Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-411, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 31 August 2016

Hydrology and Earth System Sciences
Open Access
Discussions

Socio-hydrologic perspectives of the co-evolution of humans and groundwater in Cangzhou, North China Plain

Songjun Han[1, 3], Fuqiang Tian[2], Ye Liu[2], Xianhui Duan[4]

[1]State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China;
[2]State Key Laboratory of Hydro-science and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China;
[3]National Center of Efficient Irrigation Engineering and Technology Research, Beijing 100048, China;
[4]Hydrology and Water Resources Survey Bureau of Cangzhou, Cangzhou, 061000, China.

Correspondence to: Songjun Han (hansj@iwhr.com); Fuqiang Tian (tianfq@tsinghua.edu.cn)

Abstract. This paper presents a historical analysis of the coupled human–groundwater system centered on the Cangzhou region in North China Plain, from the socio-hydrologic perspectives. The history of the co-evolution of the system is divided into five eras (i.e., natural, exploitation, degradation and restoration, drought triggered deterioration, and getting back to balance). The balance of the social productive force and natural variability dominate the evolution of the human–groundwater system in Cangzhou, which has been interpreted in terms of the Taiji-Tire model. The interaction between the groundwater utilization and the water table are regarded as the inner Taiji, with the over-exploitation as the major reason for the groundwater depletion, and the groundwater utilization pattern affected by the changing groundwater table. The external drivers of the co-evolution of the human-groundwater system in Cangzhou were specified as the social productive force and natural variability, which represents the outer Tire. An upgrading of the social productive force, which was triggered by the drought during 1997-2002, enhanced the ability to rebalance the human-groundwater system in Cangzhou, and increased the ability to mitigation climate variability. In the future, along with the launch of most strict water resource management strategy and the South-to-North Water Diversion Project, further restoration of groundwater environment could be anticipated. However, the occurrence of drought, as an external environment forcing, still remains an undetermined variable.

1 Introduction

As an almost ubiquitous source of generally high-quality fresh water, the groundwater system is closely connected with human system. Driven by the increasing water resources demand, improper exploitation of groundwater resources resulted in serious groundwater crisis, especially in regions with primarily groundwater-fed irrigation (Taylor et al., 2013), such as the North China Plain (Liu et al., 2001; Chen et al., 2003; Zheng et al., 2010). Except for the social forcing, natural variability is another external forcing. The climate variations influence the groundwater system both directly through replenishment by recharge and indirectly through variations in groundwater demand (Taylor et al., 2013). Different from the inherent human forcing, the natural variability induced changes in human activities (such as drought triggered pulse in water demand) are extrinsic (Gurdak, 2012), and often appear as shocks (droughts, for example), which may push the system beyond its salience threshold (Sivapalan et al., 2012).

On the other hand, water resources management decisions would produce positive or negative impacts on both the environment and the society (Kandasamy et al., 2014). Linked by the processes of adaption, the human society co-evolves with the hydrological system. There is an urgent need to improve the ability of understanding the human-groundwater systems involving feedbacks and interactions between the two sub-systems (Kandasamy et al., 2014). The importance of socio-hydrology has been recognized by The International Association of Hydrological Sciences (IAHS) through their "Scientific Decade" (2013–2022) "Panta Rhei (Everything flows)" (Montanari et al., 2013), which aims "to reach an improved interpretation of the processes governing the water cycle by focusing on their changing dynamics in connection with rapidly changing human systems".

The challenge of understanding the co-evolution of human-groundwater system is clearly illustrated in this case study from North China Plain (NCP). The NCP is an extremely important agricultural region of China. The main crops area wheat and maize. Irrigation is necessary to maintain high levels of grain production (Liu et al., 2001), with 70% of cultivated land is irrigated and consumes 70% of total water supply. As over exploitation causes the lower reaches of streams to dry up, groundwater has become the regular supply for irrigation since the 1970s. The density of pumped wells have led to severe groundwater depletion of both unconfined and confined aquifers (Zhang et al., 1997). Simulation efforts have been made for a better understanding of the spatiotemporal variations in groundwater depletion across the NCP, aiming for sustainable groundwater management options (Cao et al., 2013; Liu et al., 2008), with the impact of human-induced change evaluated with a scenario-based method (Wang et al., 2008; Liu et al., 2011; Liu et al., 2008). However, as the human impacts are more and more significant, two-way feedbacks should be seriously considered for a better understanding of coupled human-natural systems (Montanari et al., 2013).

A vivid example of the co-evolution of human-groundwater system is in Cangzhou with the most serious depression cone since 1970s, a region in the northeastern coastal plain of the NCP (Liu et al., 2001). This paper will chart the history of the co-evolution of the coupled human–groundwater system in Cangzhou, with a particular focus on how the groundwater crisis unfolded and how people attempted to settle the crisis.

2 Study area, data and methods

Because that groundwater pumping from the aquifer increases obviously since middle of the 1960s, the NCP aquifer system becomes one of the most overexploited aquifer in the world (Kendy et al., 2007; Liu et al., 2008). Cangzhou region is located in the east of the NCP, and in the downstream of the Haihe River Basin (Fig. 1), with a total area of 14,056 km^2. In Cangzhou, precipitation has strong inter-annual variability, with extremely drought happens occasionally. In the year 2013, the total population is 7.34×10^6. The cultivated land area is 8,066 km^2, of which 5,424 km^2 is irrigated. Because surface water intercepts by reservoirs in the upstream, natural streams have almost dried up, leaving groundwater as the last choice.

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-411, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 31 August 2016

Hydrology and Earth System Sciences
Open Access
Discussions

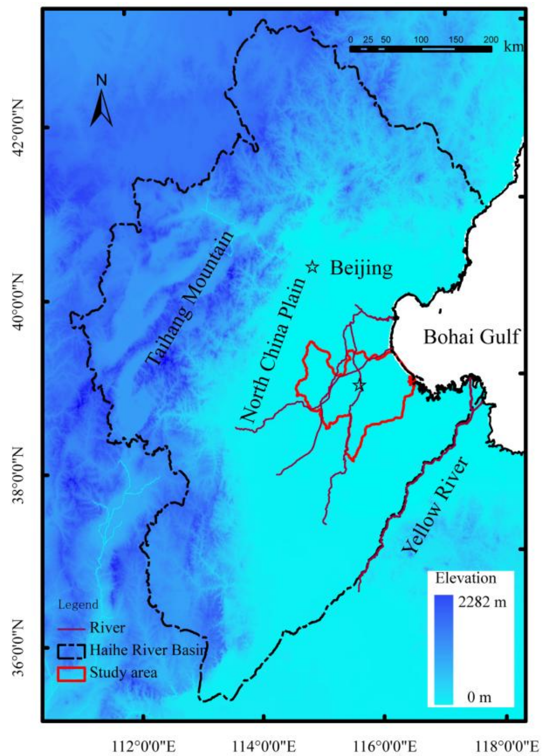

Figure 1. Location of Cangzhou within the North China Plain

The groundwater resides in aquifers of porous Quaternary alluvial deposits, which can be divided into four major aquifer layers (I–IV). The thickness of each layer ranges between 20 and 350 m. Aquifer layer I is unconfined, and infiltration from precipitation is the main recharge source. The other three are confined. Salt water accounted for 98% of aquifer layer II, with a small exploitation capacity. As a result, pumping wells extract fresh groundwater from the aquifer layer I and III. In this study, the top layer and the third layer are referred to as "shallow aquifer" and "deep aquifer", respectively. The average annual renewable groundwater resources in the shallow aquifer is around 500×10^6 m^3, and 235-292$\times10^6$ m^3 in the deep aquifer (Wang and Wang, 2007; Zhang and Fei, 2009). Nevertheless, the groundwater withdrawal from the shallow and deep aquifers were 297×10^6 m^3 and 701×10^6 m^3 in the year 2010. Due to over-pumping, the groundwater levels declined steadily, resulting saltwater intrusion and land surface subsiding (Kendy et al., 2003). In recent years, several measures have been taken to achieve sustainable groundwater management, resulting in a backup of the aquifer depletion.

One objective of the study is to analyze the co-evolution of the human-groundwater system in Cangzhou throughout history, focusing on the interactions between the social productive force and natural variability. A specific social hydrological system contains human, hydrological and environmental sub-systems. The Taiji-Tire model proposed by Liu et al. (2014) is a framework to represent and explain a specific social-hydrological system under its outer environmental system. In the model, a Taiji wheel, a term from a special concept in Chinese philosophy, is used to describe the direct human–water relationship of a specific social hydrological system. While a human–water tire is used to represent the indirect impact of

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-411, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 31 August 2016

external natural and social factors that affect the water. The interactions and co-evolutions of the human-groundwater system within Cangzhou have been analyzed under the framework of the Taiji-Tire model. The analyses were conducted according to the data of annual precipitation, agricultural infrastructures and production, groundwater withdrawal from both the shallow and deep aquifers, groundwater table depth, sourced from the Water Resource Annals of Cangzhou (Xue, 1994), the Hebei Rural statistics yearbook (from 1994 to 2013), the Hydrology and Water Resources Investigation Bureau of Cangzhou in Hebei Province.

3 Pendulum swing in groundwater utilization

The balance between groundwater extraction and efforts to mitigate and reverse consequent degradation of the aquifer have evolved since 1949 (Li et al., 2013). The evolutionary history of the human-groundwater system from 1966 to 2015 in Cangzhou is presented in Fig. 2, and the major policies and initiatives are summarized in Table 1. The history is divided into five distinct eras:

Era 1 (-1964): natural variability dominates socio-groundwater hydrological system.

Era 2 (1965-1982): expansion of groundwater utilization and appearance of aquifer depletion.

Era 3 (1983-1996): awareness of environmental degradation and attempts for restoration.

Era 4 (1997-2002): drought triggered pulse in groundwater abstraction and aquifer depletion.

Era 5 (2003 to present): the strictest groundwater control system and the getting back to balance.

3.1 Era 1 (Pre-1964): Natural variability dominates social-hydrological change

The exploitation of groundwater resources in Cangzhou has a long history. Archaeological discoveries show that Cangzhou residents drilled wells to obtain drinking water as early as the Han Dynasty (approximately from 220 BC to 220 AD). Historical records indicate that groundwater exploitation for irrigation in Cangzhou can be traced back to 1266, which was over 700 years ago. For a long time, the scale of groundwater utilization has been small. In 1949, the irrigated area with groundwater was only 74 km^2, which was distributed in fewer places where shallow freshwater resources were abundant. From the early 1950s to the mid-1960s, the Haihe River basin was rich in surface water resources. A large number of reservoirs and diversion projects were constructed. Because of serious salinization problems, a drainage-oriented policy was established in Cangzhou for groundwater resource management. During this period, most wells were made of bricks and earth. Groundwater utilization was also restricted by the lack of infrastructure. By 1964, only 1,524 wells were pumped by motors. The irrigated area with groundwater was 321 km^2 in 1964, which is only 2.3% of the total area of Cangzhou.

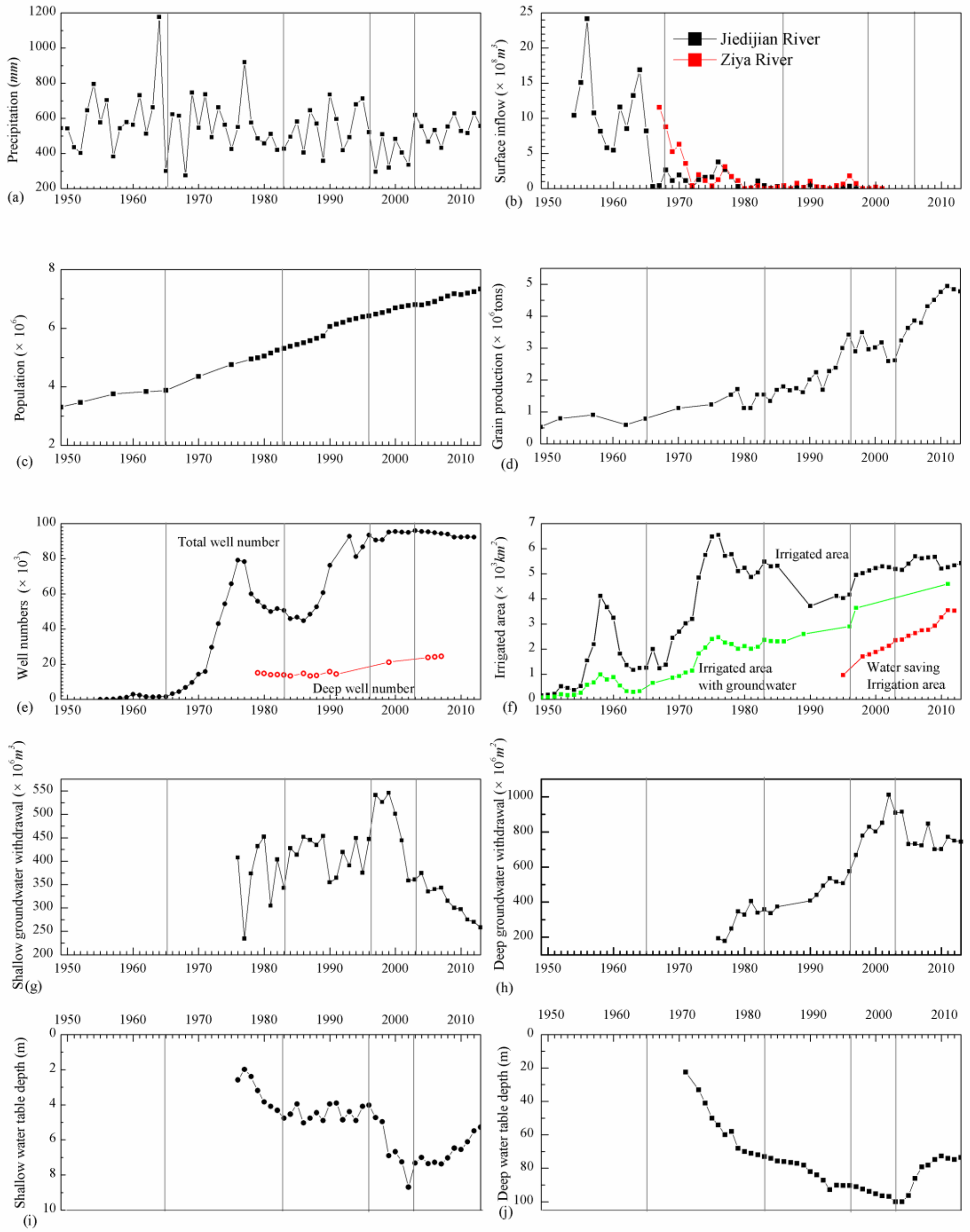

Figure 2. Time series of (a) precipitation, (b) surface inflow, (c) population, (d) grain production, (d) well numbers (red line is referred the number of deep well), (e) irrigated area, (f) shallow groundwater withdrawal, (g) deep groundwater withdrawal, (h) shallow water table depth, and (i) water table depth of the depletion cone in Cangzhou during the study period (1949-2013)

5

Table 1. Summary timeline of major policies and initiatives in Cangzhou

Year	Scale	Content
1966	State	The conference for the work of combating drought in eight provinces (municipalities) in North China
	Province	Hydrogeological investigations for agricultural water supply were conducted
	Cangzhou	Several well-drilling teams were organized in Cangzhou and other regions, thus a surge of motor-pumped well constructions began
1970	State	The agricultural conference regarding agricultural production in fourteen provinces in North China, and funding for motor-pumped well constructions.
1973	Hebei	The headquarters for construction of motor-pumped wells were established
1979	State	Environmental Protection Law of the People's Republic of China (Trail)
1983	Cangzhou	Cangzhou Hydraulic Engineering Society submitted an appeal to the government leaders at all levels
1984	State	The State Council appointed the Department of Water and Power as the general management department for water resources
1985	Hebei	Regulation of Water Resources of Hebei Province
1985	Cangzhou	Suggestions Concerning the Strengthening of the Management of Groundwater Resources
1988	State	The Water Law of the People's Republic of China
1993	State	The Implementation Measures of Licensing System for Water Taking
1993	Inter-basin	The water diversion from the Yellow River
1997	Hebei	The emergency conference for the work of combating drought
1998	Hebei	Water-saving irrigation planning
1999	Hebei	Management Method of License System for Water Taking
2002	Hebei	Specified the over-exploitation regions and serious over-exploitation regions in plain area
2003	State	Suggestions Concerning the Strengthening of the Management of Groundwater Over-exploitation Regions by the Ministry of Water Resources
2005	Hebei	Hebei Provincial Government published the notice that the urban self-supply wells should be shut down and the groundwater exploitation should be restricted
2005	Cangzhou	Cangzhou Municipal Government also decided to shut down the self-supply wells and ban the deep self-supply wells in urban areas
2012	State	the strictest water resource management strategy
	Hebei	Implementation schemes of the strictest water resource management strategy
	Cangzhou	Implementation schemes of the strictest water resource management strategy
2013	Hebei	Regulations on Groundwater Management of Hebei
2013	Cangzhou	The high-efficiency water-saving and irrigation program
2015	Inter-basin	The South-to-North Water Diversion Project was put into production

3.2 Era 2 (1965–1982): Expansion of groundwater exploitation

In 1965, North China suffered from a catastrophic drought, threatening food production. So groundwater abstracted by motor-pumped wells attracted extensive attention. In 1966, the State Council organized a conference to combat drought in North China, and they specified well-drilling as an important measure. Amounts of well-drilling teams were organized after hydrogeological investigations on agricultural water supply in the NCP. In Cangzhou, a surge of motor-pumped well construction projects began. In 1970, the number of motor-pumped wells increased to 14,328 from 1,548 in 1965, and the irrigated area with groundwater increased to 920 km^2.

The benefits of the emergency wells drilled for combating the drought made people continue the construction of the groundwater exploitation infrastructures after the drought. The primary goal of groundwater utilization was transformed to increase grain yield. In August 1970, the state government held a conference on agricultural production in Northern China and decided to accelerate the agricultural development in regions with food shortage, including Cangzhou. Specifically, the construction of motor-pumped wells was included in the national plan. From 1970 to the early 1980s, motor-pumped well constructions were generally supported by national special funds.

In 1973, the head quarters for the construction of motor-pumped wells were established in Cangzhou. Several specialized construction management departments were also set up in subsidiary cities and counties. After 1975, when the irrigated area with surface water reached a maximum of 4,084 km^2 (the area irrigated with groundwater was 2,401 km^2 in the same year), surface water resources were gradually exhausted (which can be detected from the changes in runoff of two rivers shown in Fig. 2(b)). Groundwater then became an important water resource for agricultural irrigation. In 1983, the number of motor-pumped wells reached 50,605, and the irrigated area with groundwater reached 2,365 km^2 (Figure 2(e)), which is 43.1% of the total irrigated area and 16.8% of the total area of Cangzhou. Benefit from the groundwater utilization, the grain yield in this region increased from 0.79×10^6 tons in 1965 to 1.54×10^6 tons in 1982.

Because of the rapid increase in groundwater exploitation, the groundwater level of both the shallow and deep aquifers dramatically decreased. The average annual volume of shallow groundwater abstraction from 1976 to 1982 is 372.4×10^6 m^3. In 1983, the regional average shallow groundwater table declined to 4.77 m beneath the ground, with an annual decline of 0.39 m from 1976 to 1983. Nevertheless, many shallow wells were abandoned as a result of the significant decline in groundwater table. The motor-pumped wells had to be drilled with increasing depth, and a vicious circle began. Groundwater exploitation had to go deeper than usual, and the volume of deep groundwater pumped significantly increased, from 193×10^6 m^3 in 1976 to 357.7×10^6 m^3 in 1983, which exceeded the sustainable volume since 1979. With increasing exploitation, the water table of the deep aquifer rapidly declined. The cone of depression of the deep aquifer in Cangzhou first appeared in 1967, whereas the depth of the water table at the center of the cone of depression was 22.5 m beneath the ground in June 1971. By 1983, the water level at the center of the cone of depression was as deep as 72.9 m, with an annual decline of 3.82 m from 1973 to 1983. Because of the drop in deep groundwater table, the drilling depth increased, and the cost for both well drilling and installation of new motor-pumped wells rose. In addition, a series of environmental problems was triggered.

Land subsidence occurred in Cangzhou City in 1970 as a result of the presence of the cone of depression. The cumulative volume of subsidence in 1970 was 9 mm, and it increased to 744 mm in 1986. Because of the cone of depression formed in aquifer layer III, the natural recharge–discharge balance between the fresh water originally in aquifer layer III and the salt water in the overlying aquifer layer II was destroyed. The leakage recharge of salt water from aquifer layer II to layer III increased, leading to salt water intrusion.

3.3 Era 3 (1983--1996): awareness of environmental degradation and attempts for restoration

Along with the groundwater crisis intensified, the public clamor to address the water crisis in Cangzhou became increasingly loud. The Environmental Protection Law of the People's Republic of China (Trail), which was enacted in 1979, states that groundwater should be rationally exploited to prevent water resource exhaustion and land subsidence. In 1983, the Cangzhou Hydraulic Engineering Society submitted an appeal document entitled "Appeal for the Rational Exploitation of Water Resources" to government leaders. In this appeal, proposals for comprehensive water resource management were proposed. In 1984, the State Council appointed the Department of Water and Power as the general management department for water resources in China to unify water resource management efforts. In 1985, the Hebei Provincial Government enacted the Regulation of Water Resources, which stated that the exploitable volume of groundwater in urban areas should be strictly controlled, and the exploitation of groundwater in rural areas should be reasonably planned. In June 1985, the Water Conservancy Bureau in Cangzhou issued the suggestions concerning the strengthening of the management of groundwater resources, in which a series of comprehensive water resource management measures was detailed. Specifically, priority should be given to the exploitation of shallow groundwater, whereas deep groundwater should be restricted exploited. Brackish water should be reasonably utilized. Furthermore, a licensing system for well-drilling was established, and the planting of crops, such as rice, which consumes large amounts of water, was forbidden.

In 1988, the Water Law of the People's Republic of China was released, which states that explorations should be strictly controlled in regions where groundwater resources are over-exploited. Moreover, measures should be taken to protect groundwater resources and prevent land subsidence. In 1993, the State Council issued the Implementation Measures of the Licensing System for Water Taking. As stipulated, groundwater exploitation should not exceed the annual exploitable volume of an administrative region. In regions where groundwater resources are over-exploited, including Cangzhou, groundwater exploitation should be strictly controlled, and the expansion of the exploitation scale is forbidden. Since 1980s, well drilling was no longer subsidized by the central government, which resulted in a sharp decrease in the number of wells. In order to fill the gaps, surface water was diverted from the Yellow River since 1993. As of 2002, 1.2 billion cubic meters of water were diverted from the Yellow River.

The aforementioned measures relied on comprehensive water resource management, by which deep, medium, and shallow groundwater exploitations was governed by unified planning, with priority given to the exploitation of shallow aquifer. As a result, the increasing deterioration of groundwater resources in Cangzhou was ceased. From 1984 to 1996, the volume of shallow groundwater pumped slightly decreased (approximately by 2×10^{6} m^{3} per year), whereas the average shallow groundwater table rose at the rate of 0.02 m per year (Table 2). The increase in the volume of deep groundwater pumped also became slow (approximately by 18.8×10^6 m^3 per year. As a result, the water level at the center of the cone of depression declined slower, with a annual rate 1.68 m, and the subsidence of the center of the cone of depression also became less significant (approximately by 1.68 m^3 per year).

Table 2. Changes in shallow and deep groundwater withdrawal and table depth from era 2 to era 5

	Annual precipitation	Shallow groundwater			Deep groundwater		
	mm	Withdrawal ×10^6m^3	Average m	Trends m/decade	Withdrawal ×10^6m^3	Average m	Trends m/decade
Era 2*	544.1	368.6	3.4	-0.39	299.4	56.3	-4.24
Era 3	554.9	417.2	4.4	0.02	455.2	82.9	-1.68
Era 4	391.7	485.9	6.5	-0.75	822.7	96.7	-2.47
Era 5	547.2	315.3	6.7	0.2	774.0	82.7	3.01

* According to the data from 1976 to 1983.

3.4 Era 4 (1997--2002): Drought-triggered pulse in groundwater abstraction and aquifer depletion

Unfortunately, the positive tendency was ceased after the outbreak of a serious drought in the NCP began in 1997. The precipitation in Cangzhou was only 296.3 mm (53.9% of the mean annual value) in 1997, and the average annual precipitation was only 391.7 mm from 1997 to 2002. Because surface water was already exhausted since the 1980s, well drilling seemed to be the only choice to resist the drought. During this period, the annual average volume of shallow groundwater pumped was 485.9×10^6m^3, which represented an increase of 16.5% compared with 417.2×10^6m^3 from 1984 to 1996. Accordingly, the shallow groundwater level declined rapidly again, and the average water table depth beneath the ground declined from 4.03 m in 1996 to 8.69 m in 2002, with an annual decline of 0.75 m. At the same time, the annual average volume of deep groundwater pumped rapidly increased from 455.2×10^6 m^3during the period 1984 to 1996 to 822.7×10^6m^3, which represented an increase of 80.7%. The water table at the center of the cone of depression declined rapidly again, from 90.4 m in 1996 to 111.1 m in 2001 (the deepest value), with an annual decline of 2.47 m. The area with the water table of the aquifer layer III deeper than 80 m beneath the ground dramatically increased from 157 km^2 in 1996 to 421 km^2 in 2002. Because of the sharp decline in groundwater table, the environment noticeably deteriorated.

3.5 Era 5 (2003–present): Getting back to the balance

Even during the drought, the groundwater crisis in Cangzhou drew widespread concern again, and a series of measures was implemented from the national, provincial, to the regional levels. In 1999, the Hebei Provincial Government issued the Management Method of License System for Water Taking. As stipulated, in over-exploited regions, groundwater exploitation should be strictly controlled, and the expansion of the exploitation scale should be forbidden. In 2002, the Hebei Provincial Government specified the over-exploited regions and seriously over-exploited regions in the plain area. The entire Cangzhou was included as a seriously over-exploited region of the deep aquifer. The area of over-exploited and seriously over-exploited regions in terms of shallow aquifer were 406 km^2 and 525 km^2, totally accounting for 6.6 % of the total area of Cangzhou. In 2003, the Ministry of Water Resources issued the Suggestions Concerning the Strengthening of the Management of Groundwater Over-Exploitation Regions, in which several targets and measures for groundwater management were proposed. In 2005, the Hebei Provincial Government published a notice stating that urban wells out of the management of the department for water resources should be shut down, and groundwater exploitation should be restricted. The Cangzhou Municipal Government subsequently began to shut down these wells in urban areas.

In order to adapt the restrictions on groundwater exploitation, the Hebei Provincial Government formulated a program for water saving technologies development in 1998. Investments in water-saving projects were enhanced, and subsidies were provided. Accordingly, the irrigated area with water-saving technologies (mainly low-pressure pipeline irrigation and sprinkler irrigation) in Cangzhou rapidly increased from 96.4 km^2 in 1995 to 3,526.5 km^2 in 2012, which is accounting for 65% of the total irrigated area. Meanwhile, rainwater collection, inter-basin water transfer project, sea water desalination, and expansion of water source, were also implemented. The water supply volume from non-groundwater sources significantly increased from 110.66×10^6 m^3in 2002 to 292.08×10^6 m^3 in 2010.

Remarkable effects were obtained through the implementation of these measures. The volume of shallow groundwater pumped gradually decreased from 360.4×10^6 m^3 in 2003 to 258.2×10^6 m^3 in 2013. As a consequence, the shallow groundwater table rose again, to 5.28 m beneath the ground in 2013, with an annual rise of 0.2 m. The volume of deep groundwater pumped decreased from $1,011\times10^6 m^3$ in 2002 to 743.2×10^6 m^3 in 2013. The water table at the center of the depression cone of the deep aquifer rose to 73.47 m beneath the ground in 2013, with an annual rate of 3.0 m. According to the latest groundwater over-exploited regions specified by the Hebei Provincial Government in 2014, an area of 413 km^2 is alleviated from seriously over-exploited region to over-exploited region of the deep aquifer. An area of 525 km^2 is alleviated from seriously over-exploited region to over-exploited region of the shallow aquifer, and the former 406 km^2 over-exploited region in terms of shallow aquifer is abolished.

In 2012, the strictest water resource management strategy in China was launched, in which many strict groundwater management and protection measures were proposed. Subsequently, the Hebei Provincial Government and the Cangzhou Municipal Government published the implementation schemes. According to the implementation scheme, groundwater exploitation in Cangzhou will be strictly controlled. Except for the purpose of obtaining domestic water for use, the construction of new motor-pumped wells will not be approved. Groundwater exploitation is forbidden in urban regions already covered by a public water supply network. Since the establishment of the South-to-North Water Diversion Project in 2015, with annual water diverted to Cangzhou is 483×10^6 m^3, all wells in urban regions not controlled by the water resources administrators will be shut down and groundwater over-exploitation in rural regions will be gradually cut down. Instead, according to the High-Efficiency Water-Saving and Irrigation Program in Cangzhou launched in 2013, all-around water savings in agricultural production will be achieved by 2020.

4 Discussions: interactions of the human-groundwater system

According to above analysis about the co-evolution of the human–groundwater system in Cangzhou, the specific application of the Taiji-Tire model for the human-groundwater system is provided in Fig. 3. The inner Taiji represents the direct interacting human activities and hydrologic variables at short-term, reflecting the human-water relation. In Cangzhou, the Taiji represents the direct interactions between groundwater utilization and the water table.

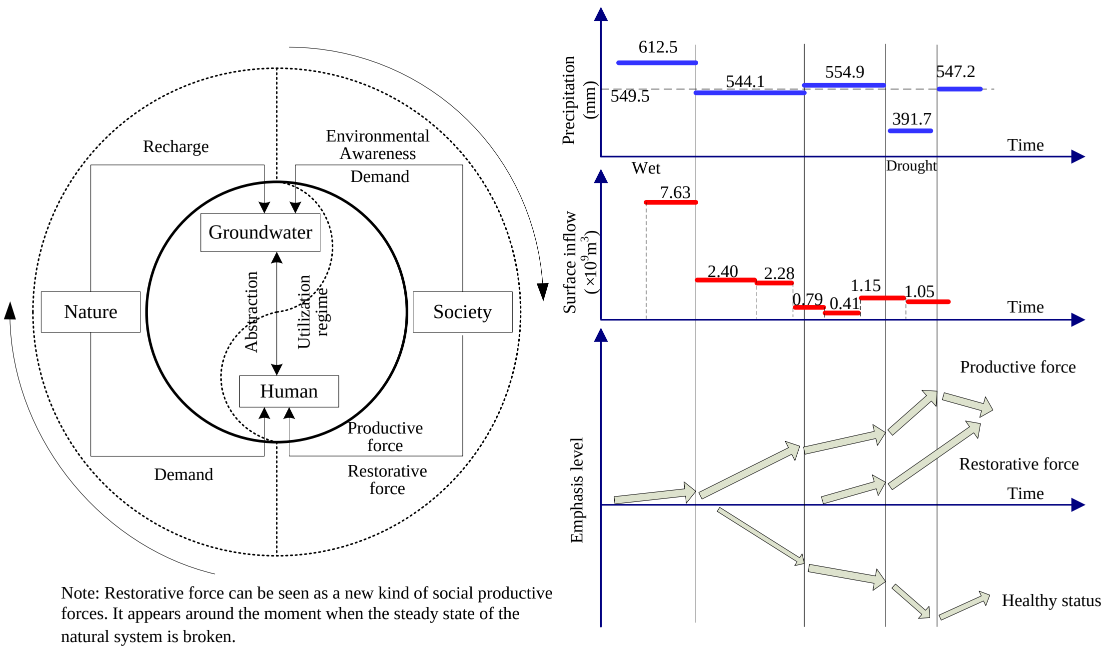

Figure 3. (a) Taiji-Tire model representation of the interactions of the human-groundwater system in Cangzhou; (b) The change in natural variability (precipitation and surface inflow), social productive and restorative forces in Cangzhou through five eras (Emphasis level used in relation to the vertical axis refers to the degree of increase in the parameters described in the figure).

With increasing groundwater utilization, both the shallow and deep groundwater table declined, and groundwater depression cone extended in Cangzhou. The contributions of increasing shallow groundwater utilization on groundwater table declines can be found from the positively correlation between annual shallow water table fluctuations and water withdrawal (Fig. 4(a)). The increasing deep groundwater utilization contributed to the decline of the water table depth of the depression core before 2002. After that, the rapid groundwater utilization reduction resulted that water table at the center of the cone of depression of deep groundwater rose quickly (Fig. 4(b)).

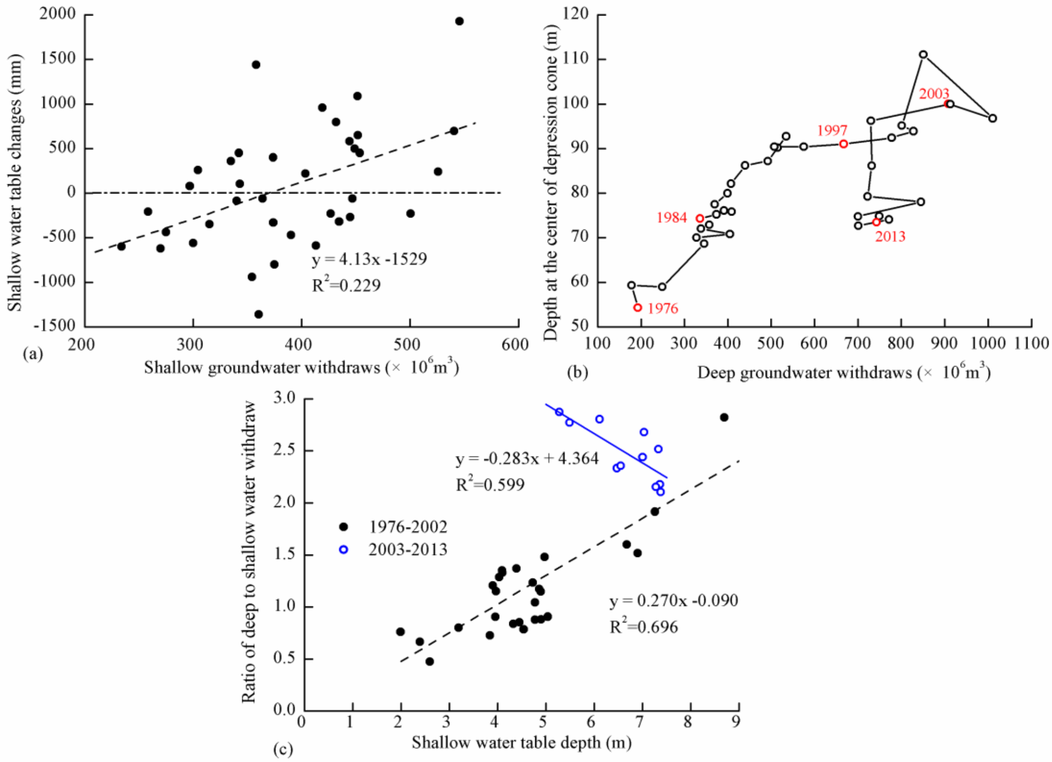

Figure 4. (a) the relationship between shallow water changes and withdrawal; (b) co-evolution of the depth of the depression cone center of deep aquifer with water withdraw from 1976 to 2013; (c) the ratio of deep to shallow water withdrawal against the shallow water table depth before and after 2002.

The groundwater availability also affects human activities, i.e., the declining shallow water table makes the groundwater utilization turn to the deep aquifer. In year 1976, the average shallow water table depth was 2.59 m, and the water withdrawal from the deep aquifer was only 47.4% of that from the shallow aquifer. The ratio of deep to the shallow water withdrawal increased with the declining shallow water table from 1976 to 2002, especially during the drought 1997-2002. In 2002 with deepest shallow water table, the water withdrawal from the deep aquifer were 2.82 times of that from the shallow aquifer. This feedbacks of the groundwater sub-system to the human groundwater utilization can be detected from the high correlations between the ratio of deep to shallow water withdrawal and the shallow water table depth before 2002 (Fig. 4(c)).

On the other hand, the outer Tire represents all those social and natural factors that indirectly influence the system, for instances, the vegetation, climate, soil, institutions, laws and culture. The interactions of inner Taiji usually leads to over-exploitation of natural resources and corresponding more human input on development while the feedback of outer Tire will bring the negative effect of over-exploitation back to society and therefore stimulate new responsive social behaviors to protect the environment and reduce the impulse of blind development. Elshafei et al. (2014) uses a new concept of community sensitivity to represent this social awareness of environment welfare. While the interactions of inner Taiji leads to serious problems in ecosystems, the community sensitivity will rise and cause environmental protection actions. These environmental protection actions can be seen as a new kind of social productive forces, we call it natural restorative forces, similar as van Emmerik et al. (2014) defined. The social restorative force is NOT the natural variations, and also, should not be seen as an opposite force of social productive forces, for that the social productive force can be restorative. The only difference is the social values and norms. In another word, it is human itself who decide how to use technology and design policies. Therefore, it is more reasonable to regard the social restorative force as a branch of social productive force (the other branch can be social destructive force). The social restorative force appears around the moment when the steady state of the natural system is broken. When its effect exceeds the social demand for natural resources, specifically, the pendulum swing shall happen. When the social restorative force dominate the productive force, the social productivity can be seen as green productivity (Tuttle and Heap, 2007; Mohanty and Deshmukh, 1998), or the societies can be seen as green (the other type is technological) (Sivapalan, 2015).

Environmental change, especially precipitation and surface water change/variability, is an external driver of the human-groundwater system. With decreasing surface water resources, the recharge to the groundwater system decreased, and the demand for groundwater increased. The precipitation variability impacted both the groundwater and human sub-systems. The larger precipitation means larger recharge to the shallow groundwater. As shown in Fig. 5(a), the shallow groundwater table fluctuations are highly negatively correlated with the annual precipitation. Nevertheless, the drought years with low precipitation are characterized with not only small recharge to the shallow aquifer, but also large groundwater demand before 2002 (Fig. 5(b)).

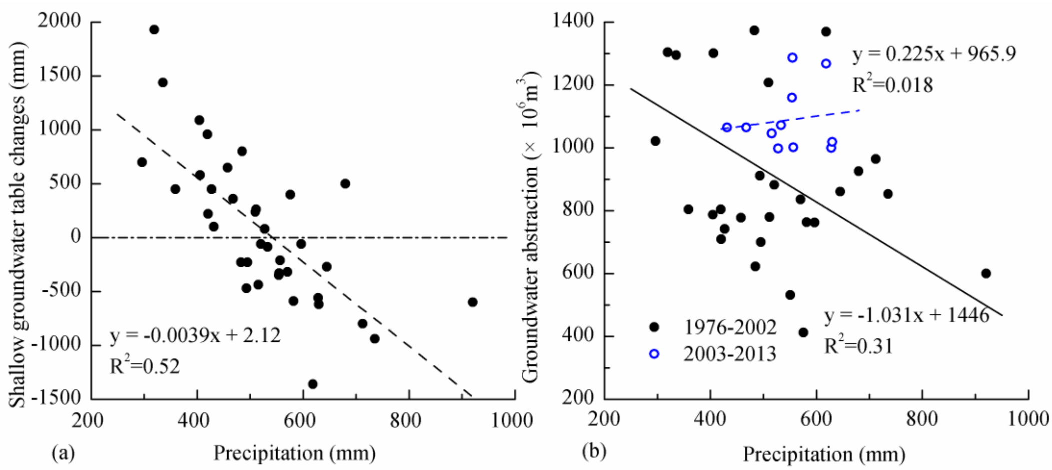

Figure 5 (a) The shallow water table fluctuations, and (b) the total water withdrawal against the annual precipitation.

The external drivers of the co-evolution of the human-groundwater system in Cangzhou can be specified as the social productive force and natural variability. Before 1965, the human-groundwater system can be considered stationary without significant external drivers. However, the stationary condition was broken in 1966, since then, the groundwater abstraction was driven by the need for resisting the drought. However, since 1970s the demand for food became one of the principal

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-411, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 31 August 2016

drivers of societal evolution. The numbers of motor pumping wells increased rapidly to abstract adequate water to enlarge the irrigated area. The growth of the social productive force has sustained significant increasing of groundwater consumption. The negative externality gradually accumulates but still at low level during quite a long period, not enough to reverse this developing trajectory.

Until 2002, groundwater withdrawal increased with the population and GDP of Cangzhou, but decreased after that (Fig. 6(a)). This is because at around 2002, after decades of accumulation, the community sensitivity about environment has causes new actions on environment protections (Elshafei et al., 2014). More directly, the broken stationary condition of natural system means higher uncertainty and risks of extreme hydrometeorological events like floods, droughts and rainstorms, causing higher social awareness of risks and resultant actions. The drought during 1997-2002 reminds the public and policy makers about taking measures to modify the existing development pattern. New policies are established to restrict the groundwater exploitation, and improving and applying the water saving technology are strongly encouraged, after the drought. The social productive forces therefore reach a critical point. New technology and management tools are development solely on protecting the environment, even that they are extremely costly. These new improvements can be seen as an effort of humans on raising the natural restorative ability. This is also why some scholars believes that the human-water system is determined by the interactions between social productive and natural restorative forces and in this way explain the Taiji-Tire model (Kandasamy et al., 2014). However, as we have pointed out, a more precise description is that the natural restorative force is a new kind of social productive force.

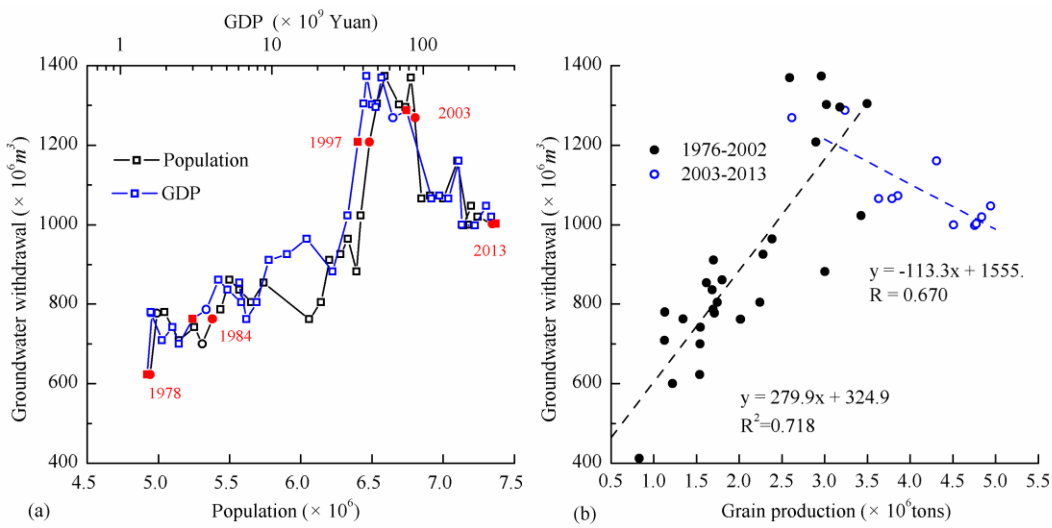

Figure 6. (a) annual groundwater withdrawal with the population and GDP; (b) co-evolution of the total groundwater withdrawal against the annual grain production before and after 2002.

With the increasing social awareness of environment, which can be represented by the community sensitivity, new technology and management enhance not only the natural restorative but also the social productive forces. The grain production grows still rapidly together with relative stable irrigated area and decreasing groundwater utilization after 2002

(Fig. 6(b)). Meanwhile, after the drought during 1997-2002, the ability to mitigate the climate variability increased, with the construction of water-saving irrigation projects. As a result, the groundwater withdrawal decreases after 2002, no matter how the precipitation varies (Fig. 5(b)).

5 Conclusions

The historical socio-hydrological analysis in Cangzhou enabled us to recognize five eras of the co-evolution of the human–groundwater system. At the first stage, the intensity of groundwater exploitation was quite low. The human–groundwater system was primarily dominated by natural factors. No records on groundwater crisis induced by human activities was found. At the second stage, groundwater was first exploited to combat the drought. Thereafter, groundwater exploitation was driven by the need for grain yield. Moreover, with the decrease in surface water resources, the intensity of groundwater exploitation was elevated, and the human–groundwater system was driven by the social productive force. Meanwhile, intensive human activities led to the deterioration of the groundwater environment, which drew considerable attentions from society. At the third stage, comprehensive management measures were implemented to address the groundwater crisis, and the deterioration was somewhat mitigated. At the fourth stage, drought appeared as a shock, which terminated the mitigation because humans make more efforts on enhancing the productive force to meet the challenge by pumping more water. Because comprehensive and coordinated drought management plans were lacking, people responded to ad hoc drought by drilling emergency wells or relying on unregulated groundwater withdrawal from existing wells. As a result, the intensity of groundwater exploitation rapidly increased, which led to the dramatic deterioration of the groundwater environment. Nevertheless, the drought induced deterioration has also triggered the split of social productive forces and generate new natural restorative force. At the fifth stage, the drought was eased, and a series of measures was used to reduce groundwater exploitation. Water-saving technologies became acceptable economically and ideologically, and the groundwater environment began to be restored. The strictest water resource management scheme was launched in 2012, and the South-to-North Water Diversion Project was commenced in 2015. Public awareness concerning water crisis has been enhanced, and further restoration of the groundwater environment is anticipated. However, the external environment variations, especially drought, still remain an unexplored variable.

The Taiji-Tire model was used to interpret the interaction and co-evolutionary dynamics of the coupled human-groundwater system in Cangzhou. The interaction between the groundwater utilization and the water table are regarded as the inner Taiji. The over-exploitation is the major reason for the groundwater depletion. The decreasing shallow groundwater table also affected the groundwater utilization pattern, making the groundwater withdrawal turned to the deep aquifer. Precipitation variation directly impacted the groundwater recharge, and affected the groundwater demand, which affected the human-groundwater system. Triggered by the drought, the natural restorative force, as an upgrading of the social productive force, enhanced the ability to rebalance the human-groundwater system in Cangzhou with new water-saving technology and corresponding management, and increased the ability to mitigation climate variability. This feedback rebalanced the interactions of the inner Taiji that has intensifies the human-water relations with the occurrence of expected pendulum swing that the groundwater withdrawal decreases since 2002.

Acknowledgments

This research was partially sponsored by the National Natural Science Foundation of China (No. 51579249), Ministry of Science and Technology (SQ2016YFSF020004), the Research Fund (No. 2016ZY06) of State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research. We acknowledge valuable input and feedback from members of the Panta Rhei Working Group on Socio-hydrologic Modelling and Synthesis.

References

Cao, G., Zheng, C., Scanlon, B. R., Liu, J., and Li, W.: Use of flow modeling to assess sustainability of groundwater resources in the North China Plain, Water Resour Res, 49, 159-175, 10.1029/2012wr011899, 2013.

Chen, J. Y., Tang, C. Y., Shen, Y. J., Sakura, Y., Kondoh, A., and Shimada, J.: Use of water balance calculation and tritium to examine the dropdown of groundwater table in the piedmont of the North China Plain (NCP), Environ Geol, 44, 564-571, 10.1007/s00254-003-0792-3, 2003.

Elshafei, Y., Sivapalan, M., Tonts, M., and Hipsey, M. R.: A prototype framework for models of socio-hydrology: identification of key feedback loops and parameterisation approach, Hydrol Earth Syst Sc, 18, 2141-2166, 10.5194/hess-18-2141-2014, 2014.

Gurdak, J.: Climate change goes underground: Implications for groundwater, Climate Science and Policy, 2012.

Kandasamy, J., Sounthararajah, D., Sivabalan, P., Chanan, A., Vigneswaran, S., and Sivapalan, M.: Socio-hydrologic drivers of the pendulum swing between agricultural development and environmental health: a case study from Murrumbidgee River basin, Australia, Hydrol Earth Syst Sc, 18, 1027-1041, 10.5194/hess-18-1027-2014, 2014.

Kendy, E., Wang, J., Molden, D. J., Zheng, C., Liu, C., and Steenhuis, T. S.: Can urbanization solve inter-sector water conflicts? Insight from a case study in Hebei Province, North China Plain, Water Policy, 9, 75, 10.2166/wp.2007.046, 2007.

Li, Y., Fei, Y., Qian, Y., Jian, M., Han, Z., Wang, P., and Zhang, Z.: Discussion on evolution characteristics and formation mechanism of deep groundwater depression cone in Cangzhou region, Journal of Arid Land Resources & Environment, 27, 181-184, 2013.

Liu, C., Jingjie, Y., and Kendy, E.: Groundwater exploitation and its impact on the environment in the North China Plain, Water Int, 26, 265-272, 2001.

Liu, J., Zheng, C., Zheng, L., and Lei, Y.: Ground water sustainability: methodology and application to the North China Plain, Ground Water, 46, 897-909, 10.1111/j.1745-6584.2008.00486.x, 2008.

Liu, J., Cao, G., and Zheng, C.: Sustainability of Groundwater Resources in the North China Plain, 69-87, 10.1007/978-90-481-3426-7_5, 2011.

Mohanty, R., and Deshmukh, S.: Managing green productivity: some strategic directions, Prod Plan Control, 9, 624-633, 1998.

Montanari, A., Young, G., Savenije, H., Hughes, D., Wagener, T., Ren, L., Koutsoyiannis, D., Cudennec, C., Toth, E., and Grimaldi, S.: "Panta Rhei—Everything Flows": Change in hydrology and society—The IAHS Scientific Decade 2013–2022, Hydrological Sciences Journal, 58, 1256-1275, 2013.

Sivapalan, M., Savenije, H. H. G., and Blöschl, G.: Socio-hydrology: A new science of people and water, Hydrol Process, 26, 1270-1276, 10.1002/hyp.8426, 2012.

Sivapalan, M.: Debates-Perspectives on socio-hydrology: Changing water systems and the "tyranny of small problems"-Socio-hydrology, Water Resour Res, 51, 4795-4805, 10.1002/2015wr017080, 2015.

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., Van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J. S., and Edmunds, M.: Ground water and climate change, Nature Climate Change, 3, 322-329, 2013.

Tuttle, T., and Heap, J.: Green productivity: moving the agenda, International Journal of Productivity and Performance Management, 57, 93-106, 2007.

van Emmerik, T. H. M., Li, Z., Sivapalan, M., Pande, S., Kandasamy, J., Savenije, H. H. G., Chanan, A., and Vigneswaran, S.: Socio-hydrologic modeling to understand and mediate the competition for water between agriculture development and environmental health: Murrumbidgee River basin, Australia, Hydrol Earth Syst Sc, 18, 4239-4259, 10.5194/hess-18-4239-2014, 2014.

Wang, C., and Wang, W.: The exploiration and protection of groundwater resources in Cangzhou (in Chinese), Water Resources Protection, 23, 77-80, 2007.

Wang, S., Shao, J., Song, X., Zhang, Y., Huo, Z., and Zhou, X.: Application of MODFLOW and geographic information system to groundwater flow simulation in North China Plain, China, Environ Geol, 55, 1449-1462, 2008.

Xue, G.: Water resouces annals of Cangzhou (in Chinese), Science and technology literature press, Beijing, 1994.

Zhang, Z., Shi, D., Ren, F., Yin, Z., Sun, J., and Zhang, C.: Evolution of quaternary groundwater system in North China Plain, Science in China Series D: Earth Sciences, 40, 276-283, 1997.

Zhang, Z., and Fei, Y.: Sustainable Utilization Investigation and Assessment of Groundwater in North China Plain, Geological Publishing House, Beijing, 2009.

Zheng, C., Liu, J., Cao, G., Kendy, E., Wang, H., and Jia, Y.: Can China cope with its water crisis?—Perspectives from the North China Plain, Ground Water, 48, 350-354, 2010.