

Evolution mechanisms and fundamental equations of social water cycle fluxes

Baodeng Hou, Ruixiang Yang, Yuyan Zhou, Weihua Xiao, Jianhua Wang, Yong Zhao and Xuzhu Zhan

ABSTRACT

The rise of socio-hydrology, addressing the interactions between human and water systems, is regarded as an innovative perspective to researches achieving the sustainable use of water resources. Revealing the social water fluxes, in terms of magnitude, structure, and variations under changing environment, could advance the understanding of water cycling under the dual driving forces: natural and anthropogenic. This study attempts to formulate the fundamental equations of the social water cycle by focusing on the evolution mechanisms of social water cycle fluxes. The endogenously dynamic characteristics of social water cycling are portrayed, i.e., the gradual change mechanism and the catastrophe mechanism, therefore dividing the evolution processes into four stages. Then, social water cycle flux reaches its peak and completes the first stage of evolution. The evolution process is an S-shaped curve process. After the peak, it enters the next evolutionary stage, where the pattern varies with the intensities of the gradual change mechanism and the catastrophe mechanism. The coordination relationships of these two mechanisms and the fluctuating characteristics in each stage are studied as well. Case studies are investigated in 39 countries globally to verify the fitting of the fundamental equations and evolution mechanisms.

Key words | evolution mechanisms, social water cycle fluxes, socio-hydrology, water demand, water use

Baodeng Hou
Yuyan Zhou
Weihua Xiao
Jianhua Wang (corresponding author)
Yong Zhao

State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, A-1 Fuxing Road, Haidian District, Beijing, China
 E-mail: jhwangiwthr@126.com

Ruixiang Yang
 Pearl River Comprehensive Technology and Network Information Centre of Pearl River Water Resources Commission, Ministry of Water Resources, No. 80 Tianshou Road, Guangzhou, China

Xuzhu Zhan
 Beijing Water Consulting Co., Ltd., No. 20 Chegongzhuang West Road, Haidian District, Beijing, China

INTRODUCTION

The initiation and the promotion of socio-hydrology have provided a brand new perspective in investigating the water cycling processes under natural and anthropogenic forces (Vörösmarty *et al.* 2010; Sivapalan *et al.* 2012). A wide range of discussions have been focused on conceptualization (Sivakumar 2012; Sivapalan *et al.* 2014; Di Baldassarre *et al.* 2013, 2015; Ertsen *et al.* 2013; Montanari 2015; Sivapalan 2015), and simulation and parameterization (Elshafei *et al.* 2014; Gober & Wheeler 2014; Lane 2014; Liu *et al.* 2015; Loucks 2015; Srinivasan 2015; Mount *et al.* 2016). Case studies have mainly focused on human and

flood interactions (Di Baldassarre *et al.* 2013; Gober & Wheeler 2015; Fuchs *et al.* 2017), and human and wetland systems (Zlinszky & Timár 2013), etc.

While the interactions of anthropogenic forces and hydrological processes have been studied, the water fluxes in socio-economic activities are the key variables in water cycling processes under natural and anthropogenic forces (Chen & Graedel 2012; Drenkhan *et al.* 2015). Those studies that focused on these fluxes, especially the occurrence, migration, and transformation characteristics, were named social water cycle research

(Merrett 1997; Wang *et al.* 2002). These studies were driven by the urgent need to understand the water cycling processes in river basins under widely spread intensified human activities, e.g., over-exploitation of groundwater, intensifying transboundary water conflicts due to over-loading, and imbalance of water resources development.

Significant progress has been made in the past decade, for instance, Wang *et al.* (2013) explicitly proposed the definition, contents, and characteristics of the social water cycle, which eventually formulated the theory of the 'natural-social' dualistic water cycle as a new perspective in interpreting the whole water cycling processes in the Anthropocene (Wang *et al.* 2013; Qin *et al.* 2014). There are four components of the social water cycle, i.e., water supply, water consumption, water drainage, and water recycling (Figure 1). Liu *et al.* (2010) revealed the mode and evolution principles of the dualistic water cycle. Case studies were conducted in the Yellow River Basin and Haihe River Basin, two of the most anthropogenic river basins in the world (Jia *et al.* 2006, 2010; Liu *et al.* 2010). However, as a new field of research area in water science, previous studies were mainly regional studies driven by local monitoring data and water problems. Few of them have extracted the evolution mechanism and fundamental equations of the social water cycle, especially focusing on the social water cycle fluxes.

The objectives of this study are: (i) identifying the contents and influencing factors of the social water cycle fluxes; (ii) revealing the evolution mechanisms of the social water cycle fluxes; (iii) formulating the evolution equations and validating the rationality via fitting to cases studies in total water usage in 39 countries.

METHODS

Concept of social water cycle fluxes

Social water cycle flux is the amount of water that enters the social water cycle system from the natural water cycle system and is used to meet the demand of an eco-social system. The concept shows that the social water cycle flux must meet the following requirements simultaneously. First, it is from the natural water cycle system and does not include the internal exchange and reutilization of the social water cycle system. Thus, the effective precipitation entering the agricultural water system and the direct water withdrawal from land surface and groundwater sources via artificial water withdrawal projects are part of the social water cycle flux. However, the internal utilization of recycled water and the direct water exchange between different water-use units inside the social water cycle system do not contribute to the social water cycle. Second, it must meet certain eco-social demands. Water that enters the social water cycle system from the natural water cycle system but is not used to meet eco-social system water demand does not contribute to the social water cycle flux, e.g., the amount of farmland precipitation that directly flows away as runoff or penetrates to the groundwater system and water that falls over cities and enters natural water bodies directly through a rainwater network; these waters do not contribute to the social water cycle flux.

According to its definition, social water cycle flux includes the two major parts of water withdrawal and effective precipitation (Gau & Liu 2000). Corresponding to the widely used statistical caliber, social water cycle flux is

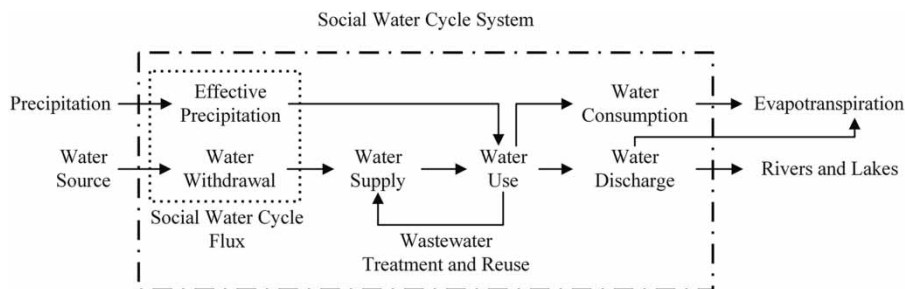


Figure 1 | Social water cycle system and flux diagram.

equivalent to the water supply minus the amount of wastewater treatment and reuse plus effective precipitation. The relevant concepts and the water balance of the social water cycle system are illustrated in [Figure 1](#).

From the perspective of meeting the water demand of humans, social water cycle flux can be divided into three types: domestic water flux, production water flux, and artificial ecological water flux.

Social water cycle flux is usually characterized by the total amount of water use or the total amount of wastewater. The total amount of wastewater and the total amount of water use are usually linearly correlated. Thus, practical research mainly studies the total amount of water use. Social water cycle flux is the result (function) of its process and structure. However, in general, the majority of attention is focused on the evolution regularity and trend of the flux itself. Understanding its evolution regularity and development trend plays a decisive role in water planning and water management strategies. In the study of flux, the social water cycle focuses on the overall understanding of the water cycle flux in the study area. On the one hand, it analyzes the evolution of the water cycle flux vertically in a certain study area and time period from the temporal perspective (such as the problems of water use increase and '0 increase') and predicts the future scientifically. On the other hand, it compares the social water cycle flux of different regions during a certain period horizontally from the spatial perspective and provides a reference for the evolution of the social water cycle in the areas of focus ([Avni et al. 2015](#)). For example, the analysis of the evolution of water use in developed countries can provide a reference for the development, planning, and utilization of water resources in developing countries. The practice of water planning usually requires prediction assessment based on the analysis of historical and current social water cycle flux – prediction of social water cycle flux (mainly expressed as water demand predictions) ([Tiwari & Adamowski 2013](#)). The evolution and prediction of social water cycle flux is one of the core subjects of regional water planning and rational allocation of water resources. The scientific and rational prediction of social water cycle flux has been one of the methods used for sustainable utilization of water resources.

Factors that influence social water cycle flux

The evolution of social water cycle flux (water resources demand) is subject to the dual effects of endogenic force and external environment.

The world's demand for water resources stems from its endogenous dynamics. Without water, organisms die, industries are unable to produce, and ecology is non-existent. Due to different dynamic requirements, each industry shows a different intrinsic demand for water. In addition, driven or constrained by the external environment, the ultimate water demand differs with the intrinsic demand, to some degree ([Archibald 1983](#)).

Overall, the demand for water resources is an integrated result of many external factors including society, the economy, and the ecological environment. The factors that influence the demand for water resources consist of both driven demand growth and constrained demand growth. For systems with different water demands, their driven or constrained factors differ significantly ([Kampragou et al. 2011](#)).

As a fundamental natural resource, water demand is affected by factors including population growth and urbanization. As a strategic economy resource, its demand is affected by factors including economic development level and industrial structure. As a controlling factor of the ecological environment, its demand is affected by issues including ecological environmental protection and restoration. The demand for water resources is limited and objective. The factors driving water demand growth are periodical. Due to the constraints of water resources conditions, water engineering conditions, water price, and water conservation and management levels, the water demand cannot increase without any limit. From the perspective of the endogenous dynamics of water resources demand, humans' intrinsic demand for water in the living and production processes promotes a 'J pattern' growth in water demand. However, due to the dual driven and constrained effects of the external environment, the ultimate water demand cannot increase infinitely but shows different characteristics at different stages. The relationships between the endogenic force and external influence factors of social water cycle flux is shown in [Figure 2](#), where water use is considered to be equal to water demand.

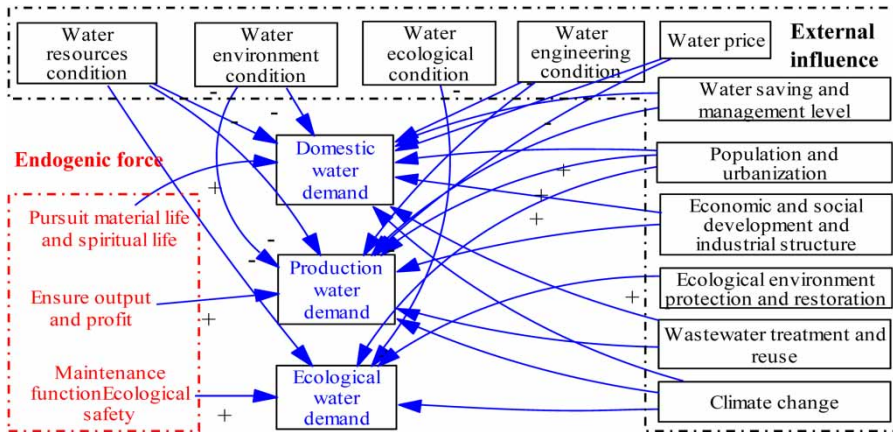


Figure 2 | Sketch of the relationships between the endogenic force and external influence factors of social water cycle flux.

Evolution mechanisms of social water cycle flux

From the perspective of natural dialectics, everything is composed of processes including formation, evolution, development, and demise. This development process follows universal laws including its interaction mechanisms and evolution paradigms. Due to the interaction, mutual effects, and transformation of things, the changes in environment, condition, or composition elements of objects inevitably lead to corresponding changes of relevant aspects. In addition, the results of each change must be the basis for subsequent change and development. Such an everlasting process where the next change is a result of the last change is evolution. The internal and external elements of all things are undergoing large or small changes. Therefore, all objective things are undergoing evolution. Because the internal and external elements of the evolution of things show similarities and differences, their evolution paths, forms, and results show similarities and differences. A tiny change may lead to gigantic effects via the interaction of various factors. This result is intensification, such as the domino effect. A great effort may completely die out due to the interaction of various factors, namely, weakening. Evolution can be divided into natural evolution and social evolution. Prior to the formation of human society, water cycle flux followed the laws of nature, being repeatedly depleted in winter and enriched in summer. After the formation of human society, within the regime of human activity, humans have controlled the evolution direction of the water cycle system via objective laws, leading to social

evolution. Thus, social water cycle flux was created and has been intensified continuously to the point of endangering the intrinsic stability and balance of the water cycle system. With the strengthening of humans' controlling ability, the effect of the social evolution of the water cycle has become wider and deeper, which is directly or indirectly changing the landscape of the Earth. Based on the complex feedback of the human-water coupling system, the evolution mechanism of the social water cycle can be divided into two types. One is the gradual change mechanism, which mainly refers to the growth of water use at the speed of the natural increase rate of the population as it grows and the expansion of the activity regime of human actions. It is a gradual process. The other is the catastrophe mechanism, which mainly refers to a drastic change in water use due to the advancement of humans' scientific and technological ability and new functions or methods of water use. It is accompanied by drastic changes in water quality.

Gradual change mechanism

The gradual change mechanism of social water cycle flux is a relatively long-term, stable, and slow evolutionary process. The consequence of evolution with the gradual change mechanism can be shown only after a long time. Its evolution principle is to slowly accumulate tiny changes over a long period and produces astonishing results. For example, in the theory of evolution, approximately 6 million years elapsed from *Australopithecus* to *Homo sapiens*. In the evolution of social water cycle flux, the long-term and lasting

effect is the gradual change mechanism. In the long era of primitive civilization, the size of the social water cycle flux was determined by only one factor, the population of the primitive tribes. The social water use at that time was limited to drinking and cooking. Therefore, the size of the social water cycle flux increased gradually with the natural population growth. In the past 5,000 years of agricultural civilization, social water cycle flux has been determined by two factors, population and farmland, which are closely related. Under the 'cattle-plow' farming model, population determines the area of land that can be cultivated; that is, it determines the agricultural water cycle flux. Thus, during the entire agricultural civilization period, the evolution of the social water cycle flux was still determined by the gradual change mechanism. However, during the transitional period from the primitive hunting civilization to the feudal agricultural civilization, the evolution of the social water cycle flux was determined by the catastrophe mechanism, which is discussed in the next section. Since the development of industrial society, the social water cycle has become extremely complex and diversified. Water use includes not only residential living and agriculture but also nearly all manufacturing enterprises in over 50 industrial categories. Currently, it is almost impossible to find a method of manufacture without water use, even in the production of a desiccant workshop. Therefore, in industrial society, it is impossible to estimate the social water cycle flux in a country or region based merely on population, farmland area, and gross industrial production because, even for the production of the same products, the amount of water use can vary up to hundreds and thousands of times. Considering thermal power generation as an example, the water use between air cooling and direct current (DC) water cooling varies significantly. In an industrial society, the evolution of the social water cycle flux is the integrated result of the gradual change mechanism and the catastrophe mechanism.

Catastrophe mechanism

The catastrophe mechanism, as the name suggests, is the driving mechanism that leads to drastic quantitative changes in a short time. In the evolution of social water cycle flux, the drivers that can cause abrupt changes of flux mainly include the

expansion of water resource functions, the discovery of new water resources, the application of alternative water resources, and new water-saving technologies.

Expansion of water resource functions. In primitive society, humans mainly used the life-supporting function of water resources; that is, water was used mainly for living. In the agricultural civilization period, humans found that the yields of irrigated farmland were higher and realized the irrigation function of water resources. Therefore, large amounts of water resources were withdrawn from rivers and lakes for farmland irrigation, leading to the formation and development of agricultural water cycle flux, which was the main flux in agricultural society. Since the rise of the industrial society, the water resource functions of cooling, rinsing, and chemical catalysis have been discovered, and water has entered each field of industrial production. With the rapid expansion of industrial production scale, industrial water use is increasing drastically with the trend of surpassing agricultural water use. In an industrial society, agricultural and industrial water uses are the top two fluxes of the social water cycle, and domestic water use holds third place.

Discovery of new water resources. With the gradual discovery of the various potential functions of water resources, the extent of water use has become wider and wider, and social water cycle flux has become larger and larger. In some water-scarce regions, social water use has drained almost all sources of land surface water resources, and drought has spread in dry years. During these periods, despite the strong water demands, water supply is unavailable. Therefore, the increases of social water cycle flux are limited by water sources. If new water sources are exploited and utilized during these periods, the cycle flux increases rapidly. For example, in the 1970s, the well-field agricultural irrigation technique was about to mature in the Northern China Plain, and a large amount of groundwater was withdrawn. Within ten years, from 1970 to 1980, groundwater withdrawal increased by approximately 20 billion m³.

Application of alternative water resources. In regions with scarce water resources, national economy and social development are constrained by the bottleneck of water shortage. This situation has prompted some industrial

enterprises to find new alternative water resources for their own development. For example, coastal industrial enterprises that face the ocean are directly or indirectly using seawater. Inland cities have started to use recycled water for landscape ecological constructions. Such extensive utilization of alternative water resources replaces the consumption of conventional water resources, leading to a sudden decrease of the social water cycle flux in a certain period and abrupt negative change in the social water cycle flux.

New water-saving technologies. With the development of science and technology, the high cost of water use has been solved by new water-saving technologies. Some water-saving technologies have a revolutionary impact on water use. For example, the difference in water use between DC cooling and air cooling of thermal power generation differs by 300–800 times. If air-cooled units are used, the total amount of water use decreases significantly, leading to abrupt negative change.

Evolution equations of social water cycle flux

Social water cycle flux is subject to the integrated effects of the gradual change mechanism, catastrophe mechanism, the type of each water user, the industrial scale, and structural adjustment, which cause increases and decreases in social water cycle flux. A deep understanding of these mechanisms and a clear picture of the quantity and scale of each water user in the eco-social system can explain the evolution process and change the mechanism of the social water cycle flux in different countries or regions. The construction of evolution equations for social water cycle flux and prediction of the evolution direction of future social water cycle flux are useful for scientific judgment and decision-making and effective responses to water crises.

It is difficult for the existing monitoring methods of social water cycle to meet the evolution equation with social factors as independent variables and social water cycle flux as dependent variables. Therefore, the social factors are generalized by the gradual change mechanism and the catastrophe mechanism to build the evolution equation of social water cycle flux in this study. Under the integrated effects of the gradual change mechanism and

the catastrophe mechanism, social water cycle flux completes an entire evolutionary sequence (i.e., S_0) consisting of an initial stage, a rapid growth stage, a gradual growth stage, and a stable stage. After the peak, it enters the next evolutionary stage, the pattern of which varies with the intensities of the gradual change mechanism and the catastrophe mechanism: S_1 continuous development, S_2 general stability, S_3 cyclic stability, S_4 gradual decrease to stability, and S_5 continuous decrease (as shown in Figure 3). The S_1 continuous development enters the next S-curve evolutionary stage, when the social water cycle flux rapidly increases. Such a time is dominated by the gradual change mechanism with little effect from the catastrophe mechanism. The S_2 general stability means that the social water cycle flux mostly remains at a certain level, entering the standard 0-growth stage when the gradual change mechanism and catastrophe mechanism both play leading roles. The S_3 cyclic stability means that the social water cycle flux enters a stage with moderate increases and decreases, when the gradual change mechanism and catastrophe mechanism both play identical leading roles with alternating strength and weakness. The S_4 gradual decrease to stability means that the catastrophe mechanism is the first to dominate, and then the gradual change mechanism and catastrophe mechanism both play identical leading roles, leading to a stable state. The S_5 continuous decrease means that the social water cycle flux decreases rapidly,

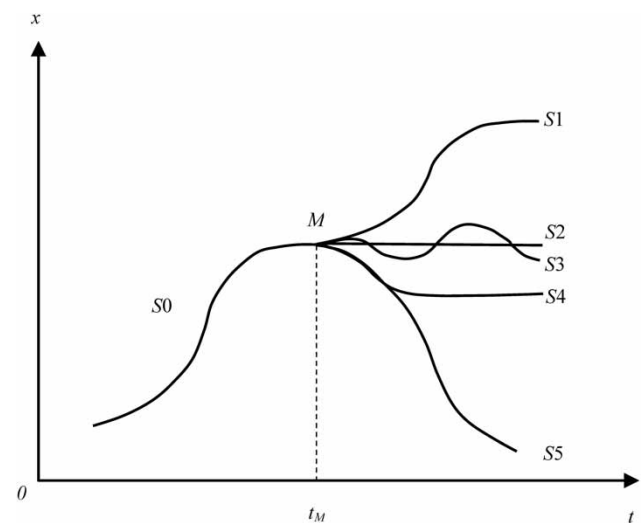


Figure 3 | The evolution patterns of social water cycle flux under the integrated effects of the two mechanisms.

which does not occur under normal conditions but with the occurrence of conditions such as a great economic downturn and a rapid decrease of population. Such a time is dominated by the catastrophe mechanism with little effect from the gradual change mechanism.

- (1) In the evolution stage of S0, the evolution equation of social water cycle flux can be expressed by S curve. The equation is:

$$x(t) = \frac{M}{1 + Ce^{-r(t-t_0)}} \quad C = \frac{M}{x_0} - 1 \tag{1}$$

where t is time (generally, the unit is years), C is parameter with $C > 0$, x is the social water cycle flux, x_0 and t_0 are the initial values, $x(t_0) = x_0$, r is the evolution speed of the social water cycle flux without water resource limitations, $r = f(z_1, z_2, \dots, z_n)$, z is the endogenic force and external environment that influence social water cycle flux, n is the number of social factors, and M is the maximum capacity of the social water cycle flux, that is, the upper limit of the evolution of the social water cycle flux, $M = g(z_1, z_2, \dots, z_n)$.

- (2) Under the S1 continuous development, the evolution equation of the social water cycle flux can still be expressed by the S curve, whereas the parameters are different:

$$x(t) = M + \frac{M'}{1 + C'e^{-r'(t-t_M)}} \tag{2}$$

where M' , C' , and r' are consistent with the previous M , C , and r , and t_M is time corresponding to the evolution of the extreme value. The others are the same as before.

- (3) Under the S2 general stability condition, the evolution value generally remains at approximately the extreme value of M , which can be expressed with a linear equation:

$$x(t) = M + \delta(t) \tag{3}$$

where $\delta(t)$ is a calibration coefficient changing with time, and the others are the same as before.

- (4) Under the S3 cyclic stability condition, the actual evolution value of each year fluctuates up and down

around the extreme value M , and the multi-year average is generally consistent with M . It can be expressed by the trigonometric function:

$$x(t) = M + N \sin(\omega(t - t_M)) + \delta(t) \tag{4}$$

where N is the possible extreme value at the next stage based on the evolution extreme M , ω is the adjustment coefficient, and the others are the same as before.

- (5) Under the S4 gradual decrease to stable condition, the equation of the gradual change mechanism can be used, whereas the final stable value is not 0. The equation is as follows:

$$x(t) = M - \frac{M''}{1 + C''e^{-r''(t-t_M)}} \tag{5}$$

where M'' , C'' , and r'' are consistent with the previous M , C , and r , and the others are the same as before.

- (6) Under the S5 continuous decrease, the evolution value drops suddenly to a low value and continues decreasing until it is close to 0. The equation is as follows:

$$x(t) = M - \left(\frac{1}{4}t^4 + \frac{1}{2}at^2 + bt \right) \tag{6}$$

where a and b are parameters.

RESULTS

We apply the above methods to analyze the evolution of the social water cycle flux in several countries. On the one hand, we analyze their historical evolution rules; on the other hand, we predict their future flux evolution. The study objects are the social water cycle fluxes (i.e., the total amount of water use) of each country. Data of the total amount of water use in China are from the *China Water Resource Bulletin (CWRB)*, published annually. Data of the total amount of water use in the United States are from *Estimated Use of Water in the United States in 2015* (U.S. Geological Survey) (Maupin 2018). Data of the total amount of water use in other countries are from the

Table 1 | Countries with evolution law of S0 only

Country	Number of data	Parameters			R-square	Predicted value (billion m ³)	
		M	C	r		2020	2050
Greece	8	13.26	2.59	0.055	0.960	11.36	12.85
Algeria	7	16.16	6.83	0.044	0.996	9.18	13.42

AQUASTAT Main Database (2016) of the Food and Agriculture Organization (FAO) of the United Nations. Only 39 countries (39 of 217) with five or more years' water use data are used to analyze the evolution law and 11 countries (11 of 39) with seven or more years' data are used to fit the evolution equation.

Countries with evolution law of S0 only

There are seven countries, both developed and developing, with the evolution law of S0 only: Greece, Algeria, China, India, New Zealand, Mexico, and Cote d'Ivoire. As

China's water use data are more detailed, it will be analyzed in the Discussion. The first two countries are used for fitting (see Table 1 and Figure 4). Greece is in the gradual growth stage and Algeria is in the rapid growth stage of S0.

Countries with evolution law of S0 and S1

There are two countries with the evolution law of S0 and S1: Libya and Mauritius, both developing countries. Libya is used for fitting (see Table 2 and Figure 5). Libya is in the initial stage of S1.

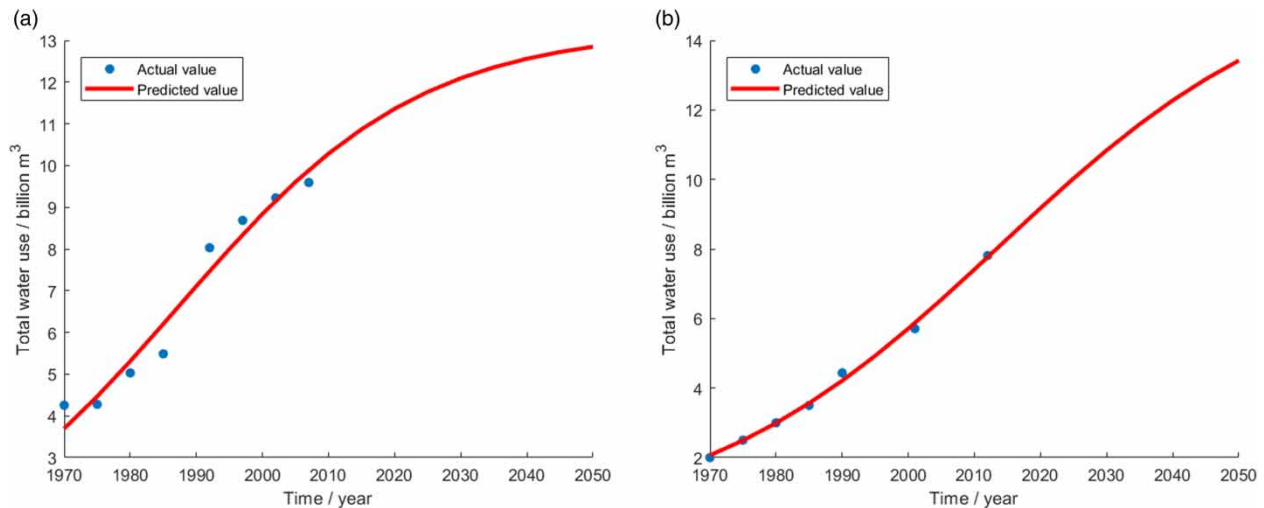


Figure 4 | Countries with evolution law of S0 only: (a) Greece and (b) Algeria.

Table 2 | Countries with evolution law of S0 and S1

Country	Number of data	Parameters of S0			R-square of S0	Parameters of S1			R-square of S1	Predicted value (billion m ³)	
		M	C	r		M'	C'	r'		2020	2050
Libya	8	4.76	5.83	0.26	0.933	1.45	397.30	1.08	1.000	5.76	5.76

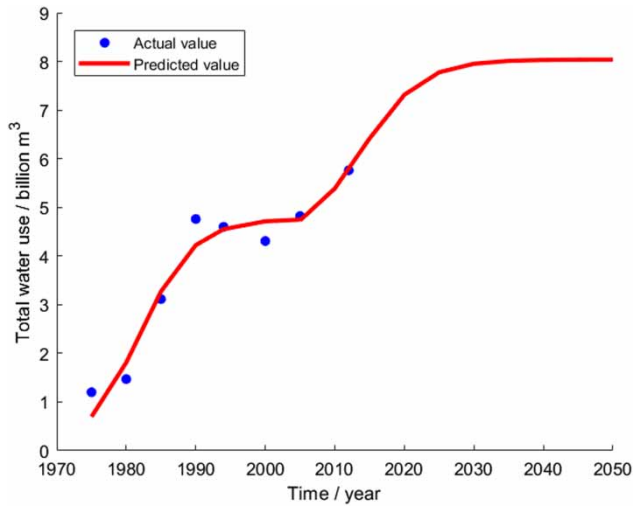


Figure 5 | Countries with evolution law of S0 and S1.

Countries with evolution law of S0 and S3

There are two countries with the evolution law of S0 and S3: Jordan and Tunisia, both developing countries. These two countries are used for fitting (see Table 3 and Figure 6),

Table 3 | Countries with evolution law of S0 and S3

Country	Number of data	Parameters of S0			R-square of S0	Parameters of S3		R-square of S3	Predicted value (billion m ³)	
		M	C	r		N	ω		2020	2050
Jordan	8	0.94	1.31	0.14	0.843	-0.17	0.16	0.635	1.10	0.96
Tunisia	7	3.07	1.89	0.21	0.956	-0.28	0.18	0.999	3.30	3.33

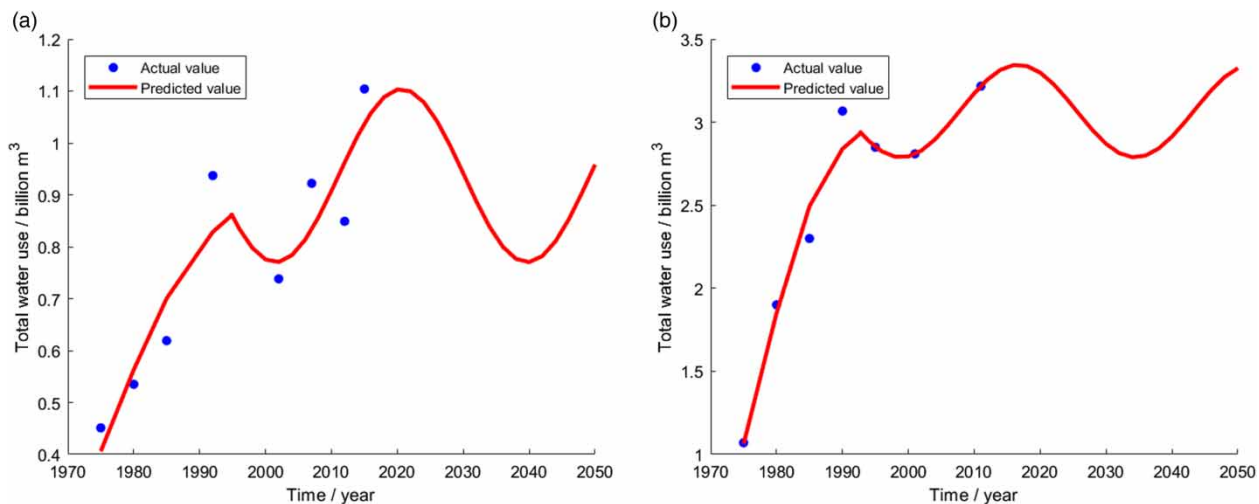


Figure 6 | Countries with evolution law of S0 only: (a) Jordan and (b) Tunisia.

but neither country has experienced a complete period of sin function.

Countries with evolution law of S0 and S4

There are ten countries with the evolution law of S0 and S4: Poland, Romania, Spain, Hungary, Denmark, France, Bulgaria, Switzerland, Japan, and Austria, and most of them are developed countries. The first two countries are used for fitting (see Table 4 and Figure 7). Poland is in the stable stage and Romania is in the gradual decline stage of S4.

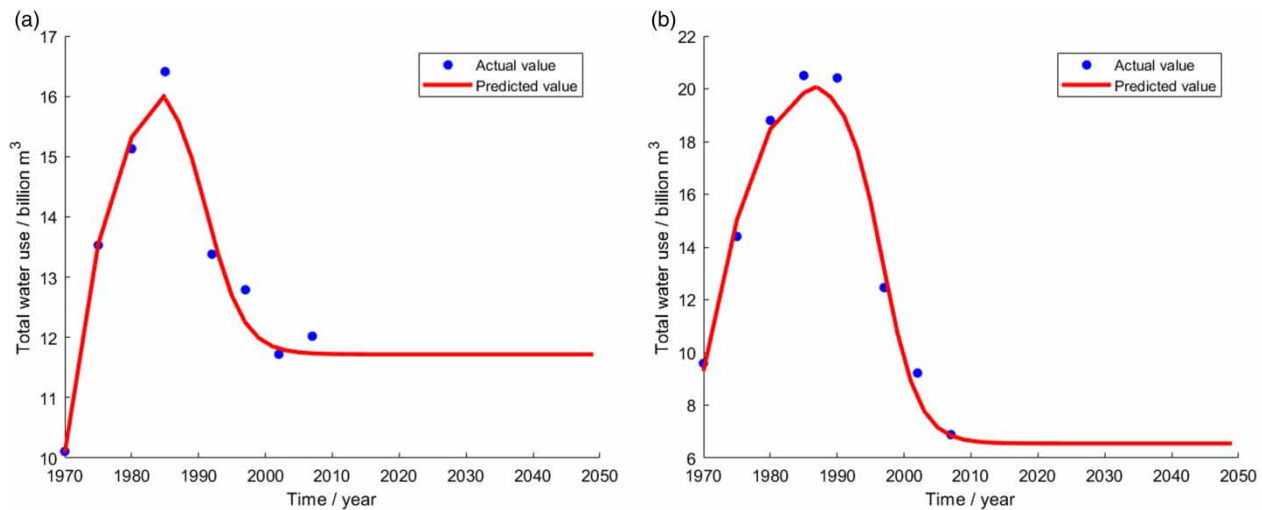
DISCUSSION

Analysis of social water cycle flux in China

Since the foundation of the People’s Republic of China, the total water use in China has increased from 103.1 billion m³

Table 4 | Countries with evolution law of S0 and S4

Country	Number of data	Parameters of S0			R-square of S0	Parameters of S4			R-square of S4	Predicted value (billion m ³)	
		M	C	r		M''	C''	r''		2020	2050
Poland	8	16.41	0.63	0.22	0.992	4.69	9.57	0.36	0.949	11.72	11.72
Romania	8	20.50	1.21	0.24	0.988	13.86	81.34	0.37	0.984	6.55	6.55

**Figure 7** | Countries with evolution law of S0 only: (a) Poland and (b) Romania.

in 1949 to 604.3 billion m³ in 2017, an increase of nearly six times with an annual increase rate of 1.52%. The total amount of water use is not increasing continuously at a high speed; rather, it shows some stages, which are described as follows (see Table 5).

The first stage: the 1949–1980 stage was a rapid growth stage. The drastic growth of pollution led to large-scale farmland development and the consequent development and utilization of water resources. This situation resulted in a significant increase in agricultural water use with a net increase of 340.6 billion m³. The increase was up to

4.3 times, and the 30-year average increase rate was up to 5.0%.

The second stage: the 1981–1999 stage was a gradual growth stage. With acceleration of reform and opening up, China gradually entered the stage of significant industrial development, leading to a rapid increase of water resources demand by the eco-social development. The per capita water demand also increased steadily, showing a growth trend. At this stage, the ratios of industrial and domestic water use increased, and that of agricultural water use decreased. The net increase of water use in China was 114.5 billion m³,

Table 5 | Changes of the total water consumption in China since 1949

Stage	Time	Description	Main water use units	Change of total amount (billion m ³)	Average increase rate (%)
First stage	1949–1980	Rapid growth	Agriculture	340.60	5.00
Second stage	1981–1999	Gradual growth	Agriculture, industry	115.40	1.20
Third stage	2000–2009	Small growth	Agriculture, industry, domestic	46.70	0.85
Fourth stage	2010–2017	Fluctuation growth	Domestic, production, ecology	2.10	0.05

increased by 1.26 times. The annual mean increase rate was 1.2%, much lower than the first stage.

The third stage, the 2000–2009 stage, was a growth stage with small amplitude. With the advance of industrialization, economic development gradually shifted to resource-saving and environmentally-friendly concepts. The water resources demand entered a stable increase stage. At this stage, the ratio of agricultural water use continued to decrease, and that of industrial water use increased to some degree, whereas that of domestic water use increased faster. During 2000–2009, the net increase of water use in China was only 46.7 billion m^3 , increased by 1.08 times. The annual mean increase rate was 0.85%, slower than the previous stage.

The fourth stage: from 2010 to 2017, the total water consumption has surpassed 600 billion m^3 , whereas the increase rate has slowed down significantly. The increase during 2010–2013 was 16 billion m^3 , whereas the amount in 2014 was less than that in 2013. The increase during the six years from 2010 to 2017 was merely 2.1 billion m^3 , with an annual increase rate of only 0.05%. The total amount of water use is expected to enter an adjustment period.

In 2012, the *Opinions on Applying the Strictest Water Resources Control System*, issued by the State Council, explicitly addressed the control index value of ‘three red lines’, requiring the total water use of China to be constrained within 700 billion m^3 with a use efficiency reaching or close to the world’s advanced level; the total water consumption of China is to be constrained within 670 billion m^3 in 2020. Studies have suggested that China will reach the stage of 0-growth in approximately 2030.

We use the constructed evolution S_0 to discuss the extreme value of the total water use of China. Based on the prediction of nationwide water resource integrated planning and historical water use data, the parameters of M , C , and r are 631.20, 4.09, and 0.068, respectively. The R -square is 0.984. That is to say, the total water use peak value will be 631.20 billion m^3 . The total water use is 610.80 billion m^3 in 2020 and 628.50 in 2030 (as shown in Figure 8). Both values are smaller than the control index of the national total water use in 2030. The extreme value of water demand will occur about 2030–2040. Compared with the previous research results (as shown in Table 6),

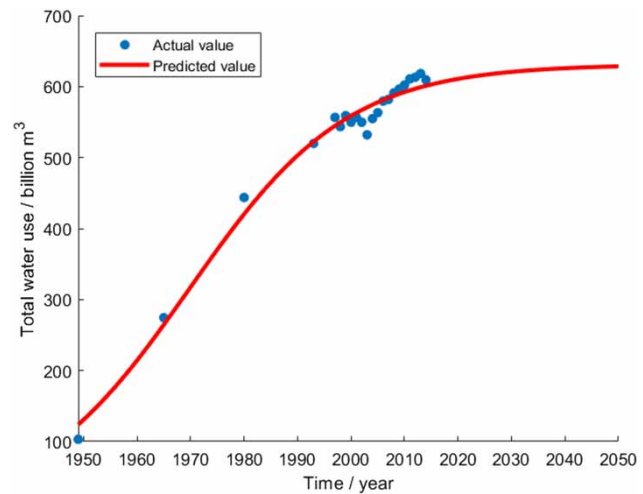


Figure 8 | The prediction of the extreme value of the China social water cycle flux.

this study considers that the peak value of total water use in China should be reached ahead of schedule, and the peak value is relatively smaller.

Countries with evolution law of exceptions

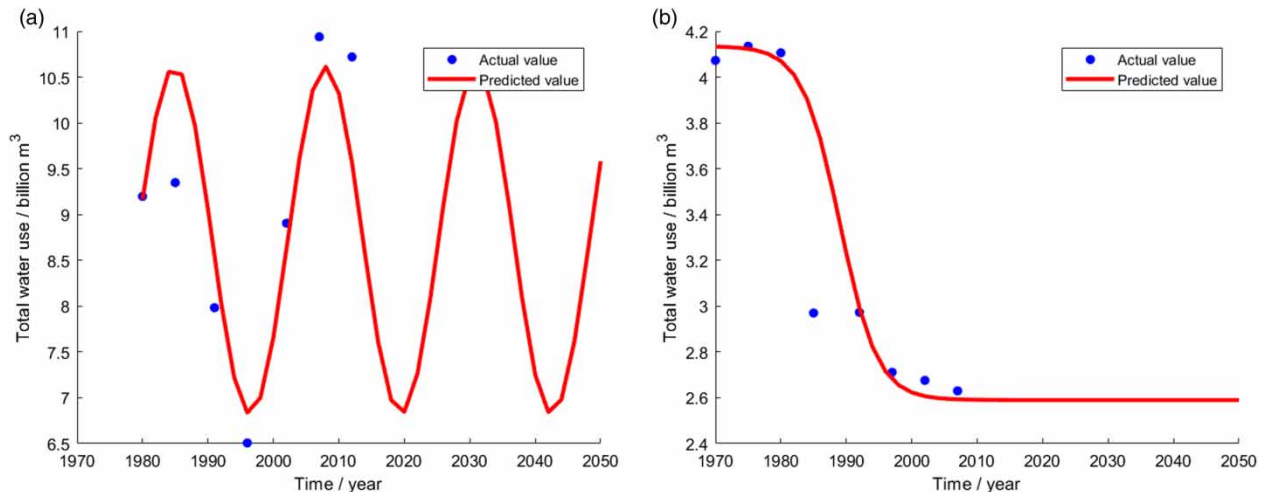
Except for the 21 countries mentioned above, the remaining 18 countries do not belong to S_0 or the combination of S_0 and another evolution mechanism. There are three main exceptions: (1) there is one evolution mechanism of S_1 – S_5 only but excluding S_0 (e.g., S_4 only); (2) there are combinations of two evolution mechanisms besides S_0 (e.g., S_0 , S_4 , and S_4); and (3) the uncertain evolution mechanism.

One evolution mechanism of S_1 – S_5 only but excluding S_0

There are 13 countries with evolution law of one evolution mechanism of S_1 – S_5 only but excluding S_0 : The Netherlands, Cyprus, Israel, Armenia, Sweden, Estonia, Latvia, Germany, Australia, Monaco, Czech Republic, Belgium, and Belarus. The first four countries are the countries with S_3 only and the others are with S_4 only. The reason may be that S_0 has already appeared before water use data were available. The Netherlands and Sweden are used for fitting (see Figure 9). R -square is 0.746 and 0.996, respectively. The predicted values are 6.85 billion m^3 and 9.58 billion m^3 for the Netherlands in 2020 and 2050, and 2.59 billion m^3 and 2.59 billion m^3 for Sweden.

Table 6 | A list of research achievements on the peak value and occurrence time of total water use in China

Author	Publication year	Publications (all in Chinese)	Peak value (billion m ³)	Occurrence year
Chen Jiaqi	1994	<i>Water Resources Planning and Design</i>		2100 (Chen 1994)
Jia Shaofeng & Zhang Shifeng	2000	<i>Advances in Water Science</i>	600–650	2010 (Jia & Zhang 2000)
Qian Zhengying and Zhang Guangdou	2000	<i>China Engineering Science</i>	700–800	2030 (Qian & Zhang 2000)
Ke Lidan	2001	<i>Groundwater</i>	700	2025 (Ke 2001)
Shen Fuxin <i>et al.</i>	2005	<i>Advances in Water Science</i>	750–800	2050 (Shen <i>et al.</i> 2005)
Liu Changming and Zhao Yanqi	2010	<i>The Impact of Science on Society</i>		2030 (Liu & Zhao 2010)
He Xiwu <i>et al.</i>	2011	<i>Journal of Natural Resources</i>	630	2026–2030 (He <i>et al.</i> 2011)
Liu Changming and Zhao Yanqi	2012	<i>Bulletin of Chinese Academy of Sciences</i>		2030 (Liu & Zhao 2012)
Zhang Peili <i>et al.</i>	2015	<i>Economic Dynamics</i>	721.7 +	2050 (Zhang <i>et al.</i> 2015)

**Figure 9** | Countries with evolution law of one evolution mechanism of S1–S5 only but excluding S0: (a) The Netherlands and (b) Sweden.

Combinations of two evolution mechanisms besides S0

There are three countries with evolution law of S0 and S4: United States, Finland, and Canada, and all of them are developed countries. This may be due to technological and industrial upgrading in developed countries. The USA is used for fitting.

Since 1950, the total water consumption of the USA has undergone a process from rapid growth to gradual stabilization, which can be generally divided into two stages.

The rapid growth stage: Prior to 1980, the total water use in the USA increased rapidly. During the 30 years from 1950 to 1980, the total water use increased from 0.68 billion m³ per day to 1.63 billion m³ per day, an annual increase rate of up to 4.6%. This stage reflected the rapid

development of US industry after World War II. After the completion of the transition from wartime to the post-war peace period, the US economy has continuously increased based on its post-war advantage since the 1950s. The western and southern USA both showed prosperity. From 1955 to 1968, the GDP of the USA increased rapidly at a rate of 4% per year. The rapid expansion of US industrial production led to a significant increase in industrial water use. The newly increased industrial water use accounted for 68% of the total amount of the newly increased water use.

The stable stage: Since 1980, the total water use in the USA has entered a stable period after a slight decrease. The total water use has remained approximately 1.51 billion m³ per day. Around the 1980s–1990s, the constraints of resources and environment on water use growth

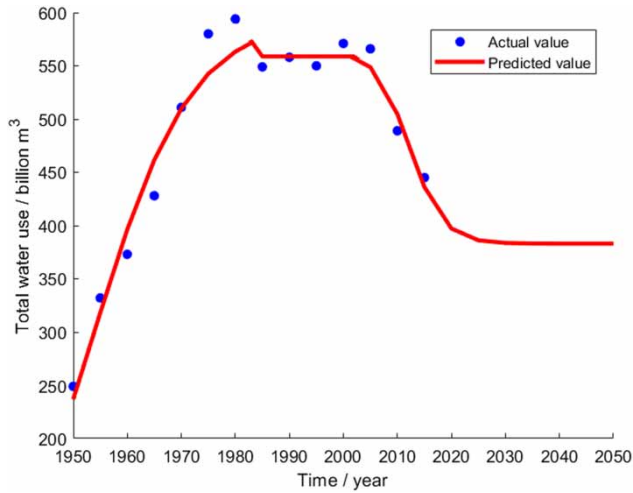


Figure 10 | The United States social water cycle flux and the evolution prediction.

gradually emerged, and the eco-social system started to adjust, leading to the stable stage of water use. During this period, the USA underwent a shortage of agricultural water, an increase in energy prices, and a shortage in the labor force, promoting the widespread use of water-saving irrigation technologies, and some surface irrigation shifted to highly efficient methods such as sprinkler irrigation. According to US irrigation area statistics released by the *Irrigation Journal* in 2000, among the 383.2 million acres (155.1 million hectares) of irrigation area, sprinkler irrigation accounted for 49.9%, surface irrigation accounted for 44.9%, and micro-irrigation accounted for 4.99%. In addition, the US Federal Water Pollution Control Act

(1972) required that the entire USA accomplish zero release of pollution by 1985, which played an important role in controlling US industrial water conservation and forced US industrial enterprises to re-focus on the reuse of industrial water. This action resulted in a significant decrease of industrial water use. US industrial water use in 1985 decreased by approximately 50 billion m³ (~15%) when compared with that in 1980.

The decrease stage: The total water withdraw for all types of uses in 2015 is estimated at 445 billion m³. This is an unreported level since 1970, down 9% from 2010. Since 2005, it has continued to show a sharp but stable downward trend. The main reason for the decrease in total water withdraw in 2015 was the dramatic decrease in the amount of heat and power withdrawals, accounting for 89% of the total water withdraw reduction. The decrease in public supply accounts for 9% of the decrease in water withdraw.

The total water use in the USA showed a three-stage evolution process; we can use the combination of S0, S4, and S4 to simulate and predict the flux evolution trend. The fitting results are seen in Figure 10. The results show that the future water use of the USA will decrease to approximately 383 billion m³ and occur around the 2030s.

Uncertain evolution mechanism

There are two countries with uncertain evolution law: the United Kingdom and Malta (see Figure 11). The reason

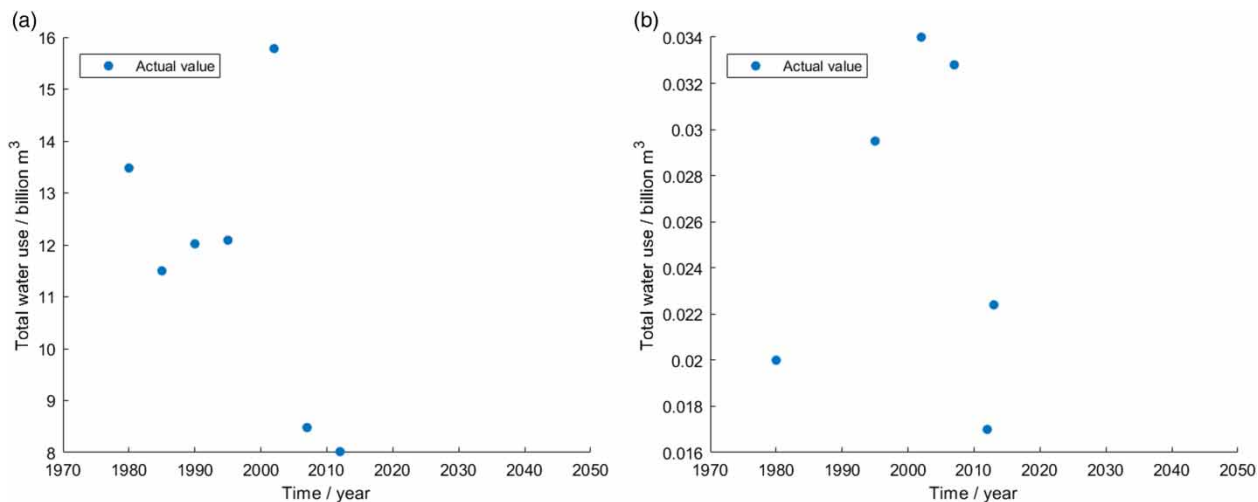


Figure 11 | Countries with uncertain evolution mechanism: (a) United Kingdom and (b) Malta.

may be inadequate water use data or other evolutionary mechanisms.

CONCLUSIONS

The evolution mechanism of the social water cycle fluxes were revealed in this paper, i.e., the gradual change mechanism and the catastrophe mechanism. Endogenous dynamic characteristics were identified and evolution equations were fitted for the social water cycle fluxes. Case studies of 39 countries, in terms of actual total water use, were examined to verify the rationality of the mechanism and the equations. Results demonstrated that all those testing countries showed different evolution stages, while there remained significant differences in evolution fitting curves. Nevertheless, long-term monitoring data of social water cycle fluxes are still scarce, and they are indispensable for future studies in this respect.

ACKNOWLEDGEMENTS

This research was financially supported by the National Natural Science Foundation of China, grant numbers 51625904, 51509267 and 51779271 and the IWHR Research & Development Support Program, grant numbers WR0145B522017 and WR0145B622017.

REFERENCES

- AQUASTAT Main Database 2016 Food and Agriculture Organization of the United Nations (FAO) <http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en>.
- Archibald, G. G. 1983 Forecasting water demand – a disaggregated approach. *Journal of Forecasting* **2** (2), 181–192.
- Avni, N., Fishbain, B. & Shamir, U. 2015 Water consumption patterns as a basis for water demand modeling. *Water Resources Research* **51** (10), 8165–8181.
- Chen, J. Q. 1994 China's water resources in a changing environment and prospects for supply and demand in the early 21st century. *Water Resources Planning and Design* **1994** (4), 13–19 (in Chinese).
- Chen, W. Q. & Graedel, T. E. 2012 Anthropogenic cycles of the elements: a critical review. *Environmental Science & Technology* **46** (16), 8574–8586.
- Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Salinas, J. L. & Blöschl, G. 2013 Socio-hydrology: conceptualising human-flood interactions. *Hydrology and Earth System Sciences* **17** (8), 3295–3303.
- Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Yan, K., Brandimarte, L. & Blöschl, G. 2015 Debates – perspectives on socio-hydrology: capturing feedbacks between physical and social processes. *Water Resources Research* **51** (6), 4770–4781.
- Drenkhan, F., Carey, M., Huggel, C., Seidel, J. & Oré, M. T. 2015 The changing water cycle: climatic and socioeconomic drivers of water-related changes in the Andes of Peru. *Wiley Interdisciplinary Reviews: Water* **2** (6), 715–733.
- Elshafei, Y., Sivapalan, M., Tonts, M. & Hipsey, M. R. 2014 A prototype framework for models of socio-hydrology: identification of key feedback loops and parameterisation approach. *Hydrology and Earth System Sciences* **18** (6), 2141–2166.
- Ertsen, M. W., Murphy, J. T., Purdue, L. E. & Zhu, T. 2013 A journey of a thousand miles begins with one small step-human agency, hydrological processes and time in socio-hydrology. *Hydrology and Earth System Sciences Discussions* **18** (11), 14265–14304.
- Fuchs, S., Karagiorgos, K., Kitikidou, K., Maris, F., Paparrizos, S. & Thaler, T. 2017 Flood risk perception and adaptation capacity: a contribution to the socio-hydrology debate. *Hydrology and Earth System Sciences* **21** (6), 3183–3198.
- Gau, H. S. & Liu, C. W. 2000 Estimation of the effective precipitation recharge coefficient in an unconfined aquifer using stochastic analysis. *Hydrological Processes* **14** (4), 811–830.
- Gober, P. & Wheeler, H. S. 2014 Socio-hydrology and the science-policy interface: a case study of the Saskatchewan River basin. *Hydrology and Earth System Sciences* **10** (5), 6669–6693.
- Gober, P. & Wheeler, H. S. 2015 Debates – perspectives on socio-hydrology: modeling flood risk as a public policy problem. *Water Resources Research* **51** (6), 4782–4788.
- He, X. W., Gu, D. F. & Tang, Q. W. 2011 Study on zero growth problem in total water demand of China. *Journal of Natural Resources* **26** (6), 901–909 (in Chinese).
- Jia, S. F. & Zhang, S. F. 2000 When will fresh water use in China reach the climax? *Advances in Water Science* **2000** (4), 470–477 (in Chinese).
- Jia, Y. W., Wang, H., Qiu, Y. Q. & Zhou, Z. H. 2006 General water resources assessment based on watershed hydrologic cycle model II: applications in the Yellow River Basin. *Journal of Hydraulic Engineering* **37** (10), 1181–1187 (in Chinese).
- Jia, Y. W., Wang, H., Zhou, Z. H., You, J. J., Gan, Z. G., Qiu, Y. Q., Lu, C. Y. & Luo, X. Y. 2010 Development and application of dualistic water cycle model in Haihe River Basin: I. Model development and validation. *Advances in Water Science* **21** (1), 1–8 (in Chinese).
- Kampragou, E., Lekkas, D. F. & Assimacopoulos, D. 2011 Water demand management: implementation principles and indicative case studies. *Water and Environment Journal* **25** (4), 466–476.
- Ke, L. D. 2001 Water resources countermeasures during the transition period from total water consumption to zero growth in China. *Groundwater* **2001** (3), 105–112 (in Chinese).

- Lane, S. N. 2014 [Acting, predicting and intervening in a socio-hydrological world](#). *Hydrology and Earth System Sciences* **10** (3), 927–952.
- Liu, C. M. & Zhao, Y. Q. 2010 Zero growth of water demand in China is achieved through water supply management and water transfer management. *The Impact of Science on Society* **2010** (2), 18–24 (in Chinese).
- Liu, C. M. & Zhao, Y. Q. 2012 Possibility of the zero growth of water requirement in China. *Bulletin of the Chinese Academy of Sciences* **27** (4), 439–446 (in Chinese).
- Liu, J. H., Qin, D. Y., Wang, H., Wang, M. N. & Yang, Z. Y. 2010 [Dualistic water cycle pattern and its evolution in Haihe river basin](#). *Chinese Science Bulletin* **55** (6), 512–521.
- Liu, D., Tian, F., Lin, M. & Sivapalan, M. 2015 [A conceptual socio-hydrological model of the co-evolution of humans and water: case study of the Tarim River basin, western China](#). *Hydrology and Earth System Sciences* **19** (2), 1035–1054.
- Loucks, D. P. 2015 [Debates – perspectives on socio-hydrology: simulating hydrologic-human interactions](#). *Water Resources Research* **51** (6), 4789–4794.
- Maupin, M. A. 2018 [Summary of Estimated Water use in the United States in 2015](#). U.S. Geological Survey Fact Sheet 2018-3035, p. 2.
- Merrett, S. 1997 [Introduction to the Economics of Water Resources: an International Perspective](#). UCL Press, London.
- Montanari, A. 2015 [Debates – perspectives on socio-hydrology: introduction](#). *Water Resources Research* **51** (6), 4768–4769.
- Mount, N. J., Maier, H. R., Toth, E., Elshorbagy, A., Solomatine, D., Chang, F. J. & Abrahart, R. J. 2016 [Data-driven modelling approaches for socio-hydrology: opportunities and challenges within the Panta Rhei Science Plan](#). *Hydrological Sciences Journal* **61** (7), 1192–1208.
- Qian, Z. Y. & Zhang, G. D. 2000 [Strategic research on sustainable development of water resource in China](#). *China Engineering Science* **2000** (8), 1–17 (in Chinese).
- Qin, D. Y., Lu, C. Y., Liu, J. H., Wang, H., Wang, J. H., Li, H. H., Chu, J. Y. & Chen, G. F. 2014 [Theoretical framework of dualistic nature-social water cycle](#). *Chinese Science Bulletin* **59** (8), 810–820.
- Shen, F. X., Geng, L. H., Cao, X. L., Wang, J. S., Zhong, H. P. & Xu, P. B. 2005 [Prospects for long-term water resources demand in China](#). *Advances in Water Science* **2005** (4), 552–555 (in Chinese).
- Sivakumar, B. 2012 [Socio-hydrology: Not a new science, but a recycled and re-worded hydrosociology](#). *Hydrological Processes* **26** (24), 3788–3790.
- Sivapalan, M. 2015 [Debates – perspectives on socio-hydrology: changing water systems and the ‘tyranny of small problems’– Socio-hydrology](#). *Water Resources Research* **51** (6), 4795–4805.
- Sivapalan, M., Savenije, H. H. G. & Blöschl, G. 2012 [Socio-hydrology: A new science of people and water](#). *Hydrological Processes* **26** (8), 1270–1276.
- Sivapalan, M., Konar, M., Srinivasan, V., Chhatre, A., Wutich, A., Scott, C. A., Wescoat, J. L. & Rodríguez-Iturbe, I. 2014 [Socio-hydrology: use-inspired water sustainability science for the Anthropocene](#). *Earth’s Future* **2** (4), 2013E–2164E.
- Srinivasan, V. 2015 [Reimagining the past – use of counterfactual trajectories in socio-hydrological modelling: the case of Chennai, India](#). *Hydrology and Earth System Sciences* **19** (2), 785–801.
- Tiwari, M. K. & Adamowski, J. 2013 [Urban water demand forecasting and uncertainty assessment using ensemble wavelet-bootstrap-neural network models](#). *Water Resources Research* **49** (10), 6486–6507.
- 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.
- Wang, H., Wang, J. H., Qin, D. Y., Chen, C. Y., Jiang, D. & Yao, Z. J. 2002 [The study on water resources assessment and subject system of water resources study on modern times](#). *Advances in Earth Sciences* **17** (1), 12–17 (in Chinese).
- Wang, H., Jia, Y. W., Yang, G. Y., Zhou, Z. H., Qiu, Y. Q., Niu, C. W. & Peng, H. 2013 [Integrated simulation of the dualistic water cycle and its associated processes in the Haihe River Basin](#). *Chinese Science Bulletin* **58** (27), 3297–3311.
- Zhang, P. L., Wang, X. X. & Lian, Y. X. 2015 [Can China’s water resources support medium and high-speed economic growth](#). *Economic Dynamics* **2015** (5), 87–97 (in Chinese).
- Zlinszky, A. & Timár, G. 2013 [Historic maps as a data source for socio-hydrology: a case study of the Lake Balaton wetland system, Hungary](#). *Hydrology and Earth System Sciences* **17** (11), 4589–4606.

First received 7 August 2018; accepted in revised form 27 January 2019. Available online 12 September 2019