Response to Editor

The manuscript has received two excellent reviews, both pointing to the potential interesting and important work reported, but also highlighting the weaknesses in the organization and presentation of the material. I would therefore encourage a thorough revision of the material, paying particular attention to language and presentation.

Response: The authors gratefully thank to the editor and two referees for their critical comments on our manuscript which drives us to improve the manuscript greatly. The comments and questions given by the two referees were addressed point by point. The text quoted from the revised manuscript is shown in red.

Response to Referee #1

General Comments

1) The objective(s) of the paper did not come across clearly. The authors state that one objective of the paper 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." Are there other objectives? The objective should also be introduced sooner to focus the reader. Both the "pendulum swing" concept and Taiji-Tire model are relatively new and untested ideas. The authors have not yet convinced me that they can assume these fit the case before completing the analysis. If assessing this fit is an additional paper objective, it should be made clear. Alternatively, if the paper seeks to further specify he model or test a specific aspect of it, that should also be clarified.

Response: In the revised manuscript, we tried to state the two objectives of the paper clearly: " (1) to chart the history of the groundwater utilization in Cangzhou, focusing on the dynamics of the human–groundwater interactions that lead to the "pendulum swing" in the balance point in groundwater allocations between humans and aquifer ecosystems, as well as the natural variability and social factors that contributed to it; (2) to use the Taiji-Tire model to interpret the interactions and co-evolutions of the human–groundwater system in Cangzhou. The Taiji-Tire model will be specific to the groundwater system and will be incorporated with the concepts of restorative force and community sensitivity"

In the revised manuscript, we added an introduction about the "pendulum swing" at first, and point out that the history of co-evolution of the human-groundwater system in Cangzhou fits a "pendulum swing":

" Through adaption processes, humans co-evolve with the hydrological system, resulting in a "pendulum swing" in the balance point of the human–water system (Kandasamy et al. 2014, Sivapalan 2015). Kandasamy et al. (2014) first characterized the concept of the "pendulum swing" by tracing 100 years history of the competition for water between agricultural development and environmental health in the Murrumbidgee River Basin. Similar dynamics were also found in the human–water system in the arid Tarim River Basin (Liu et al. 2014) and in human–flood interactions (Baldassarre et al. 2015). A pendulum swing can be divided into four typical stages: (1) the initial exploitation stage, which is focused exclusively on economic development; (2) the onset environmental degradation stage, which is accompanied by the introduction of remedial infrastructure; (3) the widespread environmental degradation stage, which leads to the necessity of mitigation measures; and (4) the recovery stage, at which ultimate solutions are implemented. The pendulum swing of a human–water system can be clarified by considering all interactions within a universal socio-hydrologic framework (Kandasamy et al. 2014, Liu et al. 2014)."

We also added a more detailed introduction of the Taiji-Tire model, and clarified that the Taiji-Tire model is specified to the groundwater system, with the incorporation of the concepts of restorative force and community sensitivity.

"A socio-hydrological system contains human, hydrological, and environmental sub-systems. The Taiji-Tire model proposed by Liu et al. (2014) was first used as a framework for elucidating the complexities of socio-hydrological systems that co-evolve with direct or indirect interactions between factors from both human and water perspectives. In the model, a Taiji wheel, which is a term originating from a special concept in Chinese philosophy, is used to describe the direct human–water relationship in a specific socio-hydrological system, whereas a human–water tire is used to represent the indirect effect of external natural and social factors affecting the system. The evolution of a socio-hydrological system is driven by the interactions between two main factors, namely, natural variability and social productive force (Liu et al. 2014). Social productive force refers to the combination of all factors that enable humans to utilize resources and create better material and spiritual products. To apply the Taiji-Tire model in interpreting the drivers of water reallocation from the economy to the environment during the recovery stage of the pendulum swing, the concept of "environmental restorative force" was defined as the opposing factor of social productive force (van Emmerik et al. 2014). During the recovery stage, environmental protection actions are usually conducted because of a high social awareness for environmental risk or welfare (Di Baldassarre et al. 2013). Elshafei et al. (2014) proposed a new concept of community sensitivity to signify the social awareness for environmental welfare. Community sensitivity refers to the sensitivity of humans to the changing environment. A high community sensitivity implies that humans feel the pressure of environmental deterioration, motivating them to restrain human activities to restore environmental health. The concept of community sensitivity was also used to analyze the switching of the support between flood protection and wetland preservation in the Kissimmee River Basin, Florida (Chen et al. 2016). Above new concepts can be incorporated into the Taiji-Tire model to improve its explanatory power on a specific human–water system."

2) The methods section needs expanding as it is not clear what methods were used to develop and analyze the historical narrative. The authors use the concept of a "pendulum swing" to introduce and organize the narrative. However, it is not clear what criteria were used to determine if and when a "pendulum swing" occurs. Five eras are presented, what criteria were used to determine that a new era had begun? The Taiji-Tire model is used to frame the analysis. How was the case mapped to the Taiji-Tire? How, for example, was the spatial boundary of the internal Tire determined? And how were forces classified as productive or restorative?

Response: In the revised manuscript, we introduced the concept and definition of "pendulum swing" in the "Introduction" section, especially the different stages of it (please refer to the response to the first comment). Then, we explained the criteria used to determine if and when a "pendulum swing" occurs, and the criteria that a new era had begun as follows:

" The time series of the groundwater withdrawal from both the shallow and deep aquifers were analyzed to detect the behaviour of water users. The average water table depth of the shallow aquifer and the water table depth of the depletion cone of the deep aquifer were used as the main indices of the groundwater system. The time series of number of wells and irrigated area (including water-saving irrigated area) were analyzed to detect the changes in infrastructure, along with the social development which were revealed by the changes in population, and grain production. The break points of the time series of the water table depth and groundwater withdrawal were determined based on trend changes. The break points were also confirmed by examining the major policies and initiatives that facilitated developments or that resulted in turning points in groundwater water management. Then, the co-evolution of the human–groundwater system was classified into several eras, which signified the points at which a “pendulum swing” occurred."

We also stated that the case mapped to the Taiji-Tire in the revised manuscript:

"Under the framework of the Taiji-Tire model, the Taiji represents the direct interactions between the groundwater utilization and the aquifers in Cangzhou, whereas the outer Tire represents all of the social and natural factors that indirectly influence the human–groundwater system. Precipitation and surface water change/variability were considered the natural variability in Cangzhou."

As for the productive and restorative forces, as mentioned in the paper, for example Fig. 4a, the restorative forces is explained as a new kind of social productive forces. The social productive force refers to the combination of all factors that help humans to utilize the resources and create better material and spiritual products that makes life better and easier. While the social productive force itself only emphasize the production but not the cost, including the direct production cost and the environmental externalities, the restorative forces refers to the specific productive forces that aiming at further increase the production by mainly lowering the environmental externalities, or, in another word, the green productivities. "The emphasis level of the social productive force is detected from the changes in the number of wells, in irrigated areas with groundwater, and in policies for groundwater exploitation. In this study, we believe that the concept of environment restorative force is misleading and should instead be regarded as a subtype of social productive force. Social restorative force can be detected from the changes in water-saving irrigation areas and in policies for creating water-saving technologies. "

3) The authors nicely demonstrate how variability in precipitation can alter the simple story of reaching a tipping point and adjusting behavior to adapt. I think this is a good contribution. However, in complex systems such as socio-hydrological systems there is great potential for multi-causality and teleconnections. In addition to groundwater levels and precipitation, were other drivers of water use behavior change considered? How were the historical narrative and data set used to focus on these drivers? Please clarify.

Response: We agree that the socio-hydrological system is multi-causality and teleconnections. The drivers of water use behavior change include precipitation, surface water resources, groundwater level, other water resources (surface inflow, water transfer from other basins, and brackish water), water-saving irrigation area, and economic conditions (the cost of groundwater abstraction and the subsidy policy). In the revised manuscript, we have aggregated these drivers from era 2 to era 5 in a new table, and give a more detailed and concentrated historical narrative on theses drivers.

Table 3. Changes in factors related to the community sensitivity from era 2 to era 5

	Precipitation mm	Surface inflow 10^6m^3	Alternatives (10^6m^3)		Water-saving irrigation area (10^3km^2) [a]	Economic conditions	
			Brackish water	Inter-basin transfer		Cost	Subsidy objective
Era 2	544.1	2144	0	0	26.7[a]	Low	Well drilling
Era 3	554.9	578	0	0	96.42	Middle	No Subsidy
Era 4	391.7	1258	38.1 [b]	41.2[c]	212.48	High	Water-saving
Era 5	547.2	1185	36.5	71.7	352.65	High	Water-saving

[a] The value at the end of each era; [b] The value of 2002, when brackish water was used at large scale; [c] The average value of 2001 and 2002;

4) While the writing did not interfere with my ability to review the manuscript there are a substantial number of grammatical errors and instances of unclear syntax. I have pointed out several, but not all, of these below. Thorough proof reading is needed before publication.

Response: We have followed closed the suggestions made by referees, and tried to improve the use of English. The revised manuscript has been edited by a native English speaker.

Specific Comments

1) On Page 1, Line 30, define or explain what is meant by the term human forcing.

Response: We revised this term as "social forcing (i.e., increase in water demand for agricultural development)"

2) On Page 2, Line 2, define or explain what is meant by the term salience threshold.

Response: "salience threshold "should be "resilience thresholds" according to (Sivapalan et al. 2012)

3) In Section 2, the authors do a great job describing the hydrological and geological setting of the case. A paragraph on the governance and institutional structure of the study region would be an excellent addition here, particularly for international readers. This would help readers less familiar with Chinese governmental divisions better follow the roles of the various entities in the narrative.

Response: We agree and added an instruction on the governance and institutional structure of the study region:

" Cangzhou is a prefecture-level city of Hubei Province consisting of 4 county-level cities and 10 counties. Cangzhou Municipal Government abides by the provincial and national policies of water resource management, and it devises policies for the entire region. The Water Resources Bureau of Cangzhou, which is a department of Cangzhou Municipal Government, is responsible for water resource affairs and guides the Water Resources Bureau of the 10 counties and 4 county-level cities. In turn, this agency is guided by the Water Resources Department of Hebei, the Ministry of Water Resources, and the Haihe River Water Resources Commission."

4) On page 4, line 2, the authors specify the sources of hydrological, agricultural and water use data sources. However, it is not clear what the data source is for policy initiatives (Table 1) or how relevance of policy initiatives was determined.

Response: We have stated the data source in the revised manuscript:

" The data before 1985 was acquired from the Water Resource Annals of Cangzhou (Xue 1994), and the data after 1985 was obtained from the Hebei Rural Statistics Yearbook, and the Hydrology and Water Resources Investigation Bureau of Cangzhou. The data on policies and initiatives were collected from the Water Resource Annals of Cangzhou (before 1985), the announcements and documents of the Ministry of Water Resources, the Government of Hebei, the Water Resources Department of Hebei, the Government of Cangzhou, and the Water Resources Bureau of Cangzhou."

5) On page 9, line 11, in the description of the drought era (1997-2002) the authors state that well drilling "seemed to be the only choice to resist the drought." Yet, in section 3.5 they describe measures such as water licensing (1999) and irrigation efficiency improvements (1998). Why aren't these measures discussed in conjunction with the expansion of well drilling?

Response: We revised this sentence as "well drilling seemed to be the immediate strategy for addressing the drought". The measures of water licensing (1999) and irrigation efficiency improvements (1998) have been discussed in conjunction with the expansion of well drilling.

6) On page 9, section 3.5, the description of era 5 (2003-present) contains several events that occur before 2003 such as the 1999 water licensing system. Why aren't these events considered as part of era 4?

Response: In the revised manuscript, the events that occur before 2003 (the 1999 water licensing system, irrigation efficiency improvements) have been moved to era 4.

7) On page 11, figure 3, I appreciate the qualitative plotting of the level of emphasis on production and restoration. However, I would like to understand how these levels were estimated. What data sources (either quantitative or qualitative) were used? I am also unsure of the meaning of the emphasis level of "healthy status" in this context. Does healthy refer to environmental or public health? And if it refers to environmental health how does the emphasis on environmental health differ from the focus on restoration (or the restorative force)? Please clarify.

Response: The emphasis level of the social productive force, can be detected from the changes in well numbers, the irrigated area with groundwater, as well as the policy for groundwater exploitation. While, the social restorative force can be detected from the changes in water saving irrigation area, as well as the policy to incent water-saving technologies.

"healthy status" is specified as "aquifers healthy status" in this context. The changes in the healthy status of the aquifers (both shallow and deep) can be detected from the changes of the average water table depth of the shallow aquifer, and the water table depth of the depletion cone of the deep aquifer. The changes of the emphasis on the aquifers healthy status are the consequences of the restorative forces.

8) Page 12, figure 4a and page 13 figure 5a: clarify the directionality of shallow water table changes. Is a negative change a decline in groundwater levels or a decrease in the depth the ground water table?

Response: We are sorry for the misleading. In the revised manuscript, we have revised it as "change in shallow water table depth", and added a explanation "a negative change indicates a rise of the groundwater table".

9) On page 12, figure 4c conveys change in the relationship between shallow groundwater table depth and the ratio of deep to shallow groundwater. The reader needs more information to properly interpret this figure. How was this data set separated into these two groups (before and after 2002)? Was the division determined solely based on the narrative or were statistical tests used? Does any of the qualitative historical data collected aid in interpretation of this plot? What does this plot illustrate about the behavior of water users in the basin?

Response: The dataset was divided into two periods (before and after 2002) based on the narrative of different eras, and significant changes in water user behavior and social response to groundwater system could be found, as:

"significant changes in water user behavior and human response to groundwater system can be observed if the dataset was divided into two periods (before and after 2002) based on the narrative of the different eras. The ratio of deep water to shallow water withdrawal was negatively correlated with the shallow water table depth after 2002, which is absolutely different from that before (Fig. 5(c)). However, the correlation of the negative relationship is considerably weaker at a starting point before 2002 (for example, the coefficient of determination (R^2) is only 0.11 according to the data from 2002 to 2013). As shown in Figs. 2(g) and 2(h), the deep groundwater withdrawal began to decrease slowly since 2002, whereas the shallow groundwater withdrawal continued to decrease rapidly as before. This finding indicates that people did not turn to shallow water as the shallow water table increased, because the infrastructure of deep water with high-quantity exploitation already existed. "

10) On page 13, line 3, the authors emphasize that the social restorative force is not necessarily in opposition to the restorative force and can be considered a subset of the productive force. Is this a modification to the original Taiji-Tire model? Please clarify.

Response: First of all, please refer to our response to the 2nd comment. Secondly, it is not a modification but a supplement to the original Taiji-Tire model. Liu et al. (2014) firstly addressed the idea of Taiji-Tire model. In their work, the socio-hydrological system are seen as consequence of interactions of two general drivers, namely natural variabilities and the social productive forces (Liu et al.., 2014). When van Emmerik et al. (2014) use this Taiji-Tire idea to their work in Murrubidgee Basin, they defined a new term of natural restorative force to substitute the natural variability as the opposite factor of social productive forces. In this study, we believe that this idea of natural restorative force is confusing and should be seen as a subtype of social productive forces.

11) On page 13, lines 8 and 24 the authors make reference to the system steady state and the date in which it was broken. Please clarify what in this instance was in steady state as I am skeptical that the socio-hydrological system broadly defined was ever in steady state. Please

also describe how 1965 was identified as the end to this steady state period.

Response: We focus on the human-groundwater system within Cangzhou, and the surface water is taken as an external driver. We means that the human-groundwater system within Cangzhou was in steady state before 1965, not including the surface water. We have explained why it is defined as a steady state and how 1965 was identified as the end to this steady state period in the revised manuscript.

"Before 1965, groundwater utilization was not large scale because of technological limitations. The volume of groundwater withdrawal was small compared with that of surface water, and the irrigated area with groundwater was constrained to a small fraction of Cangzhou. According to the Taiji–Tire model, the human–groundwater relationship was weak, lacking any kind of sophisticated interactions. The human sub-system was insensitive to the groundwater sub-system, and the groundwater sub-system was unaffected by humans at a large scale. Therefore, the human–groundwater system can be considered stationary (or a steady state) without significant external drivers."

12) On page 13, figure 5b, more information is also needed to interpret this figure including how the data set was divided into two periods.

Response: The data set was divided according to the narrative of different eras. We added some information including how the data set was divided into two periods as follow:

"The groundwater withdrawal decreased continually after 2002, although the annual precipitation kept stable. The significant negative correlation between the groundwater withdrawal and annual precipitation before 2002 (R^2 is 0.31) (Fig. 6(b)) would significantly decrease if the period is extended to after 2002 (R^2 is only 0.25 when the used data is during 1976–2003). This decoupling reveals that water demand would no longer subtly vary with precipitation. Although an uncertainty still exists because the precipitation did not vary significantly during 2003–2013, the findings indicate an increased ability to mitigate climate variability."

13) On page 14, line 6 the authors discuss the accumulation of community sensitivity. What data, either quantitative or qualitative, can back up this statement? It would also be helpful to clarify what is meant by community sensitivity. In the article referenced, Elshafei et al (2014), the authors specify what community sensitivity is theorized to depend on, that would also be useful here.

Response: We added an introduction on community sensitivity at first (please refer to our response to the 1st comment), and introduced two incidents to denote the accumulation of community sensitivity: "In 2004, a leading group headed by the executive vice mayor was established to prevent and manage the subsidence in Cangzhou. Measures for sustainable groundwater management was even emphasized in the Cangzhou Government Work Report in 2004."

14) On page 14, line 12 the authors state that costly new technologies are adopted solely to protect the environment. Please note how were other motivations or causes ruled out.

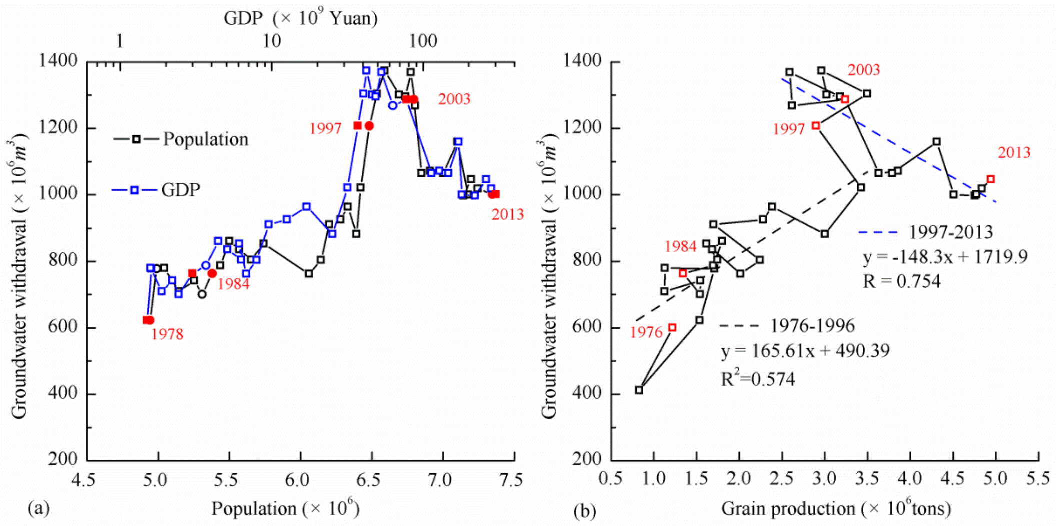
Response: We have added a statement as follow:

"Given that economic development has always been the primary target of the government and society of Cangzhou, the mitigation measures for reallocating water from the economic development to the environment, which have been implemented in Murrumbidgee River basin (Kandasamy et al. 2014), are unacceptable. Therefore, new policies are established to restrict groundwater exploitation. The development and application of water-saving technologies are strongly encouraged to protect the environment while ensuring economic development, even if such strategies are more costly than traditional groundwater exploitation."

15) On page 14, figure 6b same comment as figure 5b above.

Response: We have changed the division into 1976-1996 and 1997-2013 in the revised manuscript, and added some information as follow:

"As community sensitivity continues to increase, new technologies and management efforts would enhance the restorative forces. Supported by theses productive forces, the grain production declined slightly during the drought during 1997–2002, but it grew rapidly again with the subsequent decline in groundwater utilization after 2002 (Fig. 2(d)). Thus, the grain production was negatively correlated with the groundwater withdrawal during 1997–2013 (correlation coefficient of −0.87), which is different from that during 1976–1996 (correlation coefficient of 0.77) (Fig. 7(b))."



16) On page 15, the authors note that groundwater withdrawal no longer varies with precipitation. What enabled this decoupling?

Response: The extension of water-saving technologies and the construction of water-saving projects, as well as the restricted groundwater exploitation policies enabled this decoupling. Please also refer to the response to comment 12).

Technical Corrections

1) Page 1, Line28: Syntax is awkward: “Except for the social forcing, natural variability is another external forcing.” Could rephrase as: “In addition to the social forcing, natural variability is an external forcing.”

Response: We have revised it following the suggestion.

2) Page 2, Line 27: Correct grammatical errors: “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" perhaps as: "Because groundwater pumping from the aquifer has increased significantly since middle of the 1960s, the NCP aquifer system has become one of the most overexploited aquifers in the world."

Response: We have revised it following the suggestion.

3) Page 9, line 2: missing closing parentheses after the word year.

Response: We have revised it following the suggestion.

4) Page 14, line 14: replace development with developed.

Response: We have revised it following the suggestion.

5) The citation Liu et al. (2014) is missing from the references.

Response: We have added the reference.

Response to Referee #2

General comments

1) It would be helpful for the reader if concepts were clearly defined from the start. Currently, the use of concepts is mixed and includes the use of Taiji Tire model, the concept of pendulum swing (Kandasamy et al. 2014) and the concept of community sensitivity (Elshafei et al., 2014). While the pendulum swing is not defined as such, the concept of community sensitivity is introduced in the discussion, but at the same time forms a major part of the discussion. If the authors wish to use more than one concept, the reader would benefit from a more comprehensive introduction of these concepts early in the paper, possibly including their purpose and/or limitations, and how these concepts are used for the current analysis of the Cangzhou case. The latter would give the reader a clearer indication of what it can and cannot expect from the current analysis. For example, the Taiji-Tire model is merely offered as an organizing framework to represent and explain the human-water relationships (Liu et al., 2014). The conceptualization of interactions serves as a first step to a quantitative (numerical) model that can be used to explain the past and develop predictive insights (Liu et al., 2014). The pendulum swing refers to "an exclusive focus on agricultural development and food production in the initial stages and its attendant socioeconomic benefits, followed by the gradual realization of the adverse environmental impacts, subsequent efforts to mitigate these with the use of remedial measures, and ultimately concerted efforts and externally imposed solutions to restore environmental health and ecosystem services" (Kandasamy et al., 2014).

Response: We agree with the comment. In the revised manuscript, we added an introduction about the "pendulum swing" at first, and pointed out that the history of co-evolution of the human-groundwater system in Cangzhou fits a "pendulum swing". We also added a more detailed introduction of the Taiji-Tire model to clarify that the Taiji-Tire model is specified to the groundwater system. We also added an introduction of the concepts of restorative force and community sensitivity, and pointed out that they will be incorporated into the Taiji-Tire model.

Please also refer to the response to the 1st and 2nd comments of Referee #1.

2) The primary goal as defined by the authors is the interpretation of the case study using the

Taiji Tire model. It remains however unclear which methods are used to relate the observed feedbacks in the case study to the more abstract concepts in the model: what is used to distinguish endogenous from exogenous variables? How are the major drivers of the system resolved? When is a feedback considered to be productive or restorative? Currently, his seems to be dependent on your system boundary? The environmental burden seems to be partly shifted from groundwater to the surface water systems that deliver the water transfers?

Response: 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. Therefore, the groundwater withdrawal from the shallow and deep aquifers, as well as the status of the aquifers (denoted by the shallow water table depth and water table depth of the depletion cone) are taken as the endogenous variables. The outer Tire represents all those social and natural factors that indirectly influence the system. Environmental change, especially precipitation and surface water change/variability, is an external driver of the human-groundwater system within Cangzhou. The social productive force is another external driver of the co-evolution of the human-groundwater system in Cangzhou. It should be noted that the Taiji-Tire model is specified to the groundwater system in Cangzhou. Therefore, the surface water systems is taken as a external driver. The restorative forces is explained as a new kind of social productive forces. For Cangzhou, the emphasis level of the social productive force, can be detected from the changes in well numbers, the irrigated area with groundwater, as well as the policy for groundwater exploitation. While, the social restorative force can be detected from the changes in water saving irrigation area, as well as the policy to incent water-saving technologies.

Please also refer to the response to the first and second comments of Referee #1.

3) Environmental awareness/ community sensitivity/ natural restorative force is ultimately put forward as a driver of groundwater table restoration. It is however unclear at the moment how this is inferred from the case study. The description of the case study is detailed and shows the complexity of the system including groundwater changes in both the shallow and deep water aquifer, resulting in policy developments aimed at improved groundwater management and ultimately an increase in groundwater tables. At the same time, it is mentioned that pumping costs increase due to the deeper groundwater table, land subsides (up to almost a meter), salt intrudes and additional water is available due to water transfers. How does environmental awareness relate to economic incentives or the availability of an alternative water source? If the paper would include an interpretation (qualitative or quantitative) of the strength of the various feedbacks, if would make the current conceptualization much stronger.

Response: Environmental awareness is not only related to the measurable economic costs or incentives or the availability of an alternative water source. Community sensitivity is the sensitivity of human society to the changing environment (Elshafei et al. 2014). High community sensitivity represents that humans feel the pressure of environmental deterioration, and tend to restrain human activities to restore environmental health. The increasing economic costs would result in the increasing community sensitivity. The economic incentives can be taken as a response or adaption of the increasing community sensitivity. The water transfers may reduce the community sensitivity at a local scale during a short period, but the effects can not last for long-term if the human-groundwater relationship is not change intrinsically.

4) The text would benefit from editing and proof reading to improve its readability.

Response: We have followed the suggestions made by referees, and improve the use of English. The revised manuscript will be edited by a native English speaker.

Specific comments

Page 3, line 3. Please lengthen, since it is currently the core of the article. By which measure are feedbacks categorized? How exactly is a social productive force defined? How are main drivers distinguished among all plausible drives? Zhang et al. (2011), for example use five steps to deduct causal mechanisms in their research to link climate change and large-scale human crises.

Response: The objectives of the article have been stated clearly in the revised manuscript (Lines 29-34, page 3). We have made a detailed statement on the method about categorizing the feedbacks, defining a social productive force and distinguishing plausible drives. Please refers to the response to 2nd comment of 1# referee. And also, we agree that distinguishing the main drivers from all other plausible drivers are important. For current, however, it still need more case studies to complete. We will try to answer this question in further works.

Page 4, line 12 to 16, please check era titles with paragraph titles; not all of them match.

Response: We have revised the titles to make them consistent.

Page 4, paragraph 3.1, what are the sources used for this paragraph?

Response: The data is from the Water Resource Annals of Cangzhou (Xue 1994). We added the citation.

Page 4, paragraph 3.1, while the statements related to irrigated area argue in favor of natural variability dominating socio-hydrological change, the statements related to reservoirs, diversion projects and drainage-oriented policy currently imply that humans seems to have considerable impact already during this period. Adding a statement on the (limited?) effects of these policies on groundwater would strengthen the argument.

Response: Since we focus on human-groundwater system, so the title was revised to " Natural variability dominates the human–groundwater system . In Cangzhou, "reservoirs, diversion projects" were conducted on surface water resources, and the "drainage-oriented policy" was restrained to low lands. The groundwater sub-system was not affected by humans at a large scale. "Therefore, this era was characterized by small-scale groundwater utilization because of the low demand and technological limitations. The relationship between humans and the groundwater was weak. Humans were insensitive to groundwater change, and the groundwater sub-system was unaffected by humans at a large scale."

Page 5, figure 2, please check the figure references: subfigure d is referred to twice, resulting in a mismatch (e to i) from there on.

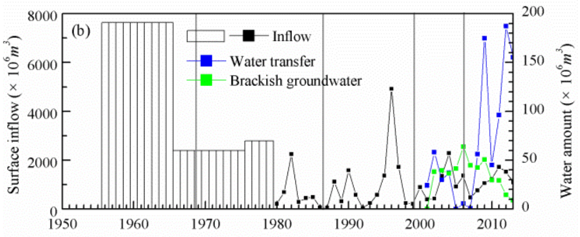
Response: We have revised the figure references.

Page 5, figure 2f (irrigated area), what is meant by irrigated area, is this total irrigated area or irrigated area using surface water?

Response: It means total irrigated area. We have revised it.

Page 5, figure 2, having a figure here showing the incoming water from all or the most important diversions/transfers into the region would complete the story. I can imagine that the availability of an alternative water source plays a significant role in the restoration of groundwater levels.

Response: We have added a figure for the variations of water diversion from outside the basin and the amount of brackish water. We think the new figure can be help.



Page 7, line 18, “Groundwater then became an important water resource for agricultural irrigation.” Should this be “the most important water resource”? Given that well drilling for groundwater started a few years earlier?

Response: During this era, surface water was still more important than the groundwater. In 1982, the irrigated area with groundwater was 41.3% of the total irrigated area of Cangzhou.

Page 7 to 10, paragraphs 3.2, 3.3., 3.4, what are the sources used for these paragraphs?

Response: The data used for paragraph 3.2 is from the Water Resource Annals of Cangzhou (Xue 1994). The data of agricultural infrastructures and production used for paragraphs 3.3, 3.4, and 3.5 is from the National Bureau of Statistics of China (2010), the Hebei Rural Statistics yearbook (from 1994 to 2013). The data of annual precipitation, groundwater withdrawal from both the shallow and deep aquifers, groundwater table depth is from the Hydrology and Water Resources Investigation Bureau of Cangzhou. The data of policies and initiatives before 1985 is acquired from the Water Resource Annals of Cangzhou (Xue 1994), the data after 1985 is detected from the announcements, documents of the Ministry of Water Resources, the Government of Hebei, the Water Resources Department of Hebei, the Government of Cangzhou, the Water Resources Bureau of Cangzhou.

We have revised the statement.

Page 9, line 19. “the environment noticeably deteriorated”. How was this the case?

Response: We will add a specific statement about it, as follow:

"In 2001, the cumulative subsidence was 2,236 mm, with a rate of 100.5 mm/a. The areas with subsidence larger than 500 and 800 mm are 9,717 and 3042 km^2, respectively, which account for 92.9% and 29.1% of the total area of Cangzhou. Moreover, the interface of saltwater and fresh water declined at approximately 10 m, with a maximum depth of 30 m, threatening the fresh water in the deep aquifer (Han and Han 2006)."

Page 9 & 10, has the reduction of overexploitation become a goal in itself or are earlier mentioned problems such as subsidence or salt water intrusion still an issue in the region? Are there specific quotes from governmental documents you could use to strengthen your argument?

Response: " Nonetheless, the aquifers still suffer from serious environmental problems. The average water table of the aquifer is still deep although the depth in 2013 is equal to that in 1984, as the center of the depression cone moved from urban areas to the rural areas (Fig. 3). According to the Geological Environment Bulletin of Hebei of 2013, the depression cone of the deep aquifer in Cangzhou is 5,551 km^2."

From Page 11 onwards, How, using what method/definitions, are the more abstract general concepts as mentioned in figure 3 related to the individual, observed feedbacks as mentioned in the text? How are productive, restorative and healthy status defined? Can anything be said about what triggered the restorative force (e.g. economic motives, a change of norms and values) and/or what is meant by the steady state of the system?

Response: The restorative forces is explained as a new kind of social productive forces. For Cangzhou, the emphasis level of the social productive force, can be detected from the changes in well numbers, the irrigated area with groundwater, as well as the policy for groundwater exploitation. While, the social restorative force can be detected from the changes in water saving irrigation area, as well as the policy to incent water-saving technologies. The emphasis level of the social productive force, can be detected from the changes in well numbers, the irrigated area with groundwater, as well as the policy for groundwater exploitation. While, the social restorative force can be detected from the changes in water saving irrigation area, as well as the policy to incent water-saving technologies.

"healthy status" is referred to the aquifers (both shallow and deep) healthy status. The changes in the aquifers healthy status can be detected from the changes of the average water table depth of the shallow aquifer, and the water table depth of the depletion cone of the deep aquifer.

We think that the community sensitivity toward aquifer environment has triggered the restorative force, and caused new actions toward environmental protection. High community sensitivity represents that humans feel the pressure of environmental deterioration, and tend to restrain human activities to restore environmental health. The change of community sensitivity is related to the change of norms and values. However, economic costs and incentives are also very important. Please also refer to the response to the 2nd and 3rd comments.

Page 12, figure 4a, how are the axis defined? Is a decrease in groundwater table indicated with a positive sign? Are values calculated with regard to the groundwater table of the previous year? Has a correction been applied for water inflow (e.g. precipitation)?

Response: In the revised manuscript, we revised it as "change in shallow water table depth", and added a explanation "a negative change means a rise of the groundwater table".

Page 12, figure 4b, out of interest, how can it be that with a larger withdrawal the center of depression in 2013 is equal to 1984?

Response: The reason is that the center of the depression cone moved from urban areas to the rural area, and the average water table of the aquifer still declined. We added a figure showing the changes in the water table depth of the aquifer III along the cross-section from the west to the east.

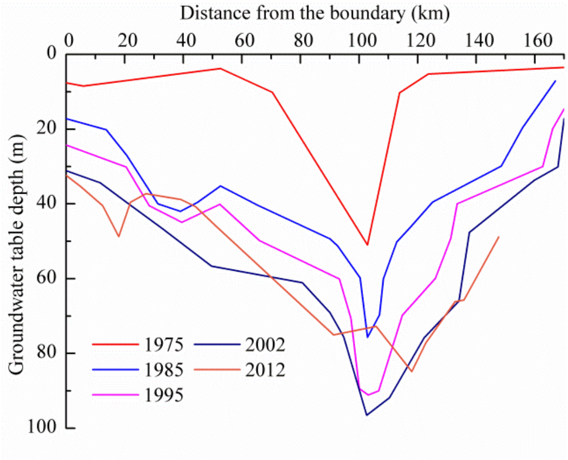
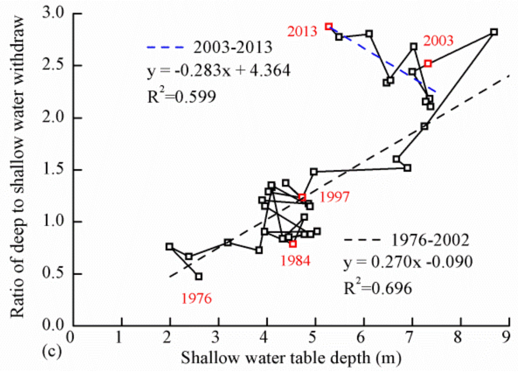


Figure. Changes in the water table depth of the aquifer III along the cross-section from the west to the east.

Page 12, figure 4c. The description of this figure is quite difficult to follow. Since two sets of data are presented in the figure, i.e. black (1976 - 2002) and blue (2003 – 2013) a discussion of these different trends would be appreciated. If individual data points are discussed as is the case now, maybe the individual years could be marked in the plot?

Response: We have marked the individual years in the plot, and added a discussion of the different trends. Please refer to the responses to the 9th comment of Referee #1.



Page 12, line 14. “The interactions of inner Taiji : : : of blind development.” On which literature is this statement based? Elinor Ostrom has, among others, done a lot of research aimed at understanding the circumstances under which overexploitation takes place.

Response: First of all, the part of sentences is trying to explain that the interactions of inner Taiji that only captures the main processes that how humans adapt to the natural variabilities and utilize the natural resources are not enough to describe the behaviors of socio-hydrologic systems at all time and space scales. There are many cases back up the statement that without fully awareness of natural deterioration, humans development pattern will still remain blind. The most famous one is the global warming issue, even today we are not taking enough measures in coping with the overexploitation of natural resourses and over consumption of chemical fuels.

Second, E. Ostrom has done great job on socio-ecological system (SES), and based on many cases, summarized many situations that leads to overexploitation. We believe we are working on the same direction with Ostrom. While Ostrom focus on her SES framework developed from IAD framework (institutional analysis and development), our works are mainly focus the water issue, which is quite different from other natural resources that are easily located and dividable, like woods, mines, fishery and wild animals. In future, in socio-hydrology, we believe more cases shall be studies.

Page 13, line 13, it would be helpful to see the definition of the restorative and productive force earlier in the paper, for example when introducing the Taiji Tire model.

Response: We have added the definition of the restorative and productive force when introducing the Taiji Tire model. Please also refer to the response to the 2nd comment.

Page 14, line 6, “This is because at : : : protections (Elshafei et al., 2014).” On what evidence is this statement based? How is community sensitivity defined? How is it measured in the case study?

Response: This statement is based on these incidents: "In 2004, a leading group headed by the executive vice mayor was established to prevent and manage the subsidence in Cangzhou. Measures for sustainable groundwater management was emphasized in the Cangzhou Government Work Report in 2004."

The definition of community sensitivity can be refer to the response to the 3rd comment. In this case study, it is indicated by the measures taken by the public and policymakers to modify the existing development pattern.

Page 14, line 13. “The social productive : : : extremely costly”. On what are these statements based? Is there evidence that technology and management tools are developed solely for environmental protections? Costly in relation to what (alternative)?

Response: We added the basis in the revised manuscript: "Given that economic development has always been the primary target of the government and society of Cangzhou, the mitigation measures for reallocating water from the economic development to the environment, which have been implemented in Murrumbidgee River basin (Kandasamy et al. 2014), are unacceptable. Therefore, new policies are established to restrict groundwater exploitation. The development and application of water-saving technologies are strongly encouraged to protect the environment while ensuring economic development, even if such strategies are more costly than traditional groundwater exploitation. As shown in Fig. 2(f), the area of water-saving irrigation has increased rapidly."

The "new technology and management tools" denotes those for water saving. It is costly in relation to traditional groundwater exploitation. We have made the statement more clear in the revised manuscript.

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

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Abstract. This paper presents a historical analysis from socio-hydrologic perspectives of the coupled human–groundwater system in the Cangzhou region in the North China Plain. The history of the "pendulum swing" for water allocation between the economic development and aquifer environmental health of the system is divided into five eras (i.e., natural, exploitation, degradation and restoration, drought-triggered deterioration, and returning to the balance). The system evolution was interpreted using the Taiji-Tire model. The interaction between the human utilization and the groundwater was regarded as the inner Taiji, wherein over-exploitation was considered as the main cause of groundwater depletion and the groundwater utilization pattern was affected by the varying groundwater tables. The external drivers of the co-evolution of the human–groundwater system in Cangzhou were specified as social productive force and natural variability (which can be detected from the precipitation and surface water change/variability). The varying groundwater tables influence the community sensitivity of humans toward environmental issues. High community sensitivity upgraded the social productive force (defined as the social restorative force), which was triggered by the drought during 1997–2002, and enhanced the ability to rebalance the human–groundwater system through new policies, and promoted the development of water-saving technologies. In the future, further restorations of groundwater environment should be implemented, along with the establishment of a strict water resource management strategy and the launch of the South-to-North Water Diversion Project. However, the occurrence of drought remains an undetermined variable.

1 Introduction

Through adaption processes, humans co-evolve with the hydrological system, resulting in a “pendulum swing” in the balance point of the human–water system (Kandasamy et al., 2014; Sivapalan, 2015). Kandasamy et al. (2014) first characterized the concept of the “pendulum swing” by tracing 100 years history of the competition for water between agricultural development and environmental health in the Murrumbidgee River Basin. Similar dynamics were also found in the human–water system in the arid Tarim River Basin (Liu et al., 2014) and in human–flood interactions (Baldassarre et al., 2015). A pendulum swing can be divided into four typical stages: (1) the initial exploitation stage, which is focused exclusively on economic development; (2) the onset environmental degradation stage, which is accompanied by the introduction of remedial infrastructure; (3) the widespread environmental degradation stage, which leads to the necessity of mitigation measures; and (4) the recovery stage, at which ultimate solutions are implemented. The pendulum swing of a human–water system can be clarified by considering all interactions within a universal socio-hydrologic framework (Kandasamy et al., 2014; Liu et al., 2014). The importance of socio-hydrology has been recognized by the International Association of Hydrological Sciences through their new “Scientific Decade” (2013–2022) entitled “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.”

A socio-hydrological system contains human, hydrological, and environmental sub-systems. The Taiji-Tire model proposed by Liu et al. (2014) was first used as a framework for elucidating the complexities of socio-hydrological systems that co-evolve with direct or indirect interactions between factors from both human and water perspectives. In the model, a Taiji wheel, which is a term originating from a special concept in Chinese philosophy, is used to describe the direct human–water relationship in a specific socio-hydrological system, whereas a human–water tire is used to represent the indirect effect of external natural and social factors affecting the system. The evolution of a socio-hydrological system is driven by the interactions between two main factors, namely, natural variability and social productive force (Liu et al., 2014). Social productive force refers to the combination of all factors that enable humans to utilize resources and create better material and spiritual products. To apply the Taiji-Tire model in interpreting the drivers of water reallocation from the economy to the environment during the recovery stage of the pendulum swing, the concept of “environmental restorative force” was defined as the opposing factor of social productive force (van Emmerik et al., 2014). During the recovery stage, environmental protection actions are usually conducted because of a high social awareness for environmental risk or welfare (Di Baldassarre et al., 2013). Elshafei et al. (2014) proposed a new concept of community sensitivity to signify the social awareness for environmental welfare. Community sensitivity refers to the sensitivity of humans to the changing environment. A high community sensitivity implies that humans feel the pressure of environmental deterioration, motivating them to restrain human activities to restore environmental health. The concept of community sensitivity was also used to analyze the switching of the support between flood protection and wetland preservation in the Kissimmee River Basin, Florida (Chen et al., 2016). Above new concepts can be incorporated into the Taiji-Tire model to improve its explanatory power on a specific human–water system.

Being a ubiquitous source of high-quality fresh water, the groundwater system is closely connected with human. Driven by the increasing demand for water resources, improper exploitation of groundwater resources has resulted in serious environmental crises, particularly in regions with primarily groundwater-fed irrigation (Taylor et al., 2013) including North China Plain (NCP) (Liu et al., 2001; Chen et al., 2003; Zheng et al., 2010). In addition to the social productive force, natural variability is another external force. Climate variations influence groundwater systems both directly through replenishments by recharge and indirectly through variations in groundwater demand (Taylor et al., 2013). Unlike the inherent social forcing (i.e., increase in water demand for agricultural development), natural variability induces changes in human activities (such as drought-triggered pulse in water demand) that are extrinsic (Gurdak, 2012) and often perceived as shocks (e.g., droughts), which may push the system beyond its resilience thresholds (Sivapalan et al., 2012). In comparison, water resource management decisions could produce either positive or negative effects on both the environment and the society (Kandasamy et al., 2014).

North China Plain is an important agricultural region of China. The main crops in this region are wheat and maize. Irrigation is necessary to maintain high levels of grain production (Liu et al., 2001), and 70% of the cultivated land is irrigated, consuming 70% of the total water supply. Given that 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; Zheng et al., 2010). Quite a few studies have been carried out to better understand the spatiotemporal variations in groundwater depletion across the NCP and develop sustainable groundwater management options (Cao et al., 2013; Liu et al., 2008); in these works, the effects of human-induced change were evaluated by a scenario-based method (Wang et al., 2008; Liu et al., 2011; Liu et al., 2008). However, two-way feedback should be considered for a better understanding of coupled human–groundwater systems (Montanari et al., 2013).

A representative example of the co-evolution of the human–groundwater system is in Cangzhou in the northeastern coastal plain of the NCP, which has the most serious depression cone since the 1970s (Liu et al., 2001). In recent years, aquifers have been recovered through the implementation of several measures (Han et al., 2013). The history of the co-evolution of the human–groundwater system in Cangzhou seems like a "pendulum swing," particularly as to how the groundwater crisis unfolded and how it was addressed, which is selected as the study area in this paper.

The objectives of this paper are as follows: (1) to chart the history of the groundwater utilization in Cangzhou, focusing on the dynamics of the human–groundwater interactions that lead to the "pendulum swing" in the balance point in groundwater allocations between humans and aquifer ecosystems, as well as the natural variability and social factors that contributed to it; (2) to use the Taiji-Tire model to interpret the interactions and co-evolutions of the human–groundwater system in Cangzhou. The Taiji-Tire model will be specific to the groundwater system and will be incorporated with the concepts of restorative force and community sensitivity.

2 Study area, data, and methods

Groundwater pumping from aquifers has substantially increased since the mid-1960s. Thus, the NCP aquifer system has become one of the most over-exploited aquifers in the world (Kendy et al., 2007; Liu et al., 2008). Cangzhou region (total area: 14,056 km^2) is located in the east of the NCP and in the downstream of the Haihe River Basin (Fig. 1). Cangzhou is a prefecture-level city of Hebei Province consisting of 4 county-level cities and 10 counties. Cangzhou Municipal Government abides by the provincial and national policies of water resource management, and it devises policies for the entire region. The Water Resources Bureau of Cangzhou, which is a department of Cangzhou Municipal Government, is responsible for water resource affairs and guides the Water Resources Bureau of the 10 counties and 4 county-level cities. In turn, this agency is guided by the Water Resources Department of Hebei, the Ministry of Water Resources, and the Haihe River Water Resources Commission. Cangzhou is characterized by strong inter-annual variable precipitation and occasional extreme droughts. In 2013, the total population of Cangzhou was 7.34×10^6. The cultivated land area is 8,066 km^2, of which 5,424 km^2 is irrigated. Given that surface water is intercepted by reservoirs in the upstream, natural streams have nearly dried up, leaving groundwater as the main water source for irrigation.

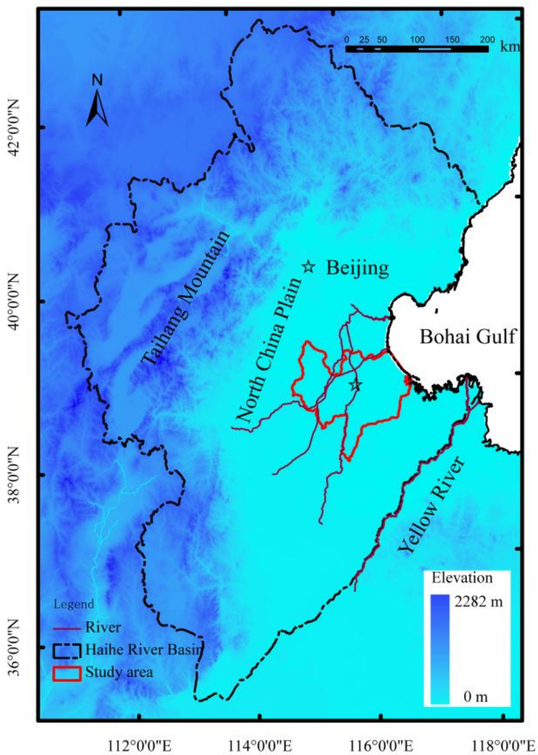

Figure 1. Location of Cangzhou in the North China Plain

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 m and 350 m. Aquifer Layer I is unconfined, and infiltration from precipitation is the main recharge source. The other three layers are confined. Saltwater accounts for 98% of Aquifer Layer II, with low exploitation capacity. Pumping wells mainly extract fresh groundwater from Aquifer Layers I and III. In this study, Aquifer Layers I and III are referred to as "shallow aquifer" and "deep aquifer," respectively. Groundwater levels have steadily declined because of over-pumping, resulting in saltwater intrusion and land surface subsiding (Kendy et al., 2003). In 2013, the groundwater withdrawal from the shallow and deep aquifers were 259×10^6 and 743×10^6 m^3.In recent years, several measures have been implemented for sustainable groundwater management to mitigate aquifer depletion (Han et al., 2013).

The analyses were performed based on the data of annual precipitation, agricultural infrastructures and production, groundwater withdrawal from both the shallow and deep aquifers, and groundwater table depth. The data before 1985 was acquired from the Water Resource Annals of Cangzhou (Xue, 1994), and the data after 1985 was obtained from the Hebei Rural Statistics Yearbook, and the Hydrology and Water Resources Investigation Bureau of Cangzhou. The data on policies and initiatives were collected from the Water Resource Annals of Cangzhou (before 1985), the announcements and documents of the Ministry of Water Resources, the Government of Hebei, the Water Resources Department of Hebei, the Government of Cangzhou, and the Water Resources Bureau of Cangzhou.

The time series of the groundwater withdrawal from both the shallow and deep aquifers were analyzed to detect the behaviour of water users. The average water table depth of the shallow aquifer and the water table depth of the depletion cone of the deep aquifer were used as the main indices of the groundwater system. The time series of number of wells and irrigated area (including water-saving irrigated area) were analyzed to detect the changes in infrastructure, along with the social development which were revealed by the changes in population, and grain production. The break points of the time series of the water table depth and groundwater withdrawal were determined based on trend changes. The break points were also confirmed by examining the major policies and initiatives that facilitated developments or that resulted in turning points in groundwater water management. Then, the co-evolution of the human–groundwater system was classified into several eras, which signified the points at which a "pendulum swing" occurred.

Under the framework of the Taiji-Tire model, the Taiji represents the direct interactions between the groundwater utilization and the aquifers in Cangzhou, whereas the outer Tire represents all of the social and natural factors that indirectly influence the human–groundwater system. Precipitation and surface water change/variability were considered the natural variability in Cangzhou. The emphasis level of the social productive force is detected from the changes in the number of wells, in irrigated areas with groundwater, and in policies for groundwater exploitation. In this study, we believe that the concept of environment restorative force is misleading and should instead be regarded as a subtype of social productive force. Social restorative force can be detected from the changes in water-saving irrigation areas and in policies for creating water-saving technologies.

3 Pendulum swing in groundwater utilization

The balance between groundwater extraction and efforts to mitigate and reverse the consequent degradation of the aquifer has evolved in Cangzhou since 1949 (Li et al., 2013). The evolutionary history of the human–groundwater system from 1949 to 2015 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 the human–groundwater system

Era 2 (1965–1982): Expansion of groundwater exploitation and onset 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–present): Returning to the balance

3.1 Era 1 (Pre-1964): Natural variability dominates the human–groundwater system

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 220 BC–220 AD). Historical records indicate that groundwater exploitation for irrigation in Cangzhou can be traced back to 1266, which was over 700 years ago. However, 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. The emergence of serious salinization problems necessitated the establishment of a drainage-oriented policy for low lands in Cangzhou. Many reservoirs and diversion projects were constructed, reducing the need for groundwater resources. Given that most wells were made of bricks and earth, groundwater utilization was restricted by the lack of infrastructure. By 1964, only a small portion of the wells (1,524) were pumped by motors, and the irrigated area with groundwater was 321 km^2, which only accounted for 2.3% of the total area of Cangzhou. Therefore, this era was characterized by small-scale groundwater utilization because of less groundwater demand as well as technological incapability. The interaction between humans and the groundwater was weak. Humans were insensitive to groundwater change, and the groundwater sub-system was unaffected by humans at a large scale.

3.2 Era 2 (1965–1982): Expansion of groundwater exploitation and onset of aquifer depletion

In 1965, North China suffered from a catastrophic drought that threatened food production. In response, the Cangzhou government promoted the construction of motor-pumped wells for groundwater exploitation. In 1966, the State Council organized a conference to combat drought in North China, and they specified well drilling as an important measure. Numerous well-drilling teams were organized after hydrogeological investigations were conducted on the agricultural water supply in the NCP. 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.

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

Year	Scale	Content
1965	Cangzhou	The government began to promote motor-pumped wells construction for groundwater exploitation
1966	China	The conference for the work of combating drought in eight provinces (municipalities) in North China
	Hebei	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	China	The agricultural conference regarding agricultural production in 14 provinces in North China, and funding for motor-pumped well constructions.
1973	Hebei	The headquarters for construction of motor-pumped wells were established
1979	China	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	China	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	China	The Water Law of the People's Republic of China
1993	China	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	China	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 self-supplying wells in urban areas should be shut down and the groundwater exploitation should be restricted
2005	Cangzhou	Cangzhou Municipal Government also decided to shut down self-supplying wells and ban deep self-supplying wells in urban areas
2012	China	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

The benefits of the emergency wells drilled to combat the drought encouraged the continued construction of 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 1982, the number of motor-pumped wells reached 51,611, and the irrigated area with groundwater reached 2,086 km^2 (Figure 2(e)), which is 41.3% of the total irrigated area. 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.

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

	Shallow groundwater			Deep groundwater		
	Withdrawal $\times10^6 m^3$	Depth m	Trends m/decade	Withdrawal $\times10^6 m^3$	Depth m	Trends m/decade
Era 2*	372.4	3.20	-0.39	291.1	64.87	-3.11
Era 3	411.9	4.47	0.03	436.4	82.22	-1.63
Era 4	485.9	6.54	-0.75	822.7	96.72	-2.47
Era 5	315.3	6.66	0.2	774.0	82.69	3.01

* According to the data from 1976 to 1982.

The rapid increase in groundwater exploitation drastically deepened the groundwater level of both the shallow and deep aquifers. The average annual shallow groundwater withdrawal from 1976 to 1982 was 372.4×10^6 m^3 (Table 2). In 1982, the regional average shallow groundwater table declined to 4.32 m beneath the ground, with an annual decline of 0.39 m from 1976 to 1982. As a result, many shallow wells were abandoned because of the significant decline in the groundwater table. Motor-pumped wells had to be drilled with increasing depth, signaling the start of a vicious cycle. Groundwater exploitation had to be drilled deeper than usual, and the deep groundwater withdrawal significantly increased, from 193×10^6 m^3 in 1976 to 357.7×10^6 m^3 in 1983, which exceeded the sustainable volume (292×10^6 m^3 according to Wang and Wang (2007)) since 1979. With increasing exploitation, the water table of the deep aquifer rapidly declined. The depression cone of the deep aquifer in Cangzhou first appeared in 1967, whereas the depth of the water table at the center of the depression cone was 22.5 m beneath the ground in June 1971. By 1983, the water level at the center of the depression cone was as deep as 72.9 m, with an annual decline of 3.82 m from 1973 to 1983. The drilling depth increased because of the drop in deep groundwater table, and the cost for both well drilling and installation of new motor-pumped wells rose. In addition, several environmental problems were triggered. Land subsidence occurred in Cangzhou City in 1970 because of the presence of the depression cone. The cumulative volume of subsidence in 1970 was 9 mm, and it increased to 744 mm in 1986. Because of the formation of the depression cone in Aquifer Layer III, the natural recharge–discharge balance was destroyed between the fresh water originally in Aquifer Layer III and the saltwater in the overlying aquifer layer II. The leakage recharge of saltwater from Aquifer Layer II to Layer III increased, leading to saltwater intrusion.

3.3 Era 3 (1983–1996): Awareness of environmental degradation and attempts for restoration

The intensification of the groundwater crisis raised the public clamor to address the water crisis. 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 suggestions for strengthening the management of groundwater resources in which comprehensive water resource management measures were detailed. Specifically, shallow groundwater exploitation should be prioritized, deep groundwater exploitation should be restricted, and 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 China was released, which states that explorations should be strictly controlled in regions where groundwater resources have already been 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 is prohibited. Since the 1980s, well drilling was no longer subsidized by the central government, resulting in a sharp decrease in the number of wells. To fill the gaps, surface water was diverted from the Yellow River in 1993.

The aforementioned measures relied on comprehensive water resource management, by which deep, medium, and shallow groundwater exploitations were governed by unified planning, with shallow aquifer exploitations given priority. Consequently, the increasing deterioration of groundwater resources in Cangzhou was halted. From 1984 to 1996, the shallow groundwater withdrawal slightly decreased (by approximately 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 deep groundwater withdrawal slowed down (by approximately 18.8×10^6 m^3 per year). Consequently, the water level at the center of the depression cone declined slowly at an annual rate of 1.63 m, and the subsidence at the center of the depression cone was also reduced.

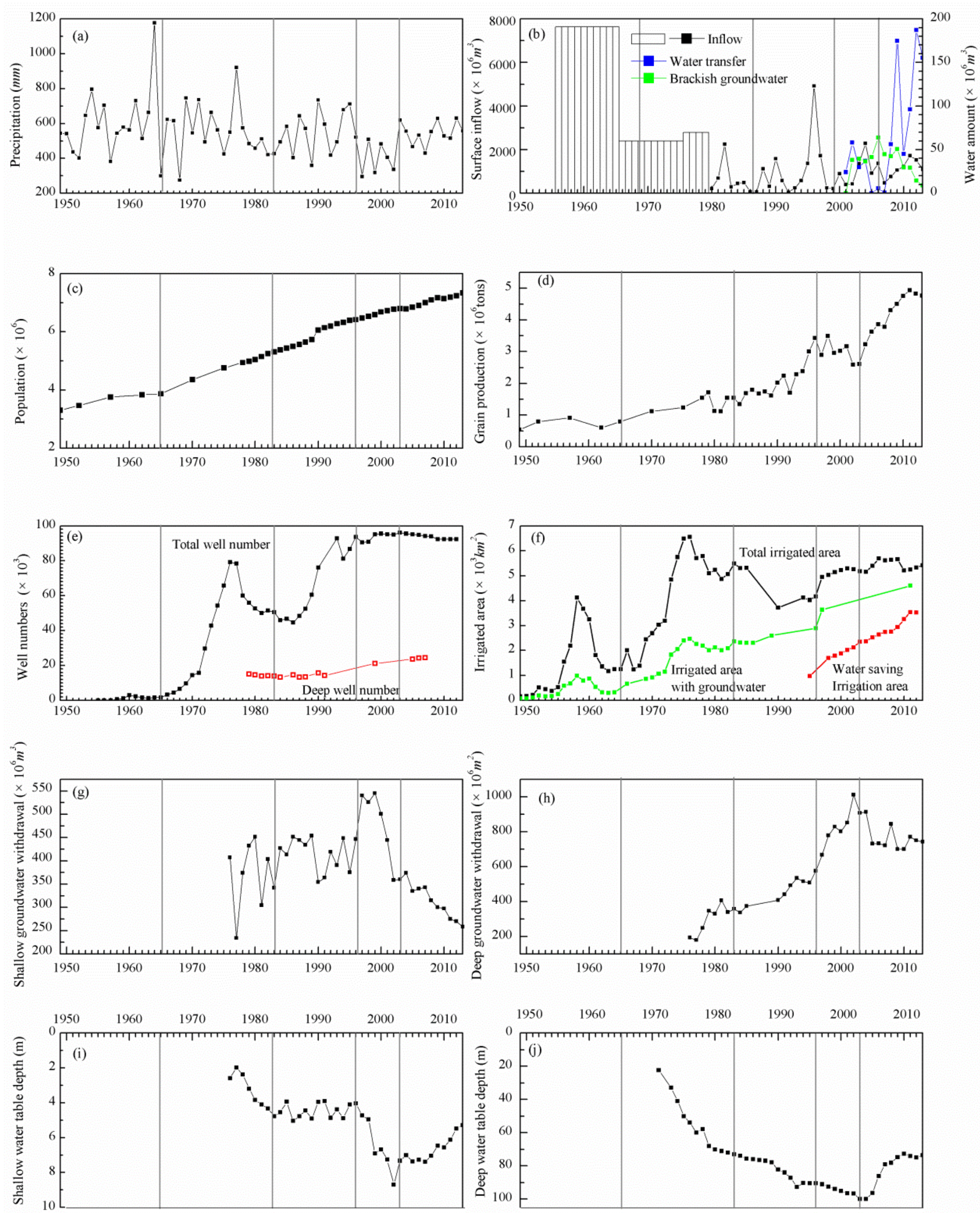

Figure 2. Time series of (a) precipitation, (b) surface inflow (before 1980 the data is the average value), (c) population, (d) grain production, (e) well numbers (red line is referred the number of deep well), (f) irrigated area, (g) shallow groundwater withdrawal, (h) deep groundwater withdrawal, (i) shallow water table depth, and (j) water table depth of the depletion cone in Cangzhou during the study period (1949–2013)

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

Unfortunately, the positive trend ceased after the outbreak of a serious drought 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 (Table 3). However, because surface water has already been exhausted since the 1980s, well drilling seemed to be the immediate strategy for addressing the drought. During this period, the annual average shallow groundwater withdrawal was $485.9\times10^6 m^3$, which represented an increase by 16.5% compared with $417.2\times10^6 m^3$ during 1984–1996, and the annual average deep groundwater withdrawal rapidly increased from 455.2×10^6 m^3 during 1984–1996 to $822.7\times10^6 m^3$, which represented an increase by 80.7%. Accordingly, the shallow groundwater level rapidly declined again, from 4.03 m depth beneath the ground in 1996 to 8.69 m in 2002, with an annual decline of 0.75 m. At the same time, the water table at the center of the depression cone rapidly declined again from 90.4 m depth beneath the ground 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. In view of the sharp decline in the groundwater table, the environment deteriorated. The cumulative subsidence to 2001 was 2,236 mm, with a rate of 100.5 mm/a. The areas with subsidence larger than 500 and 800 mm are 9,717 and 3042 km^2, respectively, which account for 92.9% and 29.1% of the total area of Cangzhou. Moreover, the interface of saltwater and fresh water declined at approximately 10 m, with a maximum depth of 30 m, threatening the fresh water in the deep aquifer (Han and Han, 2006).

During the drought 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 is prohibited. In 2002, the Hebei Provincial Government specified the over-exploited regions and the severely over-exploited regions in the plain area. The entirety of Cangzhou was included in the list of regions with severely over-exploited deep aquifer. With respect to the shallow aquifer, the over-exploited and severely over-exploited regions were 406 and 525 km^2 in area, jointly accounting for 6.6% of the total area of Cangzhou. To adopt the restrictions on groundwater exploitation, the Hebei Provincial Government formulated a program for developing water-saving technologies 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 irrigations and sprinkler irrigations) in Cangzhou rapidly increased from 96.4 km^2 in 1995 to 212.5 km^2 in 2002.

3.5 Era 5 (2003–present): Returning the balance

During the drought, the groundwater crisis in the NCP once again gained widespread concern, and several measures were implemented at the national, provincial, and regional levels. 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 that groundwater exploitation should be restricted. The Cangzhou Government subsequently began to shut down these wells in urban areas. To adopt the restrictions on groundwater exploitation, investments in water-saving projects were enhanced, and subsidies were provided in Cangzhou. Accordingly, the irrigated area with water-saving technologies in Cangzhou rapidly increased to 3,526.5 km^2 in 2012, which accounts for 65% of the total irrigated area. At the same time, inter-basin water transfer project, brackish water, and other municipal projects were also implemented. The water supply volume from non-groundwater sources (mainly the brackish water and the water transfer from other basins) significantly increased (Figure 2(b) and Table 3).

Table 3. Changes in factors related to the community sensitivity from Era 2 to Era 5

	Precipitation (mm)	Surface inflow ($10^6 m^3$)	Alternatives ($10^6 m^3$)		Water-saving irrigation Area ($10^3 km^2$) [a]	Economic conditions	
			Brackish water	Inter-basin transfer		Cost	Subsidy objective
Era 2	544.1	2144	0	0	26.7[a]	Low	Well drilling
Era 3	554.9	578	0	-	96.42	Middle	No Subsidy
Era 4	391.7	1258	19.0 [b]	41.2[c]	212.48	High	Water-saving
Era 5	547.2	1185	36.5	71.7	352.65	High	Water-saving

[a] The value at the end of each era; [b] The average value of 2001–2002, when it was used at large scale.

Remarkable effects were obtained from the implementation of these measures. The shallow groundwater withdrawal gradually decreased from 360.4×10^6 m^3 in 2003 to 258.2×10^6 m^3 in 2013. Consequently, the shallow groundwater table rose again to 5.28 m beneath the ground in 2013, with an annual rise of 0.2 m. The deep groundwater withdrawal 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 a seriously over-exploited region to an over-exploited region of the deep aquifer. An area of 525 km^2 is alleviated from a seriously over-exploited region to an over-exploited region of the shallow aquifer, and the former 406 km^2 over-exploited region in terms of shallow aquifer is abolished. Accordingly, the environment of the aquifers has been restored. Subsidence in Cangzhou City has been effectively controlled since 2005 (2005 Yearbook of Cangzhou). For example, in a monitoring site near Cangxian County, the subsidence rate decreased from 76 mm/a during 2001–2005 to 40 mm/a during 2007–2008 (Zhang et al., 2014). Nonetheless, the aquifers still suffer from serious environmental problems. The average water table of the aquifer is still deep although the depth in 2013 is equal to that in 1984, as the center of the depression cone moved from urban areas to the rural areas (Fig. 3). According to the Geological Environment Bulletin of Hebei of 2013, the depression cone of the deep aquifer in Cangzhou is 5,551 km^2.

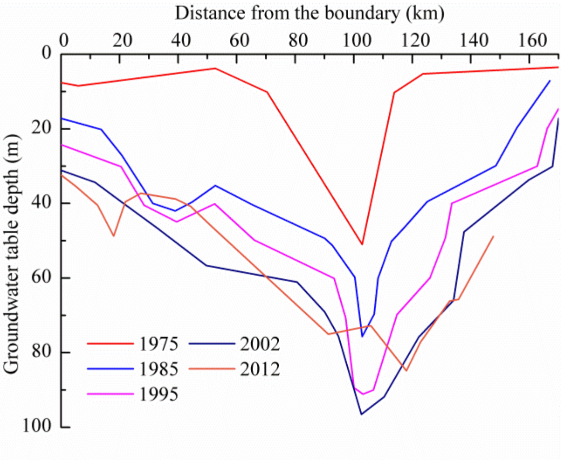

Figure 3. Changes in the water table depth of the Aquifer Layer III along the cross-section from the west to the east.

In 2012, China launched the strictest water resource management strategy 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 water for domestic use, the construction of new motor-pumped wells will not be approved. Groundwater exploitation is prohibited in urban regions already covered by a public water supply network. Since the South-to-North Water Diversion Project was established in 2015, which annually diverted 483×10^6 m^3 of water to Cangzhou, 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. According to the High-Efficiency Water-Saving and Irrigation Program in Cangzhou launched in 2013, overall water savings in agricultural production will be achieved by 2020.

4 Discussion: Interactions of the human–groundwater system

According to the preceding analysis on 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. 4(a). The changes in natural variability (precipitation and surface inflow), social productive force, and restorative force in Cangzhou through five eras are shown in Fig. 4(b).

Human groundwater utilization is the main cause of the varying groundwater table. With increasing groundwater exploitation, both the shallow and deep groundwater table declined, and groundwater depression cone extended in Cangzhou. The contributions of increasing shallow groundwater utilization on the decline in the groundwater table is evident in the positive correlation between the depth fluctuations of the annual shallow water table (a negative change indicates a rise of the groundwater table) and the water withdrawal (Fig. 5(a)). The increasing deep groundwater utilization contributed to the decline in the water table depth of the depression core before 2002. The subsequent rapid reduction in rapid groundwater utilization caused the water table at the center of the depression cone of deep groundwater to quickly rise again (Fig. 5(b)).

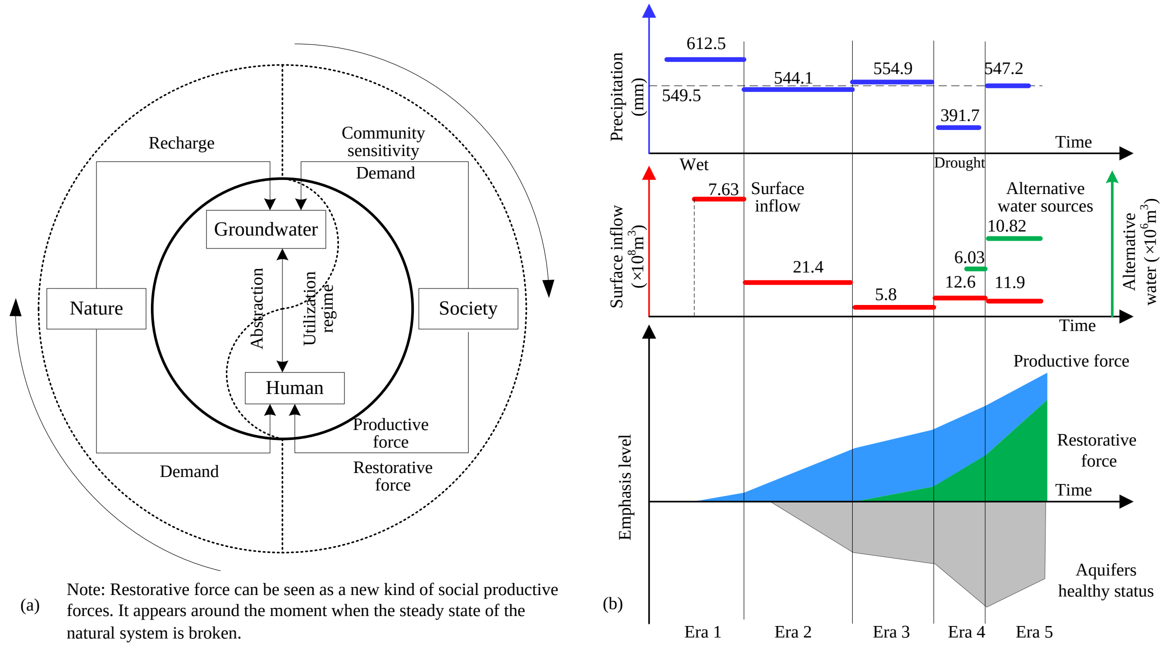

Figure 4. (a) Taiji-Tire model representation of the interactions of the human–groundwater system; (b) Changes in natural variability (precipitation and surface inflow), social productive force, and restorative force in Cangzhou through five eras (Emphasis level used in relation to the vertical axis refers to the degree of increase in the variables described in the figure).

The groundwater sub-system also affects the behavior of water users. The significant decline in the shallow water table prevents the use of many shallow wells as before. By contrast, the water in the deep aquifer is guaranteed in terms of both the quantity and quality albeit with higher cost. Consequently, groundwater utilization was directed toward the deep aquifer. In 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 water to shallow water withdrawal increased as the shallow water table declined from 1976 to 2002, especially during the drought in 1997–2002. In 2002, which had the deepest shallow water table, the water withdrawal from the deep aquifer was 2.82 times of that from the shallow aquifer. This feedback 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. 5(c)).

The co-evolution of the human–groundwater system in Cangzhou is driven by natural variability, particularly the change/variability of surface water and precipitation. With decreasing surface water resources, the recharge to the groundwater system decreased, and the demand for groundwater increased. Besides, the precipitation variability affected both the groundwater and human sub-systems. A larger precipitation implies a larger recharge to the shallow groundwater. As shown in Fig. 6(a), the changes in shallow water table depth are highly negatively correlated with the annual precipitation.

The drought years with low precipitation are characterized with not only small recharge to the shallow aquifer but also a large demand for groundwater. Thus, groundwater withdrawal is negatively correlated with annual precipitation (Fig. 6(b)).

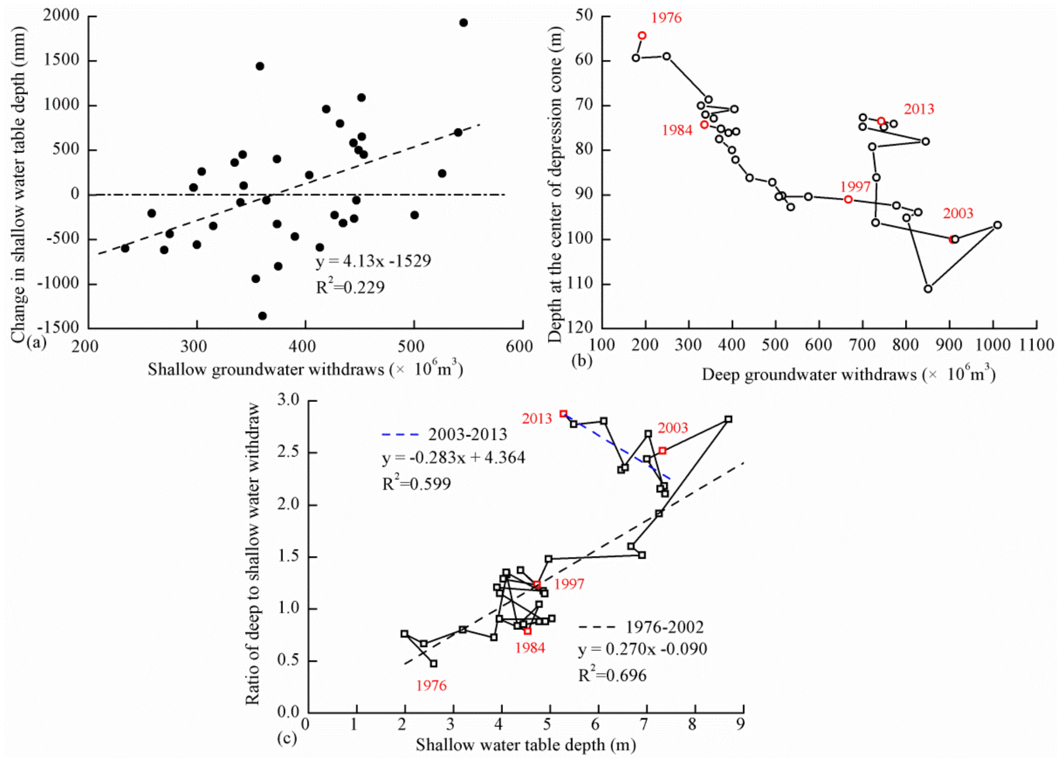

Figure 5. (a) Relationship between shallow water changes and withdrawal; (b) co-evolution of the depth of the depression cone center of deep aquifer with water withdraw from 1976 to 2013; (c) the ratio of deep to shallow water withdrawal against the shallow water table depth before and after 2002.

The co-evolution of the human–groundwater system in Cangzhou is also driven by the social productive force. Before 1965, groundwater utilization was not large scale because of technological limitations. The groundwater withdrawal was small compared with that of surface water, and the irrigated area with groundwater was constrained to a small fraction of Cangzhou. According to the Taiji–Tire model, the human–groundwater relationship was weak, lacking any kind of sophisticated interactions. Therefore, the human–groundwater system can be considered stationary (or a steady state) without significant external drivers. To overcome the drought in 1965, the Cangzhou Government proposed an expansive policy of groundwater utilization for the first time, and well drilling was rapidly accelerated. The relationship between the human and groundwater sub-systems was enhanced since then, and the stationary condition was broken. The groundwater exploitation was driven by the need to resist the drought up to the early 1970s and by the need to enlarge the irrigated area for food production. Since then, the number of motor-pumped wells increased rapidly. The growth of the social productive force has sustained a significant increase in groundwater consumption.

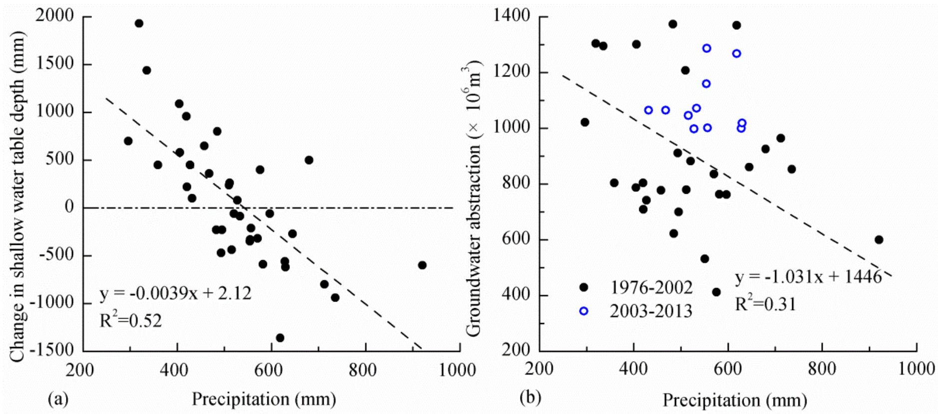

Figure 6 (a) Change in shallow water table depth; (b) total water withdrawal against annual precipitation.

The interactions of the inner Taiji usually lead to over-exploitation of natural resources and additional human input on development. Without having full awareness of natural deterioration, human development patterns will remain uninformed. The feedback of the outer Tire will educate society of the negative effect of over-exploitation and therefore promote the development of new responsive social behaviors to protect the environment and reduce the impulse of blind development. Although the negative externality still gradually persists, it does so at low levels during a long period, preventing it from reversing this developing trajectory. Although the interactions of the inner Taiji leads to serious problems in ecosystems, the community sensitivity rises, and these environmental protection actions can be considered a new kind of social productive forces, which can be called social restorative forces. The social restorative force is not the same as the natural variations and is not an opposite force to social productive forces, which can also be restorative. The only difference is the social norms and values. In other words, humans themselves must decide how to use technology and devise policies. The social productive force only emphasizes the production but not the cost, including the direct production cost and the environmental externalities, whereas the restorative forces refer to the specific productive forces that further increase the production by lowering the environmental externalities. Therefore, the social restorative force can be regarded as a sub-branch of social productive force (with social destructive force being the other sub-branch). The social restorative force appears around the moment when the steady state of the natural system is broken. However, the social restorative force in Cangzhou was not strong enough during the drought of 1997-2002, while the productive force was dominated by that utilizes groundwater. As a result, the groundwater table declined rapidly. When the social restorative force dominates the productive force, social productivity can be seen as green productivity (Tuttle and Heap, 2007; Mohanty and Deshmukh, 1998); that is, the societies can be seen as green (the other type is technological) (Baldassarre et al., 2015).

Until 2002, groundwater withdrawal increased with the population and GDP of Cangzhou, but it decreased after that (Fig. 7(a)). The reason is that since 2002, after decades of accumulation, the community sensitivity toward aquifer environment has caused new actions toward environmental protection. In 2004, a leading group headed by the executive vice mayor was established to prevent and manage the subsidence in Cangzhou. Measures for sustainable groundwater management was even emphasized in the Cangzhou Government Work Report in 2004. More specifically, the broken stationary condition of natural systems suggests higher levels of uncertainty and risks of extreme hydrometeorological events, causing higher social awareness of risks and resultant actions. The drought during 1997–2002 reminded the public and policymakers about taking measures to modify the existing development pattern.

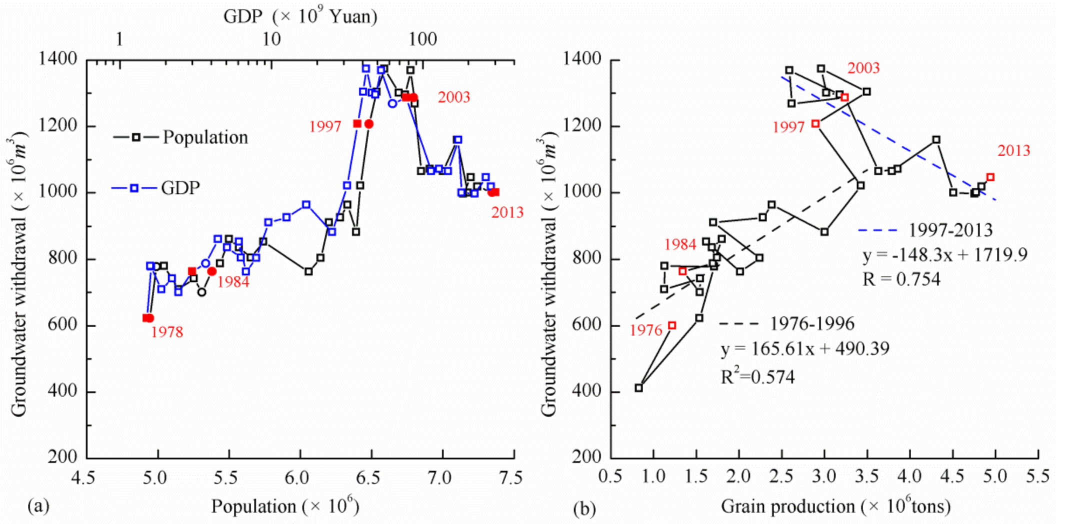

Figure 7. (a) Relation between annual groundwater withdrawal and the population and GDP; (b) Co-evolution of the total groundwater withdrawal against the annual grain production before and after 2002.

Given that economic development has always been the primary target of the government and society of Cangzhou, the mitigation measures for reallocating water from the economic development to the environment, which have been implemented in Murrumbidgee River basin (Kandasamy et al., 2014), are unacceptable. Therefore, new policies are established to restrict groundwater exploitation. The development and application of water-saving technologies are strongly encouraged to protect the environment while ensuring economic development, even if such strategies are more costly than traditional groundwater exploitation. As shown in Fig. 2(f), the area of water-saving irrigation has increased rapidly. The social productive forces have therefore reached a critical point. These new improvements can be seen as an effort of humans to raise the social restorative force. Thus, some scholars believe that the human–water system is determined by the interactions between social productive and restorative forces (van Emmerik et al., 2014). Nonetheless, as we have mentioned, a more precise description is that the social restorative force is a new kind of social productive force.

The pattern of the human–groundwater system has significantly changed since the appearance of the social restorative force. For the inner Taiji, significant changes in water user behavior and human response to groundwater system can be observed if the dataset was divided into two periods (before and after 2002) based on the narrative of the different eras. The ratio of deep water to shallow water withdrawal was negatively correlated with the shallow water table depth after 2002, which is absolutely different from that before (Fig. 5(c)). However, the correlation of the negative relationship is considerably weaker at a starting point before 2002 (for example, the coefficient of determination (R^2) is only 0.11 according to the data from 2002 to 2013). As shown in Figs. 2(g) and 2(h), the deep groundwater withdrawal began to decrease slowly since 2002, whereas the shallow groundwater withdrawal continued to decrease rapidly as before. This finding indicates that people did not turn to shallow water as the shallow water table increased, because the infrastructure of deep water with high-quantity exploitation already existed.

The groundwater withdrawal decreased continually after 2002, although the annual precipitation kept stable. The significant negative correlation between the groundwater withdrawal and annual precipitation before 2002 (R^2 is 0.31) (Fig. 6(b)) would significantly decrease if the period is extended to after 2002 (R^2 is only 0.25 when the used data is during 1976–2003). This decoupling reveals that water demand would no longer subtly vary with precipitation. Although an uncertainty still exists because the precipitation did not vary significantly during 2003–2013, the findings indicate an increased ability to mitigate climate variability.

In Cangzhou, the varying groundwater tables also influenced the community sensitivity of humans toward environment issues and motivated them to self-regulate their behaviors by establishing new policies (such as restricted groundwater exploitation policies) and developing new water-saving technologies. As community sensitivity continues to increase, new technologies and management efforts would enhance the restorative forces. Supported by theses productive forces, the grain production declined slightly during the drought during 1997–2002, but it grew rapidly again with the subsequent decline in groundwater utilization after 2002 (Fig. 2(d)). Thus, the grain production was negatively correlated with the groundwater withdrawal during 1997–2013 (correlation coefficient of −0.87), which is different from that during 1976–1996 (correlation coefficient of 0.77) (Fig. 7(b)).

5 Conclusions

The historical socio-hydrological analysis in Cangzhou enabled the recognition of the "pendulum swing" of the co-evolution of the human–groundwater system. At the first era, the intensity of groundwater exploitation was 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 era, 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 aquifers environment, which drew considerable attention from society. At the third era, comprehensive management measures were implemented to address the groundwater crisis, and the deterioration was mitigated to a certain extent. At the fourth era, drought appeared as a shock, which terminated the mitigation because humans exert effort to enhance the productive force to meet the challenge by pumping more water.

Considering that 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. Consequently, the intensity of groundwater exploitation rapidly increased, leading to the dramatic deterioration of the aquifers environment.

Nevertheless, community sensitivity concerning water crisis was enhanced in the meantime. The increasing community sensitivity has also triggered the split of social productive forces and generated new restorative forces. At the fifth era, the drought was eased, and several measures were implemented to reduce groundwater exploitation. Water-saving technologies became acceptable economically and ideologically, and the aquifers 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. Further restoration of the aquifers environment is anticipated. However, the external environment variations, particularly drought, 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 human utilization and the groundwater are regarded as the inner Taiji. 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 turn to the deep aquifer. Precipitation variation directly affected the groundwater recharge as well as the demand for groundwater, which subsequently affected the human–groundwater system. Triggered by the drought, the social 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 technologies and corresponding management efforts. This feedback rebalanced the interactions of the inner Taiji that has intensified the human–water relations with the occurrence of the expected pendulum swing that has decreased the groundwater withdrawal 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 (ID0145B292016) of 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, and on Comparative Study on the Co-evolution of Coupled Human-Water Systems.

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