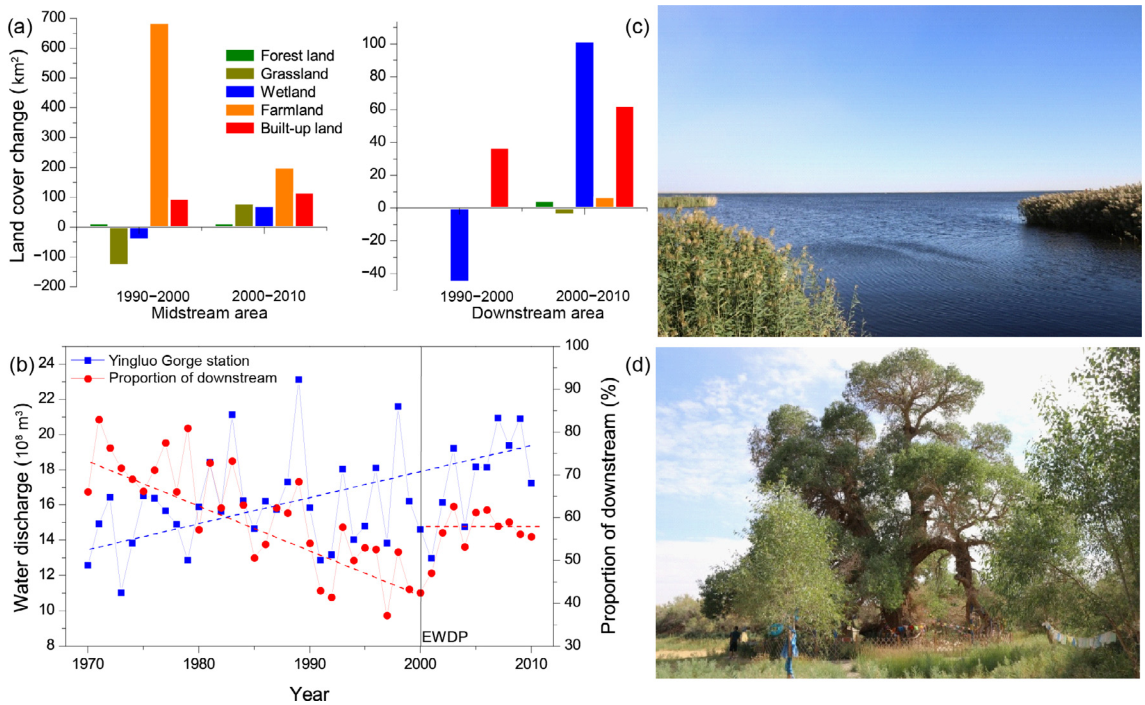

Fig. 3. EWDP-transformed ecohydrological regime shift in the downstream area of the HRB. (a) land-cover changes in the middle and downstream basins during the period of 1990–2000 and 2000–2010. (b) Water discharge from Yingluo Gorge station increased at a rate of $0.09 \times 10^8\ m^3\ a^{-1}$ from 1970 to 2010, while the water allocated to downstream users decreased from 71% during the 1970s to 47% during the 1990s, the EWDP increased the percentage to 57% during 2000–2010. (c) The terminal lake Sogo Nuur recovered and its surface area has expanded to more than 60 km^2 and has doubled compared with 1970s. It is now a well-known tourist attraction (Photo by Wang in 2016). (d) The withered *Populus euphratica* forest gradually recovered, and its area has also expanded (Photo by Wang in 2016).

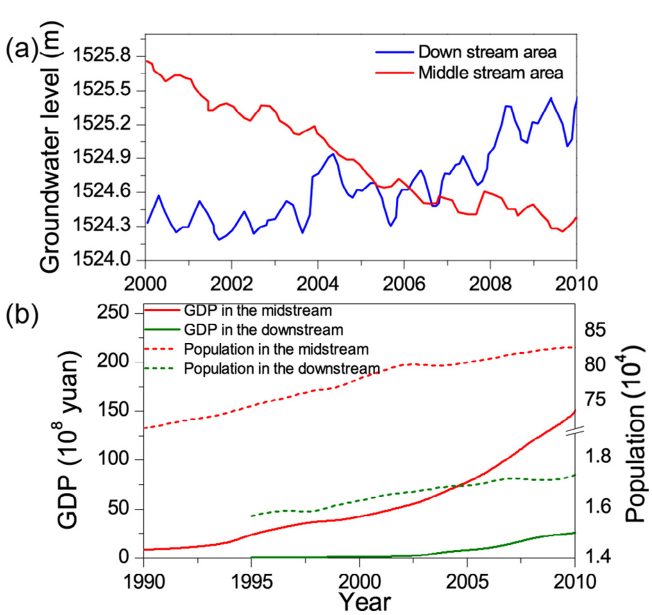

Fig. 4. Water allocation paradox in the HRB. (a) EWDP adds to downstream groundwater and raises groundwater levels, while cropland expansion and groundwater over-pumping in the middle basin area reduced the groundwater level. (b) Population and gross domestic product (GDP) development in the mid and downstream basin areas.

through EWDP [24]. Ecosystems in marginal areas around oases and forests in the midstream area have deteriorated (Fig. S2 online). Additionally, the EWDP has accelerated economic development in the downstream region attracting a large number of people and the development of the midstream basin was continuing at the expense of groundwater extraction (Fig. 4b). However, the area of farmland has doubled, and the demand for water is increasing. Similar to the paradox of efficiency [26], the ways in which water is currently allocated to various users and regions have resulted in a paradox: water allocation does not fully meet the needs of the mid and downstream regions (Fig. S3 online). Instead, it stimulates the downstream water demand and the groundwater over-extraction in the midstream area. This over-extraction is unsustainable and results in serious problems.

4. Discussion and conclusions

4.1. A high-level authority can improve social-ecological fit

Institutional fragmentation resulting from rivers spanning various human-defined boundaries constitutes an archetypical environmental problem often resulting in ecological degradation [27]. As reported here, the degradation of the downstream region of the HRB before 2000 followed this general pattern. A new deliberate and purposeful governance regime reform, can, as demonstrated here, however turn the socio-ecological system "back from the brink" [28]. The successful ecological restoration demonstrates that a third party, especially a higher, administrative agency, with whole-basin responsibility can promote effective coordination on a watershed level by establishing social ties indirectly linking actors across administrative levels [29]. This kind of transition management should, as argued here, ideally adhere to specific types of network configurations and decision-making processes [30]. In China, both river and river-basin management is the responsibility of regional government [31]. In general, China's regional administrations operate in management mode, implementing central government's policies [32]. This framework can lead to problems, but also has some advantages [33]. The central government established the Heihe River Bureau as a coordinator to establish indirect collaboration between the separate administrations of Gansu Province and Inner Mongolia and to balance their interests. Its authority also ensured the smooth implementation of the EWDP and appropriate governance under a whole-basin approach. So cross-border and cross-scale coordination exerted by an appointed higher-level authority can be seen as an effective means to overcome institutional fragmentation. Similarly, the Yellow River Conservancy Committee (YRCC), as the official administrative department for the Yellow River, acts as a mediating actor to coordinate upstream and downstream stakeholders to integrate management of river water and sediment [34]. In 2002, in order to solve the problem of the river drying up and to mitigate the siltation by removing the sediment, they initiated the water-sediment regulation scheme (WSRS). More than ten years after its initial implementation, multidisciplinary indicators showed its objective has generally been achieved [35].

4.2. The water allocation paradox demands a direct horizontal collaboration

The change of the governance structure in the HRB instigated by the establishment of the coordinating authority enhanced the institutional (socio-ecological) fit of the watershed. However, the establishment of the new governance structure is seemingly not sufficient to sustain the prosperity of the basin whose ecosystems are needed to deliver goods and services indefinitely. Fig. 1b shows that although the higher level authority indirectly connects Gansu and Inner Mongolia, there is no direct collaboration between them. As is typical with common pool resources [36], the water from the HRB extracted by Gansu leaves less water available for Inner Mongolia—so competition between these two actors without a direct connection between them led to over-exploitation of the resource [37]. Indeed, both administrations are seemingly still seeking to maximize their own interests: Gansu to ensure food production at the expense of over-extraction of groundwater in the middle reach area; Inner Mongolia to expand farmland in the downstream area. The result was the abuse of ecological water [38]. Besides irrigation, extensive hydropower exploitation and wetlands retention in the midstream of the HRB are probably important reasons for causing the water paradox and ecological degradation. Given that the establishment of the appointed high-level authority did not instigate the actors to extend their management objectives to reach beyond their geographically defined area of responsibly, we suggest there is a need to weave a more inclusive and less centralized governance structure that links these two stakeholders with common objectives directly to each other (Fig. 1c, where the dotted line represents a direct horizontal connection between these actors). The possible arguments behind our suggestion in favor of a more inclusive structure are plentiful, and here we highlight just a few. First, directly engaging with your "competitors" could stimulate a greater appreciation of their specific needs and interests, increase the joint understanding of the social and ecological structures and processes operating on the scale of the watershed, and increase the willingness to agree and commit to jointly negotiated solutions [39,40]. Further, direct engagement tends, over time, to lead to the development of trust in others' commitments to stand by any joint agreement. Such trust is crucial in raising commitment to any agreement [15,40].

Socio-ecological fit implies that the structure of governance should be aligned with the structures of the biophysical system being governed [1]. It follows that knowledge of the specific biophysical characteristics of the ecosystem is crucial. Climate warming in the HRB during these decades has led to greater precipitation, snowmelt and glacier melt, all favorable factors that lead to greater runoff and alleviate water scarcity [23]. Nevertheless, these changes still cannot satisfy the water demand of the mid and downstream areas, which appears as the water allocation paradox. Under the potential threat of increased uncertainty and even the future reduction of water resources, strengthening direct collaboration between the management of the mid and downstream HRB is here suggested as a means to maintain river integrity and sustainable use of water resources. Given the nature of this specific common-pool resource problem, our results suggest that the enhanced watershed-level coordination that followed the establishment of a high-level authority represents a significant improvement over the previous governance regime which suffered from a lack of adequate socio-ecological alignment. Nevertheless, significant problems still remain. We thus conclude by proposing that the current governance regime's abilities to achieving sustainable socio-ecological governance would benefit from the creation of a more inclusive governance structure where the coordinating role of the authority is complemented by horizontal social ties directly linking different upstream and downstream actors.

4.3. Conclusion

In conclusion, as water shortages become more common and competition for water becomes increasingly fierce, the management of trans-boundary rivers is becoming more challenging. So far, few of the world's dried up rivers have successfully recovered. We conclude that the introduction of a new authority with whole-basin responsibility is crucially important. The application of a whole-basin approach facilitates better alignment of social and ecological structures, internalizes externalities and initiates transformation which can lead to the successful restoration and management of degraded river ecosystems. Managing this kind of common pool resource requires the establishment of more direct horizontal social ties between stakeholders.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

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Author contributions

Bojie Fu and Shuai Wang designed the research. Shuai Wang and Bojie Fu wrote the manuscript. Mengmeng Zhang conducted statistical analysis. All the authors contributed to the writing of the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2019.07.016.

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