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: There are two objectives of the paper, and we will state them clear in the revised manuscript: "The objectives of the paper are: (1) to chart the "pendulum swing" history of the groundwater utilization in Canagzhou, with a particular focus on the dynamics of human–groundwater interactions that resulted in the “pendulum swing” around the balance point in groundwater allocations between humans and aquifer ecosystems, as well as the natural variability and social forcings that contributed to it; (2) to interpret the interactions and co-evolutions of the human-groundwater system within Cangzhou using the Taiji-Tire model, with the incorporation of the concepts of restorative force and community sensitivity."

We agree with the comment. In the revised manuscript, we will add 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”:

"Linked by the processes of adaption, the human society co-evolves with the hydrological system, often resulting a "pendulum swing" around the balance point of the human-water system (Kandasamy et al. 2014, Sivapalan 2015). The concept of pendulum swing was first characterized by Kandasamy et al. (2014), through tracing the 100 years history of the competition for water between agricultural development and environmental health within the Murrumbidgee River Basin. Similar dynamics was also found in the human-water system in the arid Tarim Basin (Liu et al. 2014), and the case of human-flood interactions (Baldassarre et al. 2015). A pendulum swing can be specified into three or four typical stages: the initial exploitation stage exclusively focusing on economic development, the onset environmental degradation stage accompanying with the introduction of remedial infrastructure, the widespread environmental degradation stage led to mitigation measures, and the recovery stage along with the implementation of ultimately solutions.

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

"A specific social hydrological system contains human, hydrological and environmental sub-systems. The Taiji-Tire model proposed by Liu et al. (2014) is a framework to represent and explain a specific social-hydrological system under its outer environmental system. In the model, a Taiji wheel, a term from a special concept in Chinese philosophy, is used to describe the direct human–water relationship of a specific social hydrological system. While a human–water tire is used to represent the indirect impact of external natural and social factors

that affect the water. The pendulum swing of the water competition between agriculture and environment in the Tarim Basin in a long history was revealed by the Taiji-Tire model, with attention on the interactions between natural variability and social productive force (Liu et al. 2014). In order to interpret the drivers of the reallocation of water from social-economy to the environment under the recovery stage of the pendulum swing, a concept of "environmental restorative force", which is comparative to "social productive force" was proposed (van Emmerik et al. 2014). It should be noted that the environmental protection actions during the recovery stage are usually conducted upon a high social awareness of environment risk or welfare (Di Baldassarre et al. 2013). Elshafei et al. (2014) uses a new concept of community sensitivity to represent this social awareness of environment welfare. Community sensitivity is the sensitivity of human society to the changing environment. High community sensitivity represents that humans feel the pressure of environmental deterioration, and tend to restrain human activities to restore environmental health. The concept of community sensitivity was used to analyze the switching of the favoring between flood protection and wetlands 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: At first, we will introduce 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 will explain 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 well numbers and irrigated area (including water-saving irrigated area) were analyzed to detect the changes in infrastructure, under the background of social development revealed by the changes in population, and grain production. 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 environmental health status. The break points of the time-series of the water table depth and groundwater withdrawal were obtained according to the changes of the trends. The major policies and initiatives that facilitated developments, or resulted in a turning point in the groundwater water management were examined to confirm the break points. Then, the co-evolution of the human-groundwater system was classified into different eras, which are used to determine if and when a “pendulum swing” occurs.

We will explain the Taiji-Tire model as follows:

The Taiji-Tire model is firstly used as a framework to explain how complex socio-hydrological systems coevolved with direct or indirect interactions between factors

from both human and water sides. For the case in Cangzhou, the groundwater is apparently influenced by humans during past several decades and in turn the varying groundwater tables were also shaping the community sensitivity of humans on the environment issues and drives humans to self-regulate theirs behaviors by establishing new policies and developing new technologies like water-saving technology. The most valuable contribution of the Taiji-Tire model is to provide an overall perspective of a socio-hydrological system with explicit presentation of the interactions between multi-factors that generate rich dynamics. It is not yet an accurate math or physical model, but a framework for scholars to study and exchange ideas on a specific case.

As for the productive and restorative forces, as mentioned in the paper, for example Fig. 3a, 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.

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, 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 will aggregate 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 will follow closed the suggestions made by referees, and improve the use of English. The revised manuscript will be 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 has revised this term as "social forcing (such as 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 will add an instruction on the governance and institutional structure of the study region:

Cangzhou is a prefecture-level city of Hubei Province, and has 4 county-level cities and 10 counties. Cangzhou government abides by the provincial and national policies of water resources management, and makes policies for the whole region. The Water Resources Bureau of Cangzhou, as a department of Cangzhou Government, takes charge of the water resources affairs, and guides the Water Resources Bureau of the 10 counties and 4 county-level cities, and is also 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: The data of policies and initiatives before 1985 is discovered 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. The break points of the time-series of the water table depth and groundwater withdrawal were obtained according to the changes of the trends. The major policies and initiatives that facilitated developments, or resulted in a turning point in the groundwater water management were examined to confirm the break points.

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 will revise this sentence as "seemed to be the most immediate choice to resist the drought". The measures of water licensing (1999) and irrigation efficiency improvements (1998) will be 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) will be 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 means 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. The ratio of deep to shallow water withdrawal negatively correlated with the shallow water table depth after 2002, which is absolutely different from that before (Figure 4(c)). However, the correlation of the negative relationship is much weak with a start point before 2002 (for example, the determine coefficient is only 0.11 with data from 2002 to 2013). As shown in Fig. 2(h), the deep groundwater withdrawal began to decrease slowly since 2002, while the shallow groundwater withdrawal continued to decrease rapidly as before. It indicates that people did not turn to shallow water with increasing shallow water table since the infrastructure of deep water with high quantity exploitation has 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 of 1st referee. 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 Kandassamy 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 the socio-hydrological system. We will 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, owing to the technological limitation, groundwater utilization was not be large scale. The volume of groundwater withdrawal was small relative to surface water, and irrigated area with groundwater was constrained to a small fraction of Cangzhou. As per the Taiji–Tire model, the human–groundwater relationship was weak, without any kind of sophisticated interactions. The human sub-system was not sensitive to the groundwater sub-system, and the groundwater sub-system was not affected by humans at a large scale. Therefore, the human-groundwater system can be considered stationary (or considered as in a steady state) without significant external drivers. In order to combat the drought in 1965, Cangzhou government proposed an expansive policy of groundwater utilization for the first time in history, and well drilling was rapidly accelerated. The relationship between the human and groundwater sub-systems has been enhanced since then, and the stationary condition was broken.

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: We will add some information including how the data set was divided into two periods as follow:

Meanwhile, the groundwater withdrawal decreased continually after 2002, although the annual precipitation kept stable. The groundwater withdrawal was significantly negatively correlated with annual precipitation before 2002, with the coefficient of determination (R2) 0.31. But the correlation significantly decreases if the period extends to the year after 2002 (the R2 is only 0.25 using data of 1976-2003). This decoupling reveals that water demand would no longer subtly vary with precipitation, with the extension of water-saving technologies and the construction of water-saving projects, as well as the restricted groundwater exploitation policies. Although there is an uncertainty as the precipitation did not vary significantly during 2003-2013, it indicates an increase in the ability to mitigate the 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 will add an introduction on community sensitivity at first:

It should be noted that the environmental protection actions during the recovery stage are usually conducted upon a high social awareness of environment risk or welfare, which was taken as a variable of the model (Di Baldassarre et al. 2013). Elshafei et al. (2014) uses a new concept of community sensitivity to represent this social awareness of environment welfare. Community sensitivity is the sensitivity of human society to the changing environment. The high community sensitivity represents that humans feel the pressure of environmental deterioration, and tend to restrain human activities to restore environmental health. The concept of community sensitivity was used to analyze the switching of the favoring between flood protection and wetlands in the Kissimmee River Basin, Florida (Chen et al. 2016).

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.

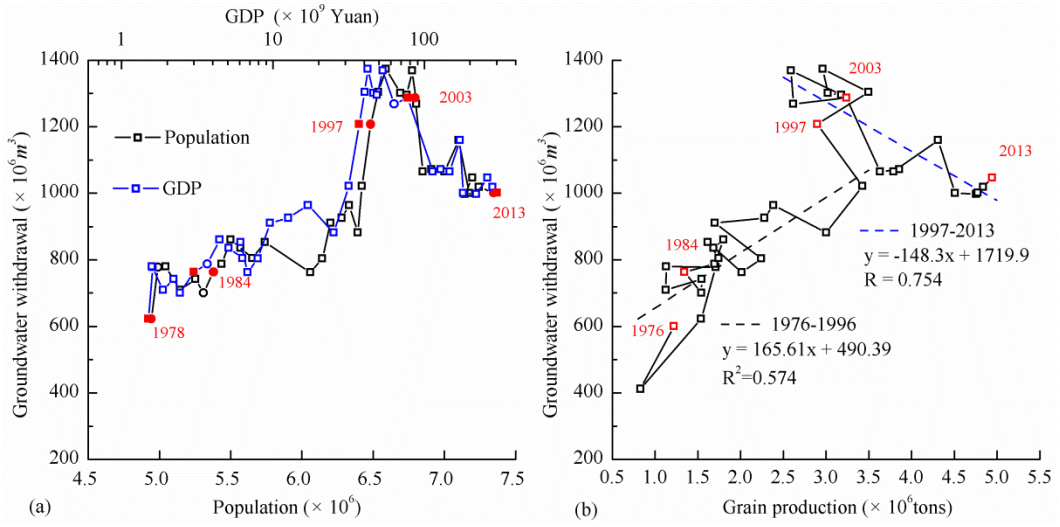
Response: We will add a statement as follow:

As economic development is always a primary target of the government and the society of Cangzhou, the mitigation measures of reallocating water from the economic development to the environment, which have been implemented in Murrumbidgee River basin (Kandasamy et al. 2014), is not acceptable. Therefore, new policies are established to restrict the groundwater exploitation. and improving and applying the water-saving technology are strongly encouraged aiming at protecting the environment on the premise of ensuring economic development after the drought, even that they are extremely costly compared to traditional groundwater exploitation. The social productive forces therefore reach a critical point.

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

Response: We will change the division into 1976-1996 and 1997-2013 in the revised manuscript, and add some information as follow:

Supported by theses productive forces, the grain production declined slightly during the drought 1997-2002, but grew rapidly again with decreasing groundwater utilization after 2002 (Fig. 2(b)). As a result, the grain production negatively correlated with the groundwater withdrawal during 1997-2013 (the correlation coefficient is -0.87), which is absolutely different from that during 1976-1996 (the correlation coefficient is 0.77) (Fig. 6(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 will revise 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 will revise it following the suggestion.

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

Response: We will add the closing parentheses.

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

Response: We will revise it following the suggestion.

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

Response: We will add the reference.

Reference:

Kandasamy, J., Sounthararajah, D., Sivabalan, P., Chanan, A., Vigneswaran, S. and Sivapalan, M. (2014) Socio-hydrologic drivers of the pendulum swing between agricultural development and environmental health: a case study from Murrumbidgee River basin, Australia. Hydrology And Earth System Sciences 18(3), 1027-1041.

Sivapalan, M. (2015) Debates-Perspectives on socio-hydrology: Changing water systems and the "tyranny of small problems"-Socio-hydrology. Water Resources Research 51(6), 4795-4805.

Liu, Y., Tian, F., Hu, H. and Sivapalan, M. (2014) Socio-hydrologic perspectives of the co-evolution of humans and water in the Tarim River basin, Western China: the Taiji–Tire model. Hydrology And Earth System Sciences 18(4), 1289-1303.

Baldassarre, G.D., Viglione, A., Carr, G., Kuil, L., Yan, K., Brandimarte, L. and Blöschl, G. (2015) Debates—Perspectives on socio-hydrology: Capturing feedbacks between physical and social processes. Water Resources Research 51(6), 4770-4781.

van Emmerik, T.H.M., Li, Z., Sivapalan, M., Pande, S., Kandasamy, J., Savenije, H.H.G., Chanan, A. and Vigneswaran, S. (2014) Socio-hydrologic modeling to understand and mediate the competition for water between agriculture development and environmental health: Murrumbidgee River basin, Australia. Hydrology And Earth System Sciences 18(10), 4239-4259.

Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Salinas, J.L. and Blöschl, G. (2013) Socio-hydrology: conceptualising human-flood interactions. Hydrology And Earth System Sciences 17(8), 3295-3303.

Elshafei, Y., Sivapalan, M., Tonts, M. and Hipsey, M.R. (2014) A prototype framework for models of socio-hydrology: identification of key feedback loops and parameterisation approach. Hydrology And Earth System Sciences 18(6), 2141-2166.

Chen, X., Wang, D., Tian, F. and Sivapalan, M. (2016) From channelization to restoration: Sociohydrologic modeling with changing community preferences in the Kissimmee River Basin, Florida. Water Resources Research 52(2), 1227-1244.

Sivapalan, M., Savenije, H.H.G. and Blöschl, G. (2012) Socio-hydrology: A new science of people and water. Hydrological Processes 26(8), 1270-1276.

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