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Unfolding the complexity in water reallocation decision-making in the Heihe River Basin, China

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Abstract

Water reallocation decision-making is a challenge in most river basins in the world. It is a highly complex process, influenced by the interdependencies between the societal, economic and ecological subsystem of a river basin. However, these interdependencies have not been fully considered in the current approach, leading to delay and failure of water reallocation. We developed a system thinking based framework to structurally unfold the complex interactions of water reallocations with the societal, economic and ecological systems in the Heihe River Basin (HRB) in China. By adopting the integrated qualitative and quantitative approaches, we found that there existed serious time lag in the response of the ecological sub-system to the human economic development. The weak and delayed responses of societal values to ecological degradation and limited considerations of technological development and government regulations contributed to un-timely and weak responses of water reallocations. The system thinking based framework developed in this study can assist strategic water reallocations decision-making in river basins.

Keywords: system-based thinking; water reallocation to environment; complexity of environmental decision-making; societal, economic and ecological sub-systems; river basin; long timeframe

1. Introduction

Global water demand has increased at a rate of about 1% per year (WWAP, 2018) and water withdrawal grew 1.7 times faster than the world population (FAO, 2018) in the past decades. Excessive water extraction has resulted in substantial and irreversible ecological consequences in many river basins in the world (Vörösmarty et al., 2010). Recently, a number of river basins (e.g., The Murray-Darling River basin in Australia, the Yellow River Basin in China, the Colorado river basin in the USA, the Erbo

River Basin in Spain) have started to reallocate water back to environment (Dietz et al., 2003; Garrick et al., 2012; Pahl-Wostl, 2015). However, successful cases of water reallocation are relatively sparse, and their expected benefits are rarely met in full (Bouckaert et al., 2021; Marston & Cai, 2016).

Water reallocation is a type of collective human decision-making. It refers to changes in historical patterns of water use when the existing allocations are unacceptable hydrologically, economically or environmentally (Garrick et al., 2019; Marston & Cai, 2016). In most cases, water reallocation is a mandatory measure taken by a centralized authority to permanently redistribute existing water entitlements. It is increasingly recognised that water reallocation, on the one hand, has to coordinate the economic development and ecological sustainability in the co-evolved river social-ecological system (Pahl-Wostl et al., 2010); on the other hand, it is deeply constructed by societal values, which is defined as the shared attitudes, cultures, beliefs, ideologies, and routines that construct the collective identities of a society (Nyborg et al., 2016; Roobavannan et al., 2018; Smith & Stirling, 2010). In addition, water reallocation is also influenced by science and technological advances, political structure and institutional arrangements and climate change (Biggs et al., 2015; Eakin et al., 2017). With the increasing connectivity and interactions among these subsystems due to human development, water reallocation decision-making should be a highly complex process.

Unfortunately, these interdependencies related to water reallocation have not been taken into full consideration in water reallocation decision-makings, which tended to be linear-thinking and reactive to problematic events (e.g., river dry-up) rather than proactive (Mirchi et al., 2012). Ignoring these interdependencies could hide potential feedbacks underlying each event and create possible time delays which can mask the ultimate effect of management (Meadows, 1974; Sterman, 2001; Wolstenholme, 2003), leading to resistance, delay and failure of water reallocation (Gohari et al., 2017; Zare et al., 2019) in many river basins. The ignorance mainly comes from the methodological challenge. Historically the biophysical sciences have been central in the study of environmental problems but at the root of the environmental crisis are human societies and their interaction with the biophysical world. Recently, the importance of including social science in water reallocation, broadly natural resource management decision-making, is increasingly recognised, but as the social sciences often use qualitative approaches, measurement, quantification and hence integration of societal variables including societal values, technology and institutional arrangement into water resources allocation decision making remain a challenge (Wei et al, 2018).

This paper aims to develop a system thinking based framework to structurally unfold the complex interactions of water reallocations with the societal, economic and ecological systems in river basins. It will identify weak links, delayed feedbacks and strong external drivers of water reallocation in river basin, thus structurally unfold the complexity in decision-making of water reallocation to the environment. Water reallocation in the Heihe River Basin in China with historical data of over 2000 years will be examined, where we have conducted over ten years' cross-disciplinary research, and multiple disciplinary methods and data are accommodated with integrated qualitative and quantitative approaches.

2. Methods

2.1 Conceptual framework

We developed a system-based conceptual framework to examine water reallocation decision-making in a river basin (Figure 1). In this framework, a river basin system is defined as a co-evolved social-ecological system according to Ostrom (2009). It consists of the societal subsystem, represented by the values of multiple stakeholders with different objectives and interests which influence water allocation, the economic subsystem represented by economic activities related to water use, and the ecological subsystem represented by the natural ecosystem related to water use. Water reallocation is central to the framework, which is the direct intervention in hydrology that aims to achieve certain economic (in most cases) and/or ecological outcomes and is driven by change in societal values. These three subsystems co-evolve and provide feedbacks to intended and unintended outcomes of water reallocation decisions (Sterman, 2001; Wolstenholme, 2003). The first reciprocal feedback exists between the economic subsystem and the ecological subsystem, which is driven by the changes in share of total available water resources between the two subsystems. The second and third feedbacks exist between the economic and societal subsystems and between the ecological and societal subsystems, respectively, representing changes in economic and ecological outcomes influence societal values on water reallocation.

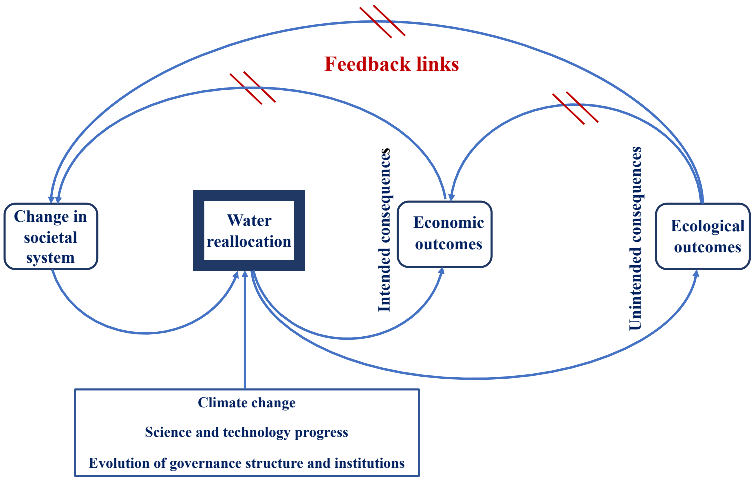


Figure 1. A system developmental framework for water reallocation.

In additions, drivers (internal and external) on water reallocation are considered in this framework. Climate change influences water reallocation through its direct impact on water availability and associated social-ecological system. Science and technological progresses influence the science model we use for understanding water reallocation and our capacity and efficiency on water development and use. Finally, water acts/regulations are considered as the institutional basis of water reallocation.

2.2 Case study

The Heihe River basin (HRB), located in north-western China, is one of the most arid regions in the world and an important part of the ancient Silk Road since the Han Dynasty (206 BC–AD 220). The Heihe River is the second longest endorheic river basin in China, with a length of 821 km and a catchment area of approximately 130,000 km^2. The HRB originates from the Qilian Mountains with annual rainfall of 500 mm and covered with forest and grassland in the northern side of the Tibetan Plateau, which is the principal water source for the HRB. Its midstream area consists of arid and heavily cultivated croplands, with mean annual precipitation ranging from 100 to 250 mm. The Heihe River enters its terminal lakes in the downstream, which mainly comprises dessert and a small area of natural grassland with a mean annual precipitation of less than 50 mm (Figure 2).

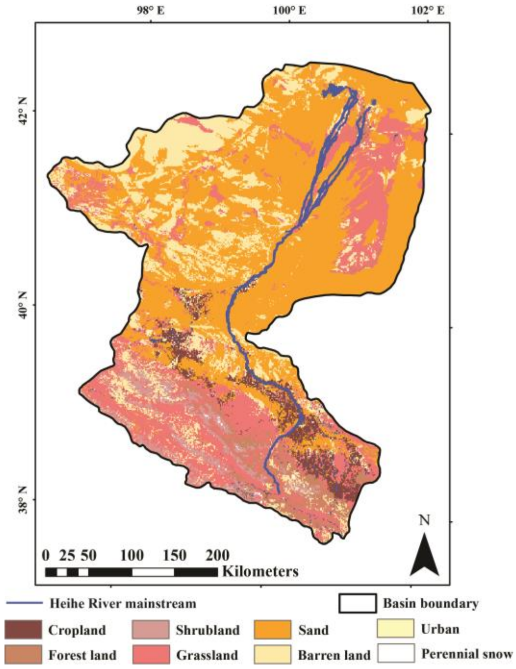


Figure 2. The Heihe River Basin (data source: https://www.tpdc.ac.cn/en/special/heihe/).

The rise and fall of civilizations in the HRB have been closely linked with water. The HRB is an important area for grain production in China and a highly developed irrigation district with an unremittingly agricultural history dating back more than 2000 years ago. Long-term water allocation for agricultural development has significantly modified the catchment vegetation conditions and led to continuing environmental degradation. The implementation of water reallocation to the environment in 2000 marked the beginning of re-balancing water use between economic development and ecological sustainability in the HRB but entangled with complex social hindrance.

There have been extensive studies on the HRB to support grain security, economic development, and ecological restoration for the national development strategy in different periods. The Eco-hydrological Processes Integration Research in Heihe River Basin, an eight-year (2010-2018) program, was one of the largest experimental catchment science programs in the world (Li et al., 2011). By the end of 2017, there were over 800 publications on HRB in Web of Science, putting HRB in the top 40 most-researched river basins globally (Wang et al., 2019). In addition, the HRB has a rich written history of over 2000 years. There are also abundant reconstructed data on climate, hydrology and land use (e.g., Qin et al., 2010; Xie et al., 2015).

2.3 Methods and Data

We selected the major indicators to represent the water reallocation, societal, economic, and ecological subsystems and external drivers in the HRB as defined in Figure 1. They are summarised in Table 1.

Table 1. Indicators for water reallocation and river basin subsystems and their data sources

Subsystems	Indicator	Data sources
Water reallocation	Water allocation agreements	Zhong et al. (2014) and Ministry of Water Resources, China.
	Human water use	Before 1950s, Lu et al. (2015); After 1950s, Gansu Hydrology Bureau, China and Chinese Bulletin of Rivers and Sediments.
	Environmental water use	Before 1950s, Lu et al. (2015); After 1950s, Gansu Hydrology Bureau, China and Chinese Bulletin of Rivers and Sediments.
Economic subsystem	Population	Before 1950s, Tang et al. (2018) and Lu et al. (2018); After 1950s, Gansu Annual Books, China.
	NPP of cultivated oasis	Extended from Lu et al. (2018).
Ecological subsystem	NPP of natural oasis	Extended from Lu et al. (2018).
	Runoff into terminal lakes	Before 1950s, Lu et al. (2015); After 1950s, Gansu Hydrology Bureau, China and Chinese Bulletin of Rivers and Sediments.
Societal subsystem	Societal value on water	Before 1950s: Zhao (2016), Zhou (2011); and Wang (2014). After 1950s: extended from Xiong et al. (2016)
Drivers (internal and external)	Temperature	Before 1950s, Ge (2011); After 1950s, China Administration of Meteorology.
	Precipitation	Before 1950s, Yang et al. (2014);

		After 1950s, China Administration of Meteorology.
	Water science and technology	Before 1950s: Wu (2017); After 1950s: Wang et al. (2019), Gansu Annual Books and Gansu Hydrology Bureau, China, Zhiwang Database, Web of Science Database.
	Government structure	Before 1950s: Ding (2019); After 1950s: PRC Government website.
	Government acts/regulations	Before 1950s: Ding (2019) and Wang et al. (2017); After 1950s: China State Council departments and China Legislative Affairs Office.

Firstly, we qualitatively examined the development history of water reallocation agreements. Then we quantitatively represented water reallocation by the amount of water consumed by the economic subsystem and those kept for the ecological subsystem (environmental water use). These are the core indicators linking water reallocation with the three subsystems and external drivers (Figure 1). For the economic subsystem, population was used as a commonly recognised indicator for human development (Holdren & Ehrlich, 1974), and the Net Primary Production (NPP) of the cultivated oasis in the HRB was also considered as an indicator to reflect human impacts on agricultural-focused terrestrial ecosystems (Haberl et al., 2007). For the ecological subsystem, runoff into terminal lakes was chosen as an indicator to reflect the health of an endorheic river ecosystem, and NPP of the natural oasis in the HRB was also considered.

The societal subsystem was characterised with the public attitudes on water reported in historical documents and newspapers. These attitudes reflect the collective societal values in the HRB and were captured via a systematic coding scheme using content analysis. This method was used to code textual data into structured categories including the issues discussed and tones regarding issues. The tones of each document were categorized into two different values: “economic-oriented” or “environmental-oriented” on a normalised scale of 0 (neutral) to 1 (100% economic-oriented or environmental-oriented) to understand their influences on water reallocation. The former focused on issues that addressed the demand of economic and human development such as construction of water storage, and irrigation delivery infrastructure for consumptive use, and the latter about issues such as concerns of river dry-up and vegetation degradation. Detailed descriptions for this method can be found in Supplementary Material A.

In additions, the impacts of internal and external drivers on water reallocations were investigated. Temperature and precipitation were included as common indicators to express the impacts of climate change, which work together to modify the hydrological processes and water shared between humans and the environment. The progress of science and technology was represented with the relevant historical documents and recent publications in the Web of Sciences to reflect their impacts on water reallocation. The governance impacts were represented with the position of the water management bureau in the Chinese government structure and acts/regulations on water resources to reflect the institutional basis of water reallocation. Similar to the societal subsystem, the impacts of science and technology and institutional arrangements were coded a scale from 0 (neutral) to 1 (complete economic or environmental perspectives) respectively. Detailed descriptions for the methods on these two variables in Supplementary Material A.

The author team, in particular the first author, had conducted nearly ten years' multiple disciplinary studies in the HRB during the implementation period of the Program 'The Eco-hydrological Processes Integration Research in Heihe River Basin'. This paper was built on over twenty journal papers produced from six PhD research projects across climatic hydrology, eco-hydrology, hydrologic economy, societal value on water, government institutions on water and science & technology development on water in the HRB, in which the integrated qualitative and quantitative approaches were adopted. Therefore, a majority of data sources for these selected indicators came from our over twenty journal publications (Table 1). It should be noted that different data sources were used for the majority of indicators before and after 1950s, with the data after 1950s being instrumentally collected in a yearly time scale.

We selected eight historical periods for this study based on the data availability and our previous work. It spanned from 0 AD when the first large-scale human settlement occurred in the HRB to 2017, covering over 2000 years (Table 2).

Table 2. Study periods

Historical period	Time span
Han	0 –220 AD
Wei – Jin Era	221–581 AD
Sui –Tang	582-960 AD
Song (Xi Xia) – Yuan	961-1368 AD
Ming – Qing	1369-1911AD
Republic of China (ROC)	1912-1949 AD
People’s Republic of China (PRC)	1949-2017 AD

2.4 Analysis approach

We applied system-based thinking to explore the complexity of water reallocation. Events, patterns, structures and drivers characterizing a complex system were analysed in a combined way (Sterman, 2001). As complex system behaviours in particular those related to the societal subsystems could not be fully understood only through quantitative analysis (Banson et al., 2016; Forrester, 1992), both qualitative and quantitative approach were used in this study. Firstly, the evolution of each subsystem was described with key events in time as decision makers usually offer solutions based on observed events. Then, the patterns (development phases) of each subsystem were analysed by identifying the abrupt changes in time which provides more meaningful information than events. This was conducted by using a change point detection algorithm if the non-linear relationship better fitted the data pattern {Killick, 2014 #1004}{Samhouri, 2017 #1005}. Following, the systemic structure characterized with the interdependencies between subsystems were analysed with Pearson correlations using the SPSS Statistics 25 software with correlation coefficients to represent the strengths of links between subsystems. Additionally, the drivers of water reallocation were analysed to identify if they were missed from the big-picture perspective by conducing Pearson correlations in a pairwise manner for both internal and external drivers with water reallocation.

Finally, our conceptual framework was tested by stepwise linear regression models, of which the societal subsystem was the key determinant of water reallocation, taking into considerations of internal and external drivers. Specifically, in these models, the human and natural water consumptions were dependent variables respectively, and societal value, temperature, precipitation, technology development, and institutions as independent variables. These regression models were assessed by adjusted R^2 for model fits and t-statistics for significance, and Variance Inflation Factors (VIF) for each variable for potential multicollinearity (Zhang et al., 2007).

3. Results

3.1 Evolution of water reallocation in the HRB

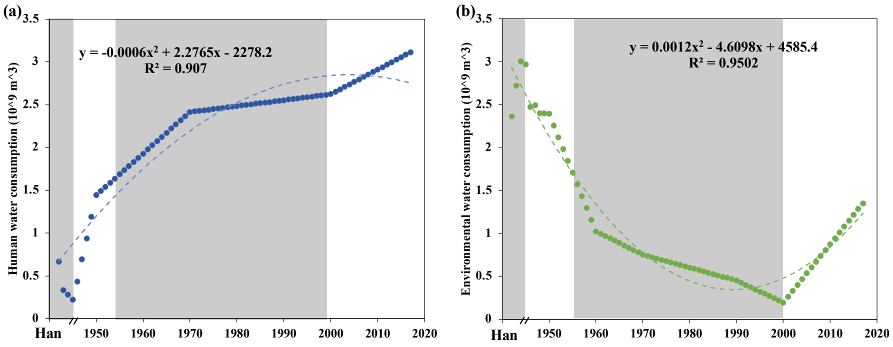
The HRB experienced a long history of water reallocation for human use, beginning with the first large scale human settlement in the Han Dynasty (200 AD) and followed by three water reallocations till 2017 (Table 3). The first water reallocation occurred during the Ming Dynasty (1400 AD), which was a response to emerging water conflicts within the economic subsystem in the midstream and aimed to allocate more water to greater cultivated areas. The second water reallocation was to address the intensified water conflicts still within the economic subsystem but between the middle and downstream, by allocating water exclusively to the downstream for 10 days before crop grain harvest every year in the Qing Dynasty (1726 AD).

The third water reallocation was a response to conflict between human water use and the environment. It was discussed for a long time and experienced great societal hinderance before actual implementation. The initial draft was proposed as early as the 1960s by the downstream community against water overexploitation in the midstream since 1950. With more than 100 dams constructed during this period, there had been river cut-offs in downstream area for over 100 days every year since the 1960s. The west terminal lake Gaxun Nur completely dried up in 1963. While this reallocation draft was under prolonged discussion from 1960 to 1992 involving repetitive bargaining between the midstream and downstream areas, the environmental conditions downstream continued to deteriorate. In the 1990s, river cut-offs extended to over 200 days per year and the east terminal lake Sogo Nur completely dried up in 1992. Although the water reallocation draft was again revised and re-issued by the Ministry of Water Resources in 1992 and 1997 respectively, neither were implemented. It was not finalized and implemented until 2000. This reallocation specified that when the incoming streamflow at Yingluoxia (boundary between the upstream and midstream) was larger than 1.58 billion m^3, the runoff into downstream at the Zhengyixia (boundary between the midstream and downstream) should be maintained at 0.95 billion m^3, equivalent to 60% of total water available.

Table 3. Water reallocation in the HRB

Water allocation	Explanation	Period
Water allocation	The first large scale extraction and use of water by humans.	Han (0-220 AD)
1st water reallocation	Within economic subsystem in the midstream.	Ming (1400 AD)
2nd water reallocation	Within economic subsystem between middle and down streams.	Qing (1726 AD)
3rd water reallocation	Between economic subsystem and ecological subsystem.	2000 AD

Regardless of the first and second water reallocations within the economic subsystem during the pre-industrial period (before 1949), significant increases in human water use in the HRB appeared in the 1950s due to unprecedented industrial development (Figure 3a), and unsurprisingly water for the environment declined during the same period (Figure 3b). It was not until 1955 that human water uses surpassed environmental water use at about 1.7 billion m^3, marking the first transition in which human water use began to dominate in the HRB. From the 1960s to 1990s, further deterioration of the natural environment was signalled by a second phase transition of the amount of environmental water use reducing to as low as 0.2 billion m^3, while the amount of human water use remained stable at about 2.5 billion m^3. In the final phase (after 2000), although human water use increased, environmental water use was also progressively restored to over 1.2 billion m^3.



Note: The historical time points before 1950 refer to the average value from the Han to Ming-Qing Period as defined in Table 2, and shadows indicate phase transitions.

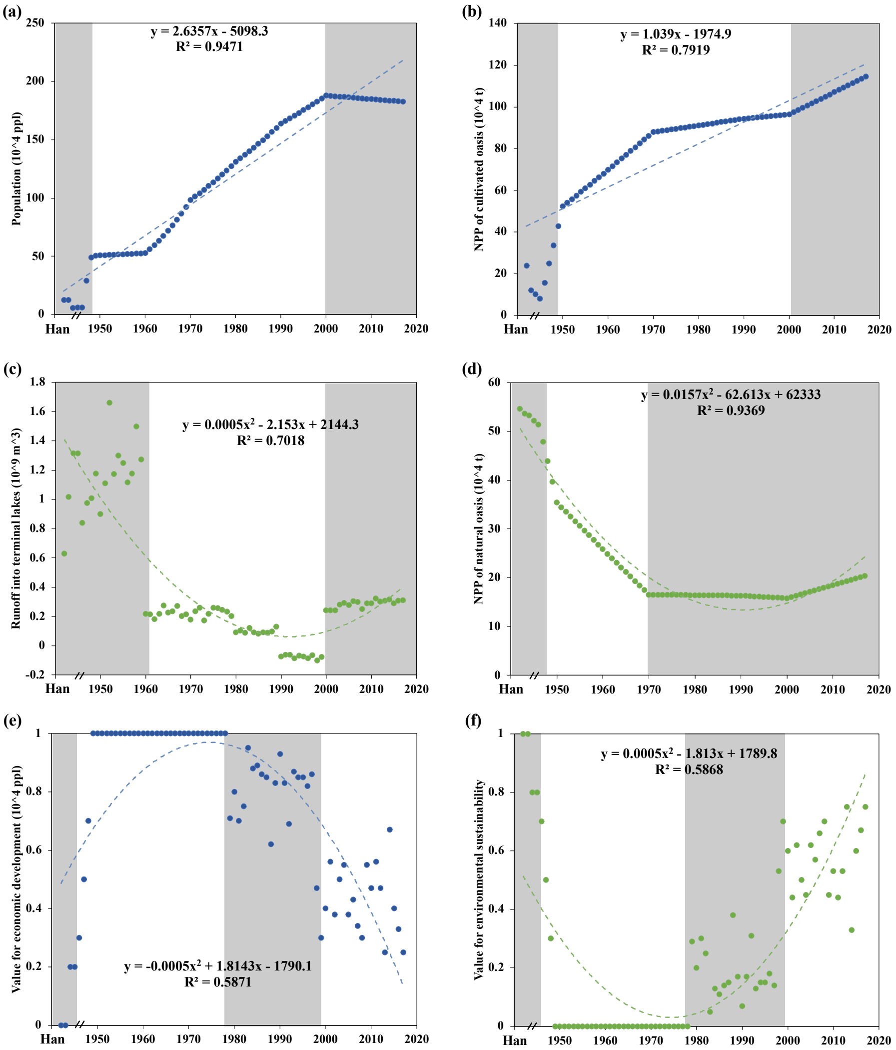
Figure 3. Temporal evolution of water reallocation: (a) human water use, and (b) environmental water use.

3.2 Evolution of the economic, ecological and societal subsystems in the HRB

The economic subsystem demonstrated clear positive development while the ecological subsystem declined in the HRB (Figure 4a-d). In the economic subsystem, population remained below 200,000 during the pre-industrial period, and increased steadily from about 500,000 since the 1950s to about 1.8 million in the 2000s (Figure 4a). Similar trend was observed for the NPP of the cultivated oasis, which supported the population growth in the HRB (Figure 4b). With an average value of about 300,000 tons during the pre-industrial period, an increase of about 3 times was observed from the 1950s to 2000s. The final phase was characterized by slight reduction of the population and continued increases in NPP of cultivated oasis.

For the ecological subsystem, both runoff to the terminal lakes and the NPP of the natural oasis presented a decreasing trend. The amount of runoffs flowing into terminal lakes varied at an average of about 1 billion m^3 per year during the pre-industrial period. A significant phase transition occurred during the late 1950s and early 1960s, when there was over 10-fold reduction in inflow to the downstream areas. The runoffs continued to reduce as the west terminal lake Gaxun Nur dried up in 1963 and lake Sogo Nur dried up in 1992. The terminal lakes reappeared after 2000 with reallocated runoffs of about 0.4 billion m^3 in 2017, indicating the beginning of a restoration phase (Figure 4c). The NPP of natural oasis dominated the total NPP (up to 90%) during the pre-industrial period and remained relatively stable at about 500,000 tons. A rapid reduction phase occurred in the 1950s with over 60% reductions. Since the 1970s, reductions in NPP of natural oasis slowed down and remained steady at about 200,000 tons (Figure 4d).

The evolution of societal values relating to water, characterised in terms of economic development and environmental protection fitted a second-degree parabola (Figure 4e-f). The change of societal values experienced four phases. The first phase spanned across the pre-industrial period to 1911, with societal values inclined towards environmental protection . During this phase, due to extremely low productivity, human survival was subject to the natural environment, humans perceived nature with strong awe. The following phase, extending from the ROC period to late 1970s, was characterised by the transition of an agricultural society into an industrial one. Water resources were considered a mean to support this transition. Environmental sustainability was overshadowed by strong socio-economic goals such as poverty reduction, rural economic development, and national food security. From the 1980s to late 1990s, the third phase was characterised by emerging societal concerns regarding the rapidly deteriorating environment. However, the majority of societal value still inclined towards economic development. In the final phase since 2000s, societal values on water waxed and waned between economic development and environmental sustainability. On one hand, large water engineering projects were constructed driven by desires for rapid economic development. On the other hand, frequent water disasters, water pollution and soil erosion remained unresolved and generated strong incentives in environmental management in the society.



Note: The historical time points before 1950 refer to the average value from the Han to Ming-Qing Period as defined in Table 2, and shadows indicate phase transitions.

Figure 4. Temporal evolutions of the economic subsystem: (a) population, (b) NPP of the cultivated oasis; the ecological subsystem: (c) runoffs into terminal lakes, (d) NPP of the natural oasis; and the societal subsystem: (e) value for economic development, (f) value for environmental sustainability.

3.3 Interdependencies among water reallocation and the three subsystems in the HRB

The interdependences between any two subsystems in the co-evolved river basin socio-ecological system are summarised in Table 4. Strong correlations were identified between the water reallocation and economic subsystem, and between the water reallocation and ecological subsystem. Both of populations (standardised correlation coefficient = 0.89 for 1 unit change of water use) and NPP of cultivated oasis were significantly ($p<0.01$) correlated to human water use, while runoff to terminal lakes (0.84) and NPP of natural oasis (0.95) were significantly ($p<0.01$) correlated to environmental water use. These correlations reflect the nature of inland river basins in arid and semi-arid regions, i.e., both of the ecological and economic subsystems heavily relied on the amount of surface runoffs distributed to each subsystem. As a result, there existed strong trade-off relationships between the economic and ecological subsystems. Population was negatively correlated to runoffs to terminal lakes (-0.72, $p<0.01$), while an even stronger negative correlation was identified between NPP of cultivated oasis and NPP of natural oasis (-0.94, $p<0.01$).

It is widely recognised that societal value plays the primary role in the decision on water reallocation. However, value on water in the HRB did not show statistically significant to human water use (0.07) or environmental water use (0.2), in another word, societal value on water alone did not play a key role in water reallocation. Regarding to the feedbacks between the societal subsystem and the economic subsystem and the societal subsystem and the ecological subsystem, values towards economy was negatively correlated to population (-0.26, $p<0.01$). When population ranged between approximately 500,000 and 1 million, value towards economic development reached 1 (i.e., all values supported economic development), but then the societal value declined and moved towards environmental sustainability. Similarly, environmental-inclined societal value was positively correlated to NPP of natural oasis (0.3, $p<0.01$), which supported the restoration of natural oasis in the HRB. The effects of societal value were less responsive to increasing NPP of cultivated oasis (0.058) or restoring runoffs into terminal lakes (0.003).

Table 4. Interdependencies among water reallocation, economic, ecological, societal subsystems

Interdependency between subsystems	Correlation coefficient (Pearson's *r*)

Water reallocation vs economic subsystem	Human water use vs Population: 0.89 ** Human water use vs Human NPP: 1 **
Water reallocation vs ecological subsystem	Environmental water use vs Runoff to terminal lakes: 0.84 ** Environmental water use vs Natural NPP: 0.95 **
Economic subsystem vs ecological subsystem	Population vs Runoff to terminal lakes: -0.72 ** Human NPP vs Natural NPP: -0.94 **
Societal subsystem vs Water reallocation	Economy inclined value vs Human water use: 0.069 Environment inclined value vs Environmental water use: 0.20
Economic subsystem vs societal subsystem	Population vs Economy inclined value: -0.26 * Human NPP vs Economy inclined value: 0.058
Ecological subsystem vs societal subsystem	Runoff to terminal lakes vs Environment inclined value: 0.003 Natural NPP vs Environment inclined value: 0.30 **

Number of sample n = 76.
**: correlation significance at $p < 0.01$ (2-tailed).
*: correlation significance at $p < 0.05$ (2-tailed).

3.4 Evolution of drivers and their influences on water reallocation in the HRB

The climate conditions represented by precipitation and temperature fluctuations remained relatively stable during the entire study period, although there was a tendency of increasing precipitations and temperature since 1950 (refer to Supplementary Material A for details). As a result, temperature did not have statistically significant correlations with either human (0.09) or environmental water use (0.048) (Table 5). On the other hand, precipitations provided water recharge to the HRB and had relatively stronger correlation with human water consumption mainly for irrigation (0.49, $p<0.01$), whereas negative correlation with environmental water use (-0.34, $p<0.01$) implying the possibility of an “irrigation efficiency paradox” (Grafton et al., 2018).

Technological progresses impacted on water reallocation by developing the capacity of water resources development and improving water use efficiency. The initial phase was characterised by focus on economic development from the Han Dynasty to 1990s, characterised by constructions of large-scale irrigation infrastructures. Science advance was reflected as follows: since the ROC period, hydrology was integrated with engineering for water resources management for economic development. After 1960s, hydrology has been widely integrated with economics and engineering in water resources management for economic growth in the most cost-effective approach. With increasing ecological degradations, it was not until about 2000 that more sciences and technologies were developed to improve environmental sustainability. More water-saving technologies were developed and were supported by Environmental Science as a major discipline since 1990s (40% of the total publication by 2017) and later supplemented by Meteorology in response to climate change since 2000s. However, only limited publications were identified in the fields of social sciences (Wang et al., 2019) (refer to Supplementary Material A for more details). This is evidenced by stronger correlation between economic development driven technology progress and human water use (0.48, p<0.01), whereas weaker correlation was identified for environmentally driven technologies on environmental water consumption (0.2, p<0.1).

The central government structure in China remained top-down and the agency/administration for water resources management remained mostly unchanged in the system for our study period (see Supplementary Material A for more details). This meant that the impacts of government structure on water reallocation in the HRB remained unchanged. On the other hand, two phases between economic and environmental focuses of water acts/regulations were identified. The initial phase spanned from the Han Dynasty to as late as the 1980s, which was economically driven with a focus on agricultural irrigation and water development projects. Environmental-protection driven water acts did not appear until 1980s as the second phase to address environmental problems. However, water acts were still dominated by more focuses on economic efficiency. This is evident by the stronger correlation between human water use and economic governance (0.54, p<0.01) than that between environmental water use and environmental governance (0.31, p<0.01).

Table 5 The influences of external drivers except science model on water reallocation.

Drivers vs Water reallocation	**Correlation coefficient (Pearson's *r*)**
Temperature vs Water reallocation	Temperature vs Human water use: 0.09 Temperature vs Environmental water use: 0.048
Precipitation vs Water reallocation	Precipitation vs Human water use: 0.49 ** Precipitation vs Environmental water use: -0.34 **
Science and technology	Economy inclined technology progress vs Human water use: -0.48** Environment inclined technology progress vs Environmental water use: -0.20

progress vs Water reallocation	
Institutional arrangement vs Water reallocation	Economy inclined water acts/regulations vs Human water use: -0.54 ** Environment inclined water acts/regulations vs Environmental water use: -0.31 **

Number of sample n = 76.
**: correlation significance at $p < 0.01$ (2-tailed).
*: correlation significance at $p < 0.05$ (2-tailed).

Finally, linear stepwise regression models on the water reallocation framework indicate that the economic-oriented technological and institutional drivers and societal values were stronger predictors to human water uses($R^2 = 0.57$) than that for the environmental-oriented drivers to the environmental water use ($R^2 = 0.29$). Specifically, economic-oriented institutions had the strongest influences on water reallocated to human water consumptions (19.57, $p < 0.01$), followed by technology (16.58, $p<0.01$) and the impacts of economic-oriented societal value were weaker (13.14, $p<0.01$). On the other hand, environmental-oriented societal values and institutions have similarly strong impacts (16.66 and 16.13, $p<0.01$), whereas technology didn't have statistically significant impacts on water reallocated to the environment. Additionally, it should note that as the external drivers, climate change represented by temperature and precipitation didn't have statistically significant impacts when taking into considerations of the societal subsystems and the internal drivers on water reallocations in the HRB.

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Table 6 Linear stepwise regression models on the water reallocation framework.

Dependent variable	Coefficients of independent variables (standard error)	t-value	VIF
Human water consumption	Temperature: not significant		
	Precipitation: not significant		
	Economic-oriented institutions: 19.57** (4.31)	4.54	1.87
	Economic-oriented technology: 16.58** (4.38)	5.59	2.11
	Economic-oriented value: 13.14** (2.35)	3.78	1.48
	Overall model fit: $R^2 = 0.53$, $p < 0.001$		
Environmental water consumption	Temperature: not significant		
	Precipitation: not significant		
	Environmental-oriented institutions: 16.13* (4.93)	3.28	1.54
	Environmental-oriented technology: not significant		
	Environmental-oriented value: 16.66** (4.38)	3.81	3.26
	Overall model fit: $R^2 = 0.29$, $p < 0.001$		

Number of sample n = 76.
**: correlation significance at $p < 0.01$ (2-tailed).
*: correlation significance at $p < 0.05$ (2-tailed).

4. Discussions and conclusions

We developed a conceptual framework for examining water reallocation based on system thinking to structurally unfold the complexity of water reallocation decision-making, a challenge faced by most river basins in the world. The Heihe River Basin in China with historical data of over 2000 years was chosen as the case study. Key findings are summarized in Figure 5:

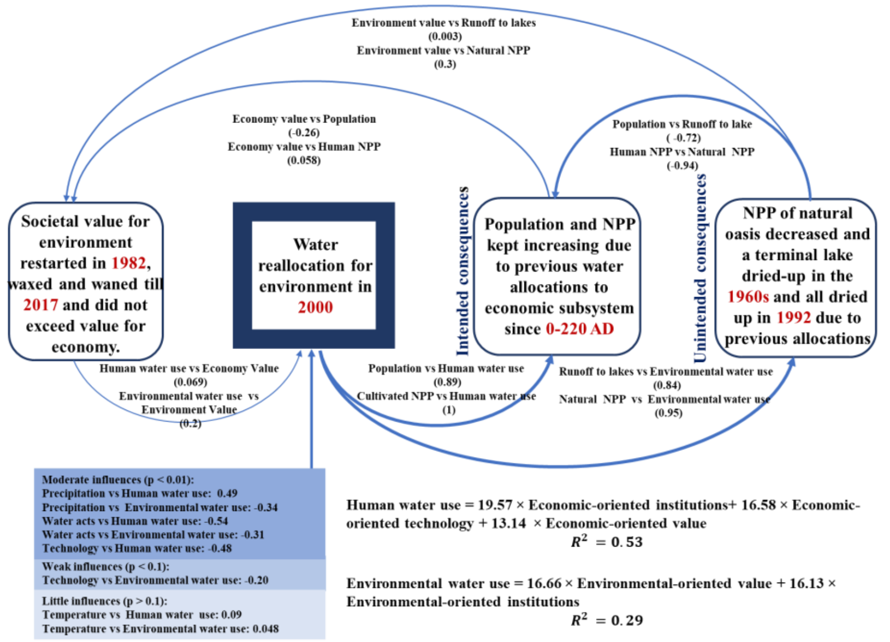

Figure 5. Unfolded complexity in water reallocation decision-making in the HRB

This study found that there was a time lag between ecological responses and economic development. The first large-scale water allocation for human development in the HRB began during 0-220 AD. With continuous growth of irrigated agricultural activities and especially constructions of over 100 dams since the 1950s, ecological degradation characterised by reduced runoff to the terminal lakes and reduced NPP from the natural oasis was observed in 1960s and worsen since 1990s with zero runoffs into all terminal lakes. This indicates a time lag of over 1000-years between the worst ecological condition reached in 1990s and the initial water resources development in 0 AD, and over 40 years between 1990s and the large scale water resources development in the 1950s. What's worse, societal value that supported environmental sustainability lagged even further behind, only emerging in the 1980s which was after two decades since the ecological issues arose and waxed and waned during the most recent decade.Water reallocation was strongly correlated with both the economic and ecological subsystems ($p < 0.01$), and the ecological and economic subsystems were also highly coupled with tradeoff relationships ($p < 0.01$). However, societal value on water in the HRB alone was not statistically correlated with either human or environmental water use. Similarly, neither the economic subsystem nor the ecological subsystem showed strong correlation with the change in the societal values in the societal subsystem. Putting the influences from all drivers and change in societal values together, it is demonstrated that they had more influences on change in the human water use ($R^2 = 0.57$) than that on the environmental water use ($R^2 = 0.29$). Specifically, all of economic-oriented institutions, technologies, and societal values had strong influences on water reallocation to human water uses, whereas only environmental-oriented societal value and institutions were found to be influential on environmental water use.

These key findings provide explanations on why the HRB had limited capacity to formulate timely responses of water reallocation to environmental problems. They were: 1) the delayed feedback of the ecological subsystem to development of the economic subsystem; 2) the weak and delayed responses of societal values to ecological degradations and very weak influences on water reallocation to environment; 3) the combined influences of societal subsystem (societal values) and internal drivers (government structures and regulatory institutions, and science and technological development) on water reallocation to the environment is also very limited.

The system thinking based conceptual framework developed in this study can assist in investigating interactions, delayed feedbacks and various drivers of the co-evolved socio-ecological system on river basins for a long timeframe. It helps structurally identify the root cause of the problem emerging from quick-fix solutions based on the traditional linear thinking, thus assist formulating strategic-level water reallocation for environmental sustainability (Matthias & Harald, 2010; McDonald et al., 2018). Broadly, it can avoid the environmental crisis caused by human fragmented decision-making. As discussed above, water reallocation incapacity in HRB represents a common challenge facing most river basins in the world, thus, the framework and findings from this study can cast lights onto water reallocation in other river basins.

The empirical and quantitative findings from this study are consistent with the recent theoretical and conceptual development for explaining the pervasive social and ecological phenomena in the Anthropocene. These include 1) the inertia (insensitiveness) of societal processes, well noted as “cultural lag” (Rosenschöld et al., 2014); 2) the punctuated equilibrium of ecological systems which is characterized as a long period of stasis being punctuated by more rapid change that disrupts the equilibrium; and 3) “Frenetic standstill” increasingly observed in the societal systems which is characterized by ever accelerating economic changes together with widespread political, cultural and institutional stagnation (the “desynchronization”) (Rosa & Trejo-Mathys, 2013).

To conclude, the conceptual framework developed in this study requires accommodation of information/data describing human societal processes, institutions, and development of science and technology paired with those from hydrological and ecosystem processes. Our study has made an empirical step in integrating qualitative and quantitative data from a multi-disciplinary perspective. However, this statistical correlation/regression analysis was only used to reveal the interdependencies among subsystems but would be not used for future prediction. Therefore, continuous efforts on theoretical development are still required to structurally unfold the complexity in decision-making of water reallocation to the environment.

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Author contributions

Y. Wei, A. Western, R. Ison, and M. Sivapalan conceptualised and designed the study, analysed and interpreted the results. S. Wu and Z. Lu collected the data, conducted the data analysis, and interpreted the results. Y. Wei, and S. Wu drafted the initial manuscript, all authors edited and reviewed the manuscript.

Declaration of interest

The authors declare no conflict of interest.

References

Andersen, T., Carstensen, J., Hernández-García, E., & Duarte, C. M. (2009). Ecological thresholds and regime shifts: approaches to identification. *Trends in Ecology & Evolution*, *24*(1), 49-57. https://doi.org/https://doi.org/10.1016/j.tree.2008.07.014

Banson, K. E., Nguyen, N. C., & Bosch, O. J. H. (2016). Using System Archetypes to Identify Drivers and Barriers for Sustainable Agriculture in Africa: A Case Study in Ghana. *Systems research and behavioral science*, *33*(1), 79-99. https://doi.org/https://doi.org/10.1002/sres.2300

Biggs, R., Schlüter, M., & Schoon, M. L. (2015). *Principles for building resilience: sustaining ecosystem services in social-ecological systems*. Cambridge University Press.

Bouckaert, F., Wei, Y., & Pittock, J. (2021). Governing the Murray-Darling Basin: Integrating social and biophysical indicators for better environmental outcomes. *Environmental Science & Policy*, *124*, 101-114. https://doi.org/https://doi.org/10.1016/j.envsci.2021.05.019

Dietz, T., Ostrom, E., & Stern, P. C. (2003). The struggle to govern the commons. *Science*, *302*(5652), 1907-1912. https://doi.org/10.1126/science.1091015

Ding, M. (2019). *Understanding the impacts of flood/drought disasters and their management on catchment socio-ecological system* University of Queensland]. Brisbane.

Dong, K. Z., & Fan, C. Y. (2000). *The History of Science and Technology in China - The Agriculture Chapter* (J. Lu, Ed.). Science Publisher.

Eakin, H., Bojórquez-Tapia, L. A., Janssen, M. A., Georgescu, M., Manuel-Navarrete, D., Vivoni, E. R., Escalante, A. E., Baeza-Castro, A., Mazari-Hiriart, M., & Lerner, A. M. (2017). Opinion: Urban resilience efforts must consider social and political forces. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(2), 186-189. https://doi.org/10.1073/pnas.1620081114

FAO. (2018). *AQUASTAT-FAO's global information systems on water and agriculture*. Retrieved 8 September from http://www.fao.org/aquastat/en/

Forrester, J. W. (1992). Policies, decisions and information sources for modeling. *European Journal of Operational Research*, *59*(1), 42-63.

Garrick, D., Bark, R., Connor, J., & Banerjee, O. (2012). Environmental water governance in federal rivers: opportunities and limits for subsidiarity in Australia's Murray–Darling River. *Water Policy*, *14*(6), 915-936. https://doi.org/10.2166/wp.2012.120

Garrick, D., De Stefano, L., Yu, W., Jorgensen, I., O'Donnell, E., Turley, L., Aguilar-Barajas, I., Dai, X., de Souza Leão, R., & Punjabi, B. (2019). Rural water for thirsty cities: A systematic review of water reallocation from rural to urban regions. *Environmental Research Letters*, *14*(4), 043003. https://doi.org/https://doi.org/10.1088/1748-9326/ab0db7

Ge, Q. (2011). *Climate Change through Ancient Chinese Dynasty*. Science Press, Beijing.

Gohari, A., Mirchi, A., & Madani, K. (2017). System Dynamics Evaluation of Climate Change Adaptation Strategies for Water Resources Management in Central Iran. *Water Resources Management*, *31*(5), 1413-1434. https://doi.org/10.1007/s11269-017-1575-z

Grafton, R. Q., Williams, J., Perry, C. J., Molle, F., Ringler, C., Steduto, P., Udall, B., Wheeler, S. A., Wang, Y., Garrick, D., & Allen, R. G. (2018). The paradox of irrigation efficiency. *Science*, *361*(6404), 748-750. https://doi.org/10.1126/science.aat9314

Graham, M. H. (2003). Confronting multicollinearity in ecological multiple regression. *Ecology*, *84*(11), 2809-2815. https://doi.org/10.1890/02-3114

Haberl, H., Erb, K. H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W., & Fischer-Kowalski, M. (2007). Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *Proceedings of the National Academy of Sciences*, *104*(31), 12942-12947. https://doi.org/10.1073/pnas.0704243104

Holdren, J. P., & Ehrlich, P. R. (1974). Human population and the global environment: population growth, rising per capita material consumption, and disruptive technologies have made civilization a global ecological force. *American Scientist*, *62*(3), 282-292.

Killick, R., & Eckley, I. A. (2014). changepoint: An R package for changepoint analysis. *Journal of statistical software*, *58*(3), 1-19.

Li, X., Nan, Z., Cheng, G., Ding, Y., Wu, L., Wang, L., Wang, J., Ran, Y., Li, H., Pan, X., & Zhu, Z. (2011). Toward an improved data stewardship and service for environmental and ecological science data in West China. *International Journal of Digital Earth*, *4*(4), 347-359. https://doi.org/10.1080/17538947.2011.558123

Liang, J. (1989). *The History of Chinese Agricultural Technologies*. Agricultural Publisher.

Lu, Z., Wei, Y., Feng, Q., Xie, J., Xiao, H., & Cheng, G. (2018). Co-evolutionary dynamics of the human-environment system in the Heihe River basin in the past 2000years. *Science of The Total Environment*, *635*, 412-422.

Lu, Z., Wei, Y., Xiao, H., Zou, S., Xie, J., Ren, J., & Western, A. (2015). Evolution of the human–water relationships in the Heihe River basin in the past 2000 years. *Hydrol. Earth Syst. Sci.*, *19*(5), 2261-2273. https://doi.org/10.5194/hess-19-2261-2015

Marston, L., & Cai, X. (2016). An overview of water reallocation and the barriers to its implementation. *WIREs Water*, *3*(5), 658-677. https://doi.org/https://doi.org/10.1002/wat2.1159

Matthias, G., & Harald, H. (2010). *Environmental Sociology: European Perspectives and Interdisciplinary Challenges*. Springer Netherlands. https://doi.org/10.1007/978-90-481-8730-0

McDonald, K. S., Hobday, A. J., Fulton, E. A., & Thompson, P. A. (2018). Interdisciplinary knowledge exchange across scales in a globally changing marine environment. *Global Change Biology*, *24*(7), 3039-3054. https://doi.org/10.1111/gcb.14168

Meadows, D. H. (1974). *The limits to growth : a report for the Club of Rome's project on the predicament of mankind*. Pan Books.

Mirchi, A., Madani, K., Watkins, D., & Ahmad, S. (2012). Synthesis of System Dynamics Tools for Holistic Conceptualization of Water Resources Problems. *Water Resources Management*, *26*(9), 2421-2442. https://doi.org/10.1007/s11269-012-0024-2

Nyborg, K., Anderies, J. M., Dannenberg, A., Lindahl, T., Schill, C., Schlüter, M., Adger, W. N., Arrow, K. J., Barrett, S., Carpenter, S., Chapin, F. S., Crépin, A.-S., Daily, G., Ehrlich, P., Folke, C., Jager, W., Kautsky, N., Levin, S. A., Madsen, O. J., . . . de Zeeuw, A. (2016). Social norms as solutions. *Science*, *354*(6308), 42-43. https://doi.org/10.1126/science.aaf8317

Ostrom, E. (2009). A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science*, *325*(5939), 419-422. https://doi.org/10.1126/science.1172133

Pahl-Wostl, C. (2015). *Water Governance in the face of global change: From understanding to transformation*. Springer International Publishing.

Pahl-Wostl, C., Holtz, G., Kastens, B., & Knieper, C. (2010). Analyzing complex water governance regimes: the Management and Transition Framework. *Environmental Science & Policy*, *13*(7), 571-581. https://doi.org/10.1016/j.envsci.2010.08.006

Pallant, J. (2020). *SPSS survival manual: A step by step guide to data analysis using IBM SPSS*. Routledge.

Poindexter, P. M., & McCombs, M. E. (2000). *Research in Mass Communication: A Practical Guide*. Bedford/St. Martin's Boston, MA.

Qin, C., Yang, B., Burchardt, I., Hu, X., & Kang, X. (2010). Intensified pluvial conditions during the twentieth century in the inland Heihe River Basin in arid northwestern China over the past millennium. *Global and Planetary Change*, *72*(3), 192-200. https://doi.org/http://dx.doi.org/10.1016/j.gloplacha.2010.04.005

Ravi, K., & Ravi, V. (2015). A survey on opinion mining and sentiment analysis: Tasks, approaches and applications. *Knowledge-Based Systems*, *89*, 14-46. https://doi.org/https://doi.org/10.1016/j.knosys.2015.06.015

Roobavannan, M., van Emmerik, T. H. M., Elshafei, Y., Kandasamy, J., Sanderson, M. R., Vigneswaran, S., Pande, S., & Sivapalan, M. (2018). Norms and values in sociohydrological models. *Hydrol. Earth Syst. Sci.*, *22*(2), 1337-1349. https://doi.org/10.5194/hess-22-1337-2018

Rosa, H., & Trejo-Mathys, J. (2013). *Social Acceleration: A New Theory of Modernity*. Columbia University Press. https://doi.org/10.7312/rosa14834

Rosenschöld, J., Rozema, J. G., & Frye-Levine, L. A. (2014). Institutional inertia and climate change: a review of the new institutionalist literature. *WIREs Climate Change*, *5*(5), 639-648. https://doi.org/10.1002/wcc.292

Samhouri, J. F., Andrews, K. S., Fay, G., Harvey, C. J., Hazen, E. L., Hennessey, S. M., Holsman, K., Hunsicker, M. E., Large, S. I., Marshall, K. N., Stier, A. C., Tam, J. C., & Zador, S. G. (2017). Defining ecosystem thresholds for human activities and environmental pressures in the California Current. *Ecosphere*, *8*(6), e01860. https://doi.org/10.1002/ecs2.1860

Sandelowski, M. (2000). Combining qualitative and quantitative sampling, data collection, and analysis techniques in mixed-method studies. *Research in Nursing & Health*, *23*(3), 246-255. https://doi.org/10.1002/1098-240x(200006)23:3<246::aid-nur9>3.0.co;2-h

Smith, A., & Stirling, A. (2010). The politics of social-ecological resilience and sustainable socio-technical transitions. *Ecology and Society*, *15*(1), Article 11.

Sterman, J. D. (2001). System Dynamics Modeling: Tools for Learning in a Complex World. *California Management Review*, *43*(4), 8-25. https://doi.org/10.2307/41166098

Tang, X., Zhao, Y., Zhang, Z., Feng, Q., & Wei, Y. (2018). Cultivated oasis evolution in the Heihe River Basin over the past 2,000 years. *Land Degradation & Development*, *29*(8), 2254-2263. https://doi.org/10.1002/ldr.2991

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Liermann, C. R., & Davies, P. M. (2010). Global threats to human water security and river biodiversity. *Nature*, *467*(7315), 555-561. https://doi.org/10.1038/nature09440

Wang, J., Wei, Y., Jiang, S., Zhao, Y., Zhou, Y., & Xiao, W. (2017). Understanding the human-water relationship in China during 722 B.C.-1911 A.D. from a contradiction and co-evolutionary perspective [journal article]. *Water Resources Management*, *31*(3), 929-943. https://doi.org/10.1007/s11269-016-1555-8

Wang, X., Wei, Y., Ma, M., & Zhang, Z. (2019). Research progress of the Heihe River Basin based on bibliometrics. *Advances in Earth Science*, *34*(3), 316-323. https://doi.org/10.11867/j.issn.1001-8166.2019.03.0316

Wei, J., Wei, Y., & Western, A. (2017). Evolution of the societal value of water resources for economic development versus environmental sustainability in Australia from 1843 to 2011. *Global Environmental Change*, *42*, 82-92. https://doi.org/10.1016/j.gloenvcha.2016.12.005

Wei, J., Wei, Y., Western, A., Skinner, D., & Lyle, C. (2015). Evolution of newspaper coverage of water issues in Australia during 1843-2011. *Ambio*, *44*(4), 319-331. https://doi.org/10.1007/s13280-014-0571-2

Wei, Y., Ison, R., Western, A., & Lu, Z. (2018). Understanding ourselves and the environment in which we live. *Current Opinion in Environmental Sustainability*, *33*, 161-166. https://doi.org/https://doi.org/10.1016/j.cosust.2018.06.002

Wolstenholme, E. F. (2003). Towards the definition and use of a core set of archetypal structures in system dynamics. *System Dynamics Review*, *19*(1), 7-26. https://doi.org/https://doi.org/10.1002/sdr.259

Wu, S. (2017). The 2000-years evolution history of technology in Heihe River Basin. In Y. Wei & Z. Zhang (Eds.), *Theory and Practice of Socio-hydrology*. China Science Publishing.

Wu, S., Wei, Y., Head, B., Zhao, Y., & Hanna, S. (2020). Using a process-based model to understand dynamics of Chinese agricultural and water technology development from 8000 bc to 1911 ad. *Ambio*. https://doi.org/https://10.1007/s13280-020-01424-7

WWAP, U. W. W. A. P. (2018). *World Water Development Report 2018: Nature-based Solutions for Water*. https://www.unwater.org/publications/world-water-development-report-2018/

Xie, Y., Wang, G., & Wang, X. (2015). Spatio-temporal process of oasification in the middle-Heihe River basin during 1368–1949 AD, China [journal article]. *Environmental Earth Sciences*, *73*(4), 1663-1678. https://doi.org/10.1007/s12665-014-3519-8

Xiong, Y., Wei, Y., Zhang, Z., & Wei, J. (2016). Evolution of China's water issues as framed in Chinese mainstream newspaper. *Ambio*, *45*(2), 241-253. https://doi.org/10.1007/s13280-015-0716-y

Xiong, Y., Zhang, Z., Wei, Y., Liu, Z., & Cheng, G. (2014). On a quantitative method for water culture evolution research: mapping knowledge domains. *Advances in Earth Science*, *29*(1), 92-103. https://doi.org/https://doi.org/1001-8166(2014)01-0092-12

Yan, W. Y., & Yin, Y. H. (1993). *The Development History of Chinese Agriculture*. Tianjing Science and Technology Publisher. https://books.google.com.au/books?id=6C0yAAAAMAAJ

Yang, B., Qin, C., Wang, J., He, M., Melvin, T. M., Osborn, T. J., & Briffa, K. R. (2014). A 3,500-year tree-ring record of annual precipitation on the northeastern Tibetan Plateau. *Proceedings of the National Academy of Sciences*, *111*(8), 2903-2908. https://doi.org/10.1073/pnas.1319238111

Zare, F., Elsawah, S., Bagheri, A., Nabavi, E., & Jakeman, A. J. (2019). Improved integrated water resource modelling by combining DPSIR and system dynamics conceptual modelling techniques. *Journal of Environmental Management*, *246*, 27-41. https://doi.org/https://doi.org/10.1016/j.jenvman.2019.05.033

Zhang, D. D., Brecke, P., Lee, H. F., He, Y.-Q., & Zhang, J. (2007). Global climate change, war, and population decline in recent human history. *Proceedings of the National Academy of Science*, *104*(49), 19214-19219. https://doi.org/10.1073/pnas.0703073104

Zhao, H. (2016). *The study of people's ecological and environmental consciousness in the excavated documents of the Northwest Region* (Publication Number K872) Northwest Normal University]. China.

Zhong, F., Xu, Z., Watian, S., Li, J., & Qiushan, Z. (2014). Understanding the evolution history of water allocation rules in the Heihe River Basin. *Journal of Economics of Water Resources*, *32*(5).

Zhou, J. (2011). *Study on the ecological consciousness in imperial rescripts of ancient China* (Publication Number K207) Beijing Forestry University]. China.