# Spatio-temporal changes of groundwater and its management in the Yellow River Basin, China

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March 2020


*A thesis submitted to McGill University in partial fulfillment of the requirements for the degree of Doctor of Philosophy*

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# ABSTRACT

The worldwide depletion of groundwater resources as detected by the Gravity Recovery and Climate Experiment (GRACE) satellites is a striking warning of the need to manage groundwater resources more sustainably. However, effective and sustainable groundwater management has proven difficult due to the complex topology of aquifers and the dynamic interactions of groundwater with other components of the socio-ecological system (e.g. surface water, human beings). A comprehensive understanding of groundwater dynamics and its main drivers at multiple scales is a prerequisite to developing targeted management strategies to cope with regional groundwater depletion. The overarching goal of my thesis is to develop scientific knowledge about the spatio-temporal changes of groundwater storage and its socio-ecological drivers to help foster new strategies for the sustainable management of groundwater resources. I used the Yellow River Basin (YRB) in northern China as a case study system because the groundwater in this basin is important for local livelihoods, and local groundwater dynamics are experiencing unanticipated spatial and temporal changes due to changes in population, climate, irrigated agriculture, and water use by different sectors. The thesis is manuscript-based and consists of five main research articles in addition to the introduction (Chapter 1) and conclusion (Chapter 7) chapters. As groundwater dynamics vary with scale, I conducted my studies mainly at the basin and provincial scales. At the basin scale, I first employed GRACE satellite data to empirically measure changes in groundwater storage in the YRB over time (2003-2016) (Chapter 2). Then I conducted time stability analysis which integrates the spatial and temporal information of groundwater storage to propose corresponding strategies for regional management (Chapter 3). Further, I applied statistical analyses to a series of socio-ecological variables collected at the basin scale, such as water use, population density, precipitation, temperature, vegetation, and irrigated area, to identify the major factors associated with changes in groundwater storage in the YRB (Chapter 4). At the provincial scale, I used water budget analysis and social investigations to explore other possible factors (e.g. management practices) that may be contributing to groundwater changes in Ningxia province

(Chapter 5). Finally, I explored a way forward to improve groundwater governance in Ningxia by revealing the potential for community-based management to fill gaps in the existing water rights transfer system (Chapter 6). Overall, this transdisciplinary research has resulted in a comprehensive analysis of the groundwater status in the YRB and the drivers of groundwater changes over the past 14 years, which help to develop evidence-based suggestions for sustainable groundwater management in the YRB. The systematic research methods used, and management strategies proposed in this study can be applied in other similar arid agricultural watersheds where water management is a priority. This improved knowledge about groundwater management is critical as groundwater plays an increasingly important role in sustaining human livelihoods in the face of environmental uncertainties such as climate change.

# RESUMÉ

L'épuisement mondial des ressources en eaux souterraines, tel que détecté par les satellites GRACE, est un avertissement frappant quant à la nécessité de gérer les ressources en eaux souterraines de manière plus durable. Cependant, la gestion efficace et durable des eaux souterraines est difficile en raison de la topologie complexe des aquifères et des interactions dynamiques entre les eaux souterraines et d'autres composants des systèmes socio-écologiques tel que les eaux de surfaces et les humains. Il est nécessaire de développer une compréhension de la dynamique des eaux souterraines et de ses principaux facteurs à de multiples échelles afin d'élaborer des stratégies de gestion ciblées pour faire face à l'épuisement régional des eaux souterraines. L'objectif principal de ma thèse est de développer des connaissances scientifiques sur les changements spatio-temporels du stockage des eaux souterraines, et des facteurs socio-écologiques connexes afin de favoriser la mise en place de nouvelles stratégies pour la gestion durable des ressources d'eaux souterraines. J'ai utilisé le bassin du fleuve Jaune (YRB) dans le nord de la Chine comme système d'étude de cas. C'est un bon système d'étude pour évaluer mes questions cibles puisque les eaux souterraines de ce bassin sont importantes pour les moyens de subsistance locaux, et la dynamique des eaux souterraines locales connaît des changements spatiaux et temporels imprévus dus aux changements démographiques, climatiques et agriculture irrigués, ainsi que l'utilisation de l'eau par différents secteurs. Ma thèse est rédigée en structure de manuscrits et comprend cinq articles de recherche principaux en plus chapitre d'introduction (Chapitre 1) et un chapitre de conclusion (Chapitre 7). Étant donné que les dynamiques des eaux souterraines varient avec l'échelle, j'ai mené mes études principalement aux niveaux des bassins versants et des provinces. À l'échelle du bassin versant, j'ai d'abord utilisé les données satellitaires GRACE pour mesurer de manière empirique les changements dans le stockage des eaux souterraines dans le YRB au fil du temps (2003-2016) (Chapitre 2). Ensuite, j'ai effectué une analyse de stabilité temporelle intégrant les informations spatiales et temporelles sur le stockage des eaux souterraines afin de proposer des stratégies correspondantes pour la gestion régionale (Chapitre 3). J'ai appliqué des analyses statistiques

à une série de variables socio-écologiques collectées à l'échelle du bassin versant, telles que l'utilisation de l'eau, la densité de population, les précipitations, la température, la végétation et la zone irriguée, afin d'identifier les principaux facteurs associés aux changements de stockage des eaux souterraines dans le YRB (Chapitre 4). À l'échelle provinciale, j'ai utilisé l'analyse du bilan hydrique et des enquêtes sociales pour explorer d'autres facteurs (exemple : pratiques de gestion) susceptibles de contribuer à la modification des eaux souterraines dans la province de Ningxia (Chapitre 5). Enfin, j'ai exploré la voie à suivre pour améliorer la gouvernance des eaux souterraines dans le Ningxia en révélant le potentiel de la gestion communautaire pour combler les lacunes du système de transfert des droits d'utilisation de l'eau existant (Chapitre 6). Dans l'ensemble, cette recherche transdisciplinaire a abouti à une analyse complète de l'état des eaux souterraines dans le YRB et des facteurs de changement des eaux souterraines au cours des 14 dernières années. Ceci a permis de formuler des suggestions factuelles pour une gestion durable des eaux souterraines dans le YRB. Les méthodes de recherche systématiques utilisées et les stratégies de gestion proposées dans cette étude peuvent être appliquées à d'autres bassins versants agricoles arides similaires où la gestion de l'eau est une priorité. L'amélioration des connaissances en lien avec la gestion des eaux souterraines apportée par mes études est essentielle face aux incertitudes environnementales telles que le changement climatique, car les eaux souterraines jouent un rôle de plus en plus important dans le maintien des moyens de subsistance de l'homme.

# ACKNOWLEDGEMENTS

This thesis cannot be done without my two supervisors, Dr. Asim Bisawas and Dr. Elena Bennett. They are always supportive and patient. Thank you Asim for providing me the opportunity to pursue my degree in McGill and thank you for introducing new techniques so that I could have concrete contributions to the groundwater discipline. Thank you Elena for having me in a lovely lab with great minds, and providing best mentorship that I have ever experienced. Dr. Biswas and Dr. Bennett are like my PhD parents who provide me most critical support for this challenging journey. I especially appreciate that they give me freedom and enough patience so that I can delve into the topics I am interested in and be bold enough to explore across disciplines. I still remember the lab lecture given by Dr. Biswas about sample issues from which I felt the rigorousness of science. I remember hearing his teaching philosophy and wish myself to be a good teacher in the future who can teach well and trigger students' curiosities. I am so grateful for Dr. Bennett's tremendous support and patience at the latter part of my thesis research and writing. I am very impressive that she generously devotes so much time to caring for each of her students. She has established such a great lab in which we can discuss papers with talented colleagues, have intellectual exchanges with great scholars around the world, and have exciting lab journeys and gatherings (so many first-time experiences!). All of these brought me a very sweet memory from which I can always be recharged whenever I feel drained by the hard work. She is such a good model for me who makes good and important decisions and who lives a balanced life full of love and passion.

There are a lot of other great minds that I would like to show my gratitude. They include my committee members Dr. Bernhard Lehner, Dr. Gordon Hickey, my labmates Yakun, Wenjun, Duminda, Anna, Amaia, Barbara, Ciara, Daniel, Dalal, Erin, Jesse, Jillian, Julie, Juno, Karina, Klara, Marianne, Marie, Peter, a lot of other colleagues, like Aurélie, Wangyue, Sam, Ashlee, Jiahua, Gregory, Mariam, Maryam, Karoline, Kate, Deasy, Kimberly, Chris, Naresh, and many other members in peer writing group, as well as lovely instructors in writing centers, like Mrs. Renee Agnes Lallier, Ms. Marieve Isabel, and Dr. Yvonne Hung. I am also very grateful for all the colleagues in the Teaching and Learning Services, which provides me an opportunity to practice my leadership skills and learn from so many interesting and energetic colleagues.

During my research work, one of the important participants as well as great supporters are the people in Ningxia. They provide me warmest welcome and make me at home. They dissipated all my concerns about being isolated or being denied in a strange place. They are very helpful, talented and warm-hearted. After three-years' visits, we are like family and I feel Ningxia as my second home in China. I would especially thank NGOers here, including Mr. Hu Yanqin, Mr. Wang Yuxiao, Mr. Chenxu, and Mr. Gancao who gave me the most essential help and support for me to conduct my research in Ningxia. Mr. Hu is especially a model for me who is so passionate and considerate and is doing so great in helping rural people in Ningxia. This research also owes a big thank to water managers in Ningxia, who generously share their knowledge, their data and their work experiences. They are much more friendly and hard-working than I would expect, and they are all very kind and talented persons who are thinking of people in Ningxia. I wish to communicate further with them in the future with my concrete results and discuss opportunities to improve the water policy in Ningxia.

Lastly, the most fundamental supports came from my family. My parents have provided me such a warm and sweet family environment which always brings me energy for going through difficulties. Special thanks to my husband, Shuang, who is my strongest backing, my intellectual friend, and my soul mate. He is such a great thinker who always shares with me inspiring thoughts, reminds me of critical thinking, and is open to have discussions with me on interdisciplinary research. He is always patient to listen to my problems and crazy ideas, considerate about my health and mood, and sets a great example for me to grow as an independent researcher.

My journey of PhD would never be so wonderful and colorful without all of these persons' companion, love and support. This gratitude will be long kept in my heart, driving me upward to give my contributions back to the world.

# CONTRIBUTIONS TO KNOWLEDGE

There is an urgent need to advance scientific knowledge that supports effective strategies for sustainable groundwater management (Gorelick & Zheng, 2015; Dillon et al., 2019). Recent studies from GRACE satellites have shown that most of major aquifers in the dry parts of the world are experiencing rapid rates of groundwater depletion, which will fundamentally affect the health of groundwater-dependent ecosystems and the ability of the society to cope with climate extremes and other environmental changes (Famiglietti, 2014; Rodell et al., 2018). Understanding how groundwater storage is changing spatially and temporally in regional aquifers and how it is impacted by socio-ecological factors remain critical gaps for addressing groundwater depletion problems (Gorelick & Zheng, 2015; Dillon et al., 2019). This thesis uses the Yellow River Basin (YRB) in north of China as a case study to obtain transferrable knowledge to help fill this gap in our understanding.

My study deepens our understanding about the complexity of the spatio-temporal changes of groundwater resources. While considerable research in the past decades has helped to improve our knowledge about the natural processes involved in groundwater flow (Arnold et al., 1993; Mcdonald et al., 2003; Bear & Verruijt, 2012; Fatichi et al., 2016), there are limited studies for developing a comprehensive understanding of regional groundwater storage. In particular, we lack spatio-temporally explicit information on changes in groundwater resources (Vanham et al., 2018), in part due to data scarcity (Ireson et al., 2006; Dillon et al., 2019). In this thesis, I applied a newly emerging technology that can non-invasively examine the groundwater storage change with an unprecedentedly high resolution (Rodell et al., 2007; Richey et al., 2015). With this new technology, I comprehensively examined regional groundwater changes at multiple scales and timeframes in the YRB. I further developed a new method to integrate the spatial and temporal information to identify the areas where groundwater decreased at accelerated speed and the areas where the groundwater resource fluctuated more frequently. This knowledge serves as a theoretical support for decision-makers to balance the needs of human and nature through reallocation of water resources across space and over time.

Second, my study advances our knowledge about the interactions between groundwater and the socio-ecological systems. Previous studies have provided considerable evidence to demonstrate the detrimental impacts of groundwater depletion on the socio-ecological system (Konikow & Kendy, 2005; Aeschbach-Hertig & Gleeson, 2012), but corresponding studies about the impacts of socio-ecological factors on groundwater are limited, and most of them focus on groundwater quality (Lake et al., 2003; Duda et al., 2020), instead of groundwater quantity. Considering that groundwater resources are playing an increasingly critical role in providing freshwater supplies due to the dual stresses of climate change and growing population (Kundzewicz & Doell, 2009; Kløve et al., 2014), it is vital to maintain reliable availability of groundwater resource in the long run. This need for sustainable groundwater use requires empirical studies on the impacts of socio-ecological factors on groundwater storage (Qureshi et al., 2010; Collin & Melloul, 2001). In this thesis, I used a series of readily available socio-ecological indicators to develop accurate predictive models for spatial and temporal changes of groundwater resource in the YRB and identified the main social and ecological correlates of these trends between 2003 and 2016. I found that while temporal changes of groundwater storage were mainly driven by anthropogenic factors more than biophysical factors during 2003 and 2016, the spatial changes were driven by both. This knowledge may help researchers to reveal the causes of groundwater depletion in other similar dry areas and can help improve management by knowing when to focus on social causes versus when to focus on ecological ones.

Last but not least, my thesis strengthens the linkage between scientific knowledge and decision-making by presenting transdisciplinary research on groundwater management. Most existing studies on groundwater storage remain monodisciplinary, either focusing on biophysical results (Rodell et al., 2007; Döll et al., 2012) or resource governance (Burness & Brill, 2001; Madani & Dinar, 2012). However, sustainable management of groundwater will require connecting our biophysical and social understanding of the causes and consequences of groundwater change with knowledge about how to govern this important resource. A unique accomplishment of this thesis is to span across disciplines to link the biophysical knowledge on groundwater storage to the management potentials. Considering that biophysical methods are often good at presenting large-scale patterns of groundwater change, and social methods can be useful to uncover local-scale interactions between human activities and groundwater, my work purposely crossed scales to apply multidisciplinary methods to explore strategies for groundwater management. In basin-scale studies, I applied biophsyical methods to investigate the groundwater storage change with explicit interpretation for management strategies. For example, I proposed strategy zones that water managers can refer to in drafting site-specific plans for groundwater use. In local scale studies, I applied both biophysical and social methods to investigate the impact of past management on the current state of groundwater and to explore possible management solutions. With this broad evidence, I pointed out the management trap that the groundwater depletion would not necessarily be a result of inadequate implementation (e.g. restriction on groundwater use) but may also be due to wrong types of management (e.g. single-target water market which lacks system thinking). This research result is expected to provide new ways of thinking for local governments in addressing water scarcity problems.

Altogether, this thesis takes a transdisciplinary approach to study sustainable groundwater management across scales, using the Yellow River Basin in China as a model system. It has made theoretical and methodological contributions to the scientific knowledge about groundwater storage change and provided evidence-based strategies that may improve groundwater management in the long run.

# CONTRIBUTIONS OF AUTHORS

This thesis is manuscript-based and consists of five main research articles in addition to the introduction (Chapter 1) and conclusion (Chapter 7) chapters. The first three articles studied the spatio-temporal changes of groundwater storage and its socio-ecological factors in the basin scale (the Yellow River Basin) and the latter two articles delved into the groundwater management at the local scale in the Ningxia Hui autonomous region which is in the middle of the Yellow River Basin. I am the first author of all chapters, in which I took main charge of idea developments, data collection, data process and analysis, as well as writing. The contributions of co-authors for the five research manuscripts are as below.

- Chapter 2 (Published)

**Lin, M.,** Biswas, A. *, & Bennett, E. M. (2019). Spatio-temporal dynamics of groundwater storage changes in the Yellow River Basin. Journal of environmental management, 235, 84-95.

Asim Biswas provided guidance on the methods and results analysis. Elena Bennett contributed to structure and refinement of the manuscript.

- Chapter 3 (Published)

**Lin, M.,** Biswas, A. *, & Bennett, E. M. (2019). Identifying hotspots and representative monitoring area of groundwater changes with time stability analysis. Science of The Total Environment, 667, 419-426.

Asim Biswas contributed to the initial ideas of the manuscript and provided instructions on the innovative methods for the analysis. Elena Bennett contributed to the result presentation, English polishing and proofreading.

- Chapter 4 (Accepted with minor revision)

Lin, M., Bennett, E. M., & Biswas, A*. (Revisions in review). Examining socio-ecological factors of spatio-temporal groundwater changes in the Yellow River Basin, China. Science of The Total Environment.

Asim Biswas contributed to the data collection and data processing. Elena Bennett contributed to the development of ideas and structure of the manuscript.

- Chapter 5 (Under review for submission)

Lin, M. *, Bennett, E. M., & Biswas, A. (In review). Management-related reasons for groundwater storage change in dry areas. Water Resources Research (Target journal).

Elena Bennett contributed to the idea development, result analysis, and the structure of the manuscript. Asim Biswas contributed to the data processing and manuscript revision.

- Chapter 6 (Under review for submission)

Lin, M., Bennett, E. M. *, & Biswas, A. (In review). Triggering the power of community for less-visible common-pool resources: managing groundwater in the Water Rights Transfer system. Agricultural, Ecosystems & Environment (Target journal)

Elena Bennett provided guidance to the idea development, result validation, and the refinement of the manuscript. Asim Biswas contributed to the manuscript revision.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| CBM | Community-based Management |
| CPR | Common-pool Resources |
| GRACE | Gravity Recovery and Climate Experiment |
| Ningxia | Ningxia Hui Autonomous Region |
| NWRB | Ningxia Water Resources Bureau |
| PCA | Principal Component Analysis |
| TEA | Tradable Environmental Allowances |
| WRT | Water Rights Transfer system |
| YRB | Yellow River Basin |
| YRCC | Yellow River Conservancy Commission |
| NASA | National Aeronautics and Space Administration |

# 1 General introduction

## 1.1 Literature review and thesis rationale

### 1.1.1 Groundwater's importance to people and nature

Groundwater is the largest reserve of freshwater available for human use on the Earth. Aquifers store about 10.53 million $km^3$ of freshwater, more than 100 times of the total amount of freshwater in lakes and rivers (USGS, 2016). Groundwater serves more than two billion people as the primary source of water for drinking and irrigation (Siebert, 2010). Importantly, groundwater also acts as an emergency alternative to surface water bodies such as lakes and rivers, ensuring that people get enough water to sustain their lives even during times of drought (Gleeson, 2012; Godfrey et al., 2019).

Similarly, groundwater helps to maintain ecosystem function during periods of extreme weather (Taylor et al., 2013). For example, in the events of heavy rainfall, excessive water can infiltrate into underground aquifers, alleviating water erosion on the surface (Taylor et al., 2013; Tague et al., 2008). When there is extreme drought, aquifers can compensate for the limited surface water by providing much-needed water for plants and animals (Maxwell & Kollet, 2008; Scanlon et al., 2016). Groundwater is an important component of water cycle which can mediate the help sustain the resilience of regional ecosystems despite unanticipated disturbances (Griebler & Avramov, 2014; Christian-Smith, 2014; Green et al., 2011).

Groundwater is an essential water supply for both people and ecosystems, and its decline may cause serious problems for socio-ecological systems (Galloway & Burbey, 2011). When groundwater is depleted, aquifers are subject to consolidation, thus leading to land subsidence (Shen et al. 2006). The phenomenon of land subsidence may lead to the extensive destruction of man-made structures on the surface (Chai et al., 2004; Shen & Xu, 2011). Similarly, when groundwater adjacent to seashore is withdrawn, sea water can intrude into the soil and rock layers, extensively contaminating wells of drinking water and damaging the buildings (Ferguson & Gleeson, 2012; William, 2010). For all of these reasons, sustainable use of groundwater resources is critical to keep the integrity and resilience of ecosystems as well as the prosperity of human society (Shah et al., 2001; Rockström, 2017). This thesis therefore focuses on the scientific knowledge needed for a sustainable use of groundwater resources, the first pillar of which is to understand the spatio-temporal dynamics of groundwater storage.

### 1.1.2 The mystery of groundwater and the GRACE data

Although groundwater plays a vital role for sustaining lives and ecosystems, it is often a mystery to human beings with its typological complexity. Aquifers are widely distributed but are hidden underground with often complex structures. Just one meter distance can be the difference between one aquifer system and another (Welch & Allen, 2014). The connections between distinct aquifer systems can be adjusted when any of these systems experiences a change of water balance (Bresciani et al., 2016). For example, when people overly extract groundwater in one local aquifer system, the stress can be also imposed to nearby aquifer systems, leading to expanded groundwater depletion (Dahl, et al, 2007; Gleeson, 2012). The direction of the recharge can be also reverted, which would cause a fundamental change of groundwater dynamics (McKenzie & Voss, 2013; Gorelick & Zheng, 2015). These dynamic connections between aquifers underground make it hard for people to measure the change of local aquifers or craft determined plans to manage its use (Bresciani et al., 2016; Garven, 1995).

Despite the invisibility of groundwater and the dynamic connections between aquifer systems, it is still possible to improve our understanding of groundwater systems (Narasimhan, 2009). Since the nineteenth century, hydrogeologists have started applying Darcy's law, an empirical relationship for water flow through a porous medium, and its derivations to measure the dynamic of groundwater (Todd & Mays, 2005). In recent decades, a series of software (e.g. Modflow, GMS) has been developed to visualize and quantify the complex structure of the aquifers based on the different soil texture in each layer of rock formations (Gogu et al., 2001). Used together with geophysical techniques (e.g. well log, transient electromagnetic methods) (Kirsch, 2006), the computer-based techniques enable humans to have a coarse overview of the aquifers of interest and roughly predict the flow of groundwater in a certain region (He et al., 2007; Kushwaha et al., 2009).

Still, the storage of groundwater resources is difficult for people to quantify. Groundwater can be stored as deep as more than 10 km (USGS, 2016), which can be reached by drilling the wells or detected through traditional geophysical methods (Hasbrouck & Morgan, 2003). Gleeson et al. (2016) addressed the challenge of groundwater storage quantification using a combination geochemical, geologic, hydrologic and geospatial data sets with numerical simulations of groundwater and analysis in tritium ages. They uncovered that around 22.6 million $km^3$ of groundwater is stored in the upper 2 km of the earth's continental crust. Even so, the connections between regional groundwater systems make it hard to define the boundary of each aquifer and therefore difficult to determine the absolute storage. Also, the high cost of well drilling (which can be up to 1 million dollars) and the impossibility to drill wells on every inch of the land makes the data-scarcity a fundamental and daunting barrier for groundwater studies (Gorelick & Zheng, 2015). There requires a comprehensive examination of the regional water system, which is currently inaccurate, labor-intensive and constrained by the data scarcity problem (Taylor et al., 2013).

The emergence of satellite-based technology has provided a new way to probe the groundwater storage. In March 2002, NASA launched a twin satellite for measuring the monthly gravity anomalies on the Earth based on their changes in distance between each other driven by variable gravity forces (Tapley & Reigber, 2002; Strassberg et al., 2007). These gravity variations at month scale are mostly due to the changes in terrestrial water storage, thus can be used to study groundwater dynamics. This twin satellite, namely Gravity Recovery and Climate Experiment (GRACE) satellites, for the first time, enables humans to non-invasively investigate the change of groundwater storage on the Earth with an unprecedentedly fine resolution. A considerable progress of groundwater studies based on the GRACE satellite data has since been promoted (Rodell et al., 2007; Voss et al., 2013; Ran et al., 2013; Gleeson et al., 2012; Richey et al., 2015; Chen et al., 2016; Rodell et al., 2018; Frappart & Ramillien, 2018). Until 2017, the GRACE satellite has run for more than 14 full years with monthly data measured on the main continents of the Earth (Famiglietti, 2014) and is expected to continue with a new round of project (Flechtner et al., 2018). Fundamentally reducing the barrier of data scarcity, the GRACE project opens a new era for hydrogeological studies (Frappart & Ramillien, 2018). In this thesis, I will take the advantage of this new technology to examine the existing situation of regional groundwater storage and analyze the implication of this information for future management.

### 1.1.3 Groundwater depletion and management need

Data accuracy is one of the traditional barriers for groundwater management (Narasimhan, 2009). While changes in groundwater storage in a single local aquifer system can be roughly inferred from well tables (Fan & Miguez-Macho, 2013), the cost of drilling wells, the difficulty of doing so over large areas, and the well-known potential for data inconsistency incurred by different measurements make this an unreliable, or even impossible method for regional or global groundwater studies (Gorelick & Zheng, 2015; De Graaf et al., 2015).

Since the launch of GRACE satellite, a series of GRACE-based studies have uncovered a surprisingly world-wide depletion of groundwater resource. For example, Rodell et al (2009) revealed a significant depletion of groundwater storage in northwestern India. Later, similar depletion has been detected in Central and South-west of the USA (Scanlon et al., 2012), Western Australia (Tregoning et al., 2012), Middle East (Voss et al., 2013), and North China (Feng et al., 2013). Almost all the important aquifers on Earth are being depleted (Wada et al., 2014; Famiglietti et al., 2011). Evidences demonstrated that the severe depletion of groundwater can lead and has led to a series of socio-ecological problems, among many are water scarcity (Konikow & Kendy, 2005), wetland shrinkage (Bernadez et al., 1993), ecosystem degradation (National Research Council, 2005), river dry-up (Bartolino & Cunningham, 2003), crop failures (Kahlown & Ashraf, 2005), sea water intrusion (Ergil, 2000), land subsidence (Galloway & Burbey, 2011; Chai, et al., 2004) and water use conflicts (Voss et al., 2013). An increasing number of scientists and policy-makers have realized the importance of groundwater for livelihoods and are looking for strategies to alleviate groundwater stress. Still, the progress needs to continue.

Specifically, concrete measures to reverse this decreasing trend of groundwater storage require further investigations (Gorelick & Zheng, 2015). Rodell (2018) attributed the possible reasons of regional groundwater depletion to groundwater consumption. But how we shall curb the groundwater consumption requires more detailed information in space and time. Some cases of excessive groundwater consumption may be due to the increased population with decreased water accessibility in the same location, while in other cases, it may be due to the reallocation of water resources across space with land use change (Carter & Parker, 2009; Cheema et al., 2014; Gleeson et al., 2012; Scanlon et al., 2005). Understanding the change of groundwater storage and its drivers in space and time respectively is fundamentally important for crafting targeted measures. This knowledge is especially important for groundwater management in developing countries where the investment on groundwater is limited and can only be distributed on priority issues (Shah, 2005).

Meanwhile, as climate change proceeds and human population booms, groundwater management is facing new kinds of challenges (Strauch et al., 2008). Increasing food demand with the expansion of irrigated land stimulates more reliance on groundwater especially in dry areas (Dalin et al., 2017). Urbanization with road constructions reduces the recharge from the surface to groundwater which may exacerbate the existing situation of groundwater depletion (Jat et al., 2009). Industrialization boosts the use of groundwater and at the same time poses a threat to the quality of groundwater in aquifers (Calderhead et al., 2012). The large-scale change of the precipitation pattern and increasing frequency of extreme weather is depleting groundwater's capacity for mitigating the impacts of climate change (Yardley, 2007). There is a pressing need to obtain a comprehensive understanding of the human and nature interaction with groundwater in addition to the knowledge on the change of groundwater storage itself.

### 1.1.4 Human and nature interaction with groundwater

Existing studies have pointed out the profound impacts of human footprint on groundwater (Changming, 2001; Braadbaart & Braadbaart, 1997; Weiskel et al., 2007; Ashraf et al., 2017). Increasing needs from a rapidly growing population and the economic development have put tremendous stress on groundwater (Rodell et al., 2018, Dalin et al., 2017). Extraction for various uses including industrial development (Chaussard et al., 2013; Rahm & Riha, 2012), agricultural irrigation (Hellegers, Zilberman & Van, 2001; Scanlon et al., 2005; Shah, 2007), and urbanization (Foster, 1990; Naik et al., 2008) can lead to a large deficit between recharge and discharge and may be a significant cause of water level declines (Döll et al., 2012).

Even though human actions are one of the most important causes of groundwater decline (Hancock, 2002), biophysical factors such as climate, physiographic and hydrologic factors can also play substantial roles in changing groundwater levels (Pan et al., 2016; Kløve et al., 2014). For example, mean annual runoff, air temperature, precipitation, and an index of ground-water exfiltration potential have affected groundwater recharge in the eastern United States (Nolan et al. 2007); while geologic, geomorphoclimatic (topography and climate) and anthropogenic factors were identified to be the major factors influencing the groundwater storage in Northern Xinjiang of China (Zhu and Wang, 2016).

Interactions among the anthropogenic and biophysical factors can make it difficult to discern the ultimate causes of groundwater decline. For example, in the northern part of the Yellow River Basin (YRB), the groundwater level showed an explicit drop (at a rate more than 1m/year) after a continuous drought during 1970s (Fu et al., 2004). Increasing temperature would increase the water evapotranspiration, accelerating the groundwater discharge (Zhang & Schilling, 2006; Xu & Chen, 2005). Moreover, the scarcity of surface water during the drought events increased the human use of groundwater (Castle et al., 2014). The decline of groundwater in this region could be attributed to a combination of biophysical and anthropogenic factors, and the interactions among these factors. This thesis would take the challenge of combing out the most responsible factors for the groundwater decline and quantify their relationships with spatio-temporal dynamics of groundwater storage so that we can determine possible levers to maintain sustainable groundwater use.

### 1.1.5 Institutional design for groundwater management

In addition to a better understanding of groundwater dynamics and its contributing factors, policy instruments also require careful examinations for groundwater management (Van Steenbergen & Shah, 2003). Existing policy instruments can be grouped into three categories: regulatory (e.g. water use permit), economic (e.g. water right trade), and voluntary (e.g. self-governance, collaborative monitoring) (Theesfeld, 2010). Traditional institutions would either apply the regulatory or economic instruments (Closas & Villholth, 2019). However, the current extensive phenomenon of groundwater depletion indicates that traditional management measures are inadequate in sustaining this resource (Wegerich, 2006; Sophocleous, 2010).

Groundwater has many special attributes that makes the governance with traditional policy instruments dauntingly challenging (Shah, 2005; Shah, 2007). The first reason is that groundwater is a common-pool resource (CPR) (Burness & Brill, 2001) and is not very visible. The CPR has typically no way to exclude some people from using it (it is not privately-owned), making it more subject to overuse. Although the stresses imposed by the common people accumulate, none of them singularly bears responsibility for the costs of overuse (Ostrom et al., 1994; Ostrom et al., 1999). This attribute of CPR and the hidden location of aquifers underground make the monitoring cost for groundwater prohibitively high (Agrawal & Goyal, 2001). Managers could hardly identify illegally drilled wells in households if not being notified, and the control of the groundwater withdrawal from scattered wells is either labor-intensive or costly. Illegally drilled wells and excessive groundwater consumption are therefore prevalent in developing countries (Ayvaz & Karahan, 2008; De Stefano & Lopez-Gunn, 2012). Groundwater overexploitation can be even exacerbated by an increasing need of water resource under a drying climate or a deteriorating quality of surface water (De Stefano & Lopez-Gunn, 2012). This attribute of groundwater makes the regulatory and economic policy instruments pale. As Theesfeld (2010) pointed out, groundwater governance must rely on voluntary compliance.

Second, groundwater has fuzzy boundaries and scale effects (Bresciani et al., 2016). Because aquifers are dynamically connected, local groundwater systems can have hydrological exchange with neighboring systems, thus impacting regional groundwater distribution. A deep aquifer system with long flow paths between areas of recharge and discharge may be overlain by, and in hydraulic connection with, several shallow, small-size, aquifer systems (Alley et al., 1999). Thus, the result examined in a small region may be different if seen in a larger size (Dagan, 1986). With this regard, the definition of a groundwater system is relatively subjective and depends in part on the scale of a study. The difficulty of discerning the system's boundary and having different results at multiple scales make it hard to specify administrative responsibilities. It is therefore very important to involve multi-scale stakeholders to manage the system (Blomquist and Schlager, 2005)

Third, impacts on groundwater are often irreversible, or at least difficult to reverse (Theesfeld, 2010). Aquifers usually store water in rock layers with certain porosity (Niwas & Singhal, 1981). Once the aquifers have been depleted for a certain amount of time, the pores can be squeezed out by the gravity and the rock layers can no longer store water (Vouillamoz et al., 2015). It means that we may lose the "underground reservoir" forever if the groundwater depletion continues. This loss of places to store water underground means a loss of the ability for the ecosystem to mitigate the climate extremes and provide emergency water when the surface water is drying up, which crosses out the back-up plan for human-beings to survive under the threat of environmental uncertainties (Issar, 2008). It is therefore necessary to have strategic planning in using groundwater for the long term.

With all these regards, the traditional policy instruments may have system weaknesses in managing groundwater in a sustainable manner. For example, the regulatory instrument like water use permit fails to effectively restrict the illegal exploitation of groundwater (Nowlan, 2005). Establishing an accurate monitoring network for the government requires a considerable amount of investment in time and labor which for some developing countries is currently impossible. The economic instrument like water market is more popular in a recent decade (Kemper, 2007) yet shows system weaknesses for groundwater management as well (Dietz et al., 2003; Rose, 2002).

Water users are allocated with initial quota of water rights and are allowed to trade the quota they haven't used. Because of the fuzzy boundary and scale effects, groundwater is usually vaguely defined in the water market, thus cannot benefit from the market-driven reallocation of the resource (Theesfeld, 2010). At the same time, both the regulatory and economic instruments have limited influence in regulating individual behavior in the long term. The main motivator for a water permit system is to avoid punishment which may not encourage the innovation in water-saving technology and people may not compulsorily save the water without a strict rule (Giordano, 2009). The main motivator for a water market system is economic profit, which influences wider groups of people than the water traders. It is much needed to have a closer investigation of where this policy instrument works and where it doesn't and how we can take actions to effectively prevent the irreversible damage of the groundwater depletion to our socio-ecological system.

In summary, the scientific knowledge that remains to be acquired for sustainable groundwater management includes explicit information on groundwater dynamics in space and time at multiple scales, a comprehensive analysis of socio-ecological factors contributing to groundwater change and an exploration of better institutional design for managing groundwater in a sustainable manner. This thesis would aim to fill the abovementioned gaps in scientific knowledge to contribute to an alleviation of global groundwater stress and a strategic plan for a water-secure society.

## 1.2 The study area and case context

### 1.2.1 The Yellow River Basin

My study area is the Yellow River Basin (YRB), the cradle of Chinese civilization (Liu et al., 2008). The river nourishes more than 120 million people (12 percent of China's population) and provides water to more than 200,000 km$^2$ of arable land (15 percent of China's farmland) and generates nearly 8 trillion yuan per year from agriculture on this land (14 percent of China's GDP) (Gao & Yao, 2013; Moore, 2014; International Monetary Fund, 2019). The basin produces the majority of China's wheat, approximately half its coal, and one fourth of its oil (Moore, 2014)

This river basin is highly heterogeneous. It has three distinct parts with different elevations, slopes, and topography. The upper reach consists of the Tibetan Plateau where the Yellow River begins. With steep slopes, the runoff in this reach contributes 56% of the river flow (Zhu et al., 2004). In the middle reach, the topography changes to plains and desert, with a high evaporation rate, several times higher than that of precipitation. In the middle reach, the Yellow River has a U-shape bend, changing flow direction from northward to southward. Many major tributaries, such as the Fenhe and Weihe, join the Yellow River in the middle reach, contributing 43% of the total runoff. Before flowing to the lower reach, the river cuts through the Loess Plateau, from which it picks up silt and carries it to the downstream. This large amount of silt is then spilled at the river mouth onto the flat North China Plain, forming the Yellow River Delta.

Despite the Chinese government's effective efforts to manage the river water of the YRB in the past, the sustainable management of underlying aquifers, which have frequent water exchanges with river water, remains challenging. Given the heterogeneous geography in the river basin, the Yellow River is traditionally difficult to manage with drought frequently happening in the upper stream and flood occurring in the lower stream (Huang et al., 2007; Shiau et al., 2007). In recent decades, the Chinese government has established a series of management strategies, including constructing dams and water channels, to reallocate the spatial and temporal distribution of the Yellow River water (Shu & Finlayson, 1993; Yang et al., 2008), having effectively reduced the frequency of the flood and drought events (Huang et al., 2015; Wang et al., 2015). A comprehensive network of river stations has made it possible to monitor the change of river flow in real-time (Wu & Xia, 2014). However, the problem of groundwater remains. Currently, we still lack a fine-scale monitoring network of groundwater flow. At the same time, signs of serious groundwater depletion have been revealed in the lower reach, like land subsidence (Dong, 2014) and sea water intrusion (Cui et al., 2010). As the frequency of climate extremes increases, groundwater will play an increasing role for the livelihoods of the YRB communities. There is a pressing need to understand the spatio-temporal dynamics of groundwater storage in the YRB and reasons of the groundwater depletion to assist in the effective management for the sustainable use of groundwater.

### 1.2.2 Water Rights Transfer system in Ningxia

Ningxia autonomous region, which is referred to as Ningxia in this thesis, is in the center of the YRB. It is the only province in the YRB the entirety of which is embedded into the Yellow River Basin. It therefore can be a good sub-scale region for the interaction of manmanagement practices and groundwater changes in the YRB. Also, it is one of the most water stressed regions in China. The water available to each person, 176 $m^3$ per year, is just 1/12 of the national average for China (NWRB, 2016; Yang & Zehnder, 2001). Ninety percent of this water supply comes from the Yellow River. However, "not all the water passing through Ningxia belongs to Ningxia" (Li et al., 2016). To equitably distribute water among all nine provinces along the Yellow River, the Yellow River Bureau assigns a certain amount of water available to use within each province. For Ningxia, the water quota is 4 billion cubic meter per year (Moore, 2014), and the region is already straining against this limit, given demands for water to meet industrial, agricultural, residential and ecological needs. By 2012, Ningxia was already using nearly all its annual allotment (Bebb, 2011); further growth in agriculture, industry, and population threatens to increase water demand (Li et al., 2008).

To seek further development without aggravating existing water stress, Ningxia applies an innovative water management system. This system is called the Water Rights Transfer (WRT) system. It is like a water market in which the rights of using water have been quantified and can be traded. Slightly different from the water market, the WRT is right now still regulated by the government instead of the market. The government plays the role of an intermediary agent who facilitates the exchange of water use rights between the agricultural sector and the industrial sector. Also, the trade is mostly unidirectional, from agriculture to industry.

These one-way transfers of water use rights are helpful for the structural transformation and reducing surface water use (Niu, 2012). Ningxia is a relatively less developed province in China, with GDP per capita below the national average (National Bureau of Statistics of China, 2018). The local government aims at transforming the sector structure from agricultural-dominant to industrial-dominant (Chen, 2006). At the same time, the water use efficiency in industry is much higher than in agriculture with the economic value per unit water use in industry is 50 times higher than agriculture (only 0.5 dollar/ $m^3$) (Liu et al., 2013). Transferring water from agriculture to industry would potentially increase the water efficiency. Furthermore, the local government would use industrial payments to construct water-saving infrastructures for agriculture (e.g. canal lining and drip irrigation), helping to increase the water use efficiency in agriculture at the same time (Niu, 2012; Bebb, 2011).

However, how this system would affect groundwater is unknown. Groundwater is especially important for the dry areas like Ningxia, which is at the forefront of water stress and will rely on groundwater to mediate climate extremes like drought (Lu et al., 2016). Because of groundwater's extensive distribution, it also serves as an essential drinking water source for the places distant from open waters (Qi & Chen, 1998; Li et al., 2010). Failure in managing this resource would not only devastate the aquifer system but may also bring harm to the whole water cycle and socio-ecosystem (Foster & Chilton, 2003; Griebler & Avramov, 2014).

## 1.3 Thesis objectives and outline

The overarching goal of my thesis is to develop scientific knowledge about the groundwater storage, its driving factors and related institutional design to assist in the long-term management of groundwater resources. This research aims at three main objectives: 1) Analyzing the spatio-temporal dynamics of groundwater change in the YRB; 2) Understanding the socio-ecological factors affecting groundwater change in the YRB; 3) Exploring effective measures to manage groundwater in the YRB.

The thesis consists of seven chapters. Chapter 1 reviews the existing scientific knowledge about groundwater storage, its changing factors and related management schemes, and states the rationale and objectives of the research. Chapter 2, 3 & 4 apply quantitative methods (e.g. remote sensing, geostatistical analysis) to study the spatio-temporal changes of groundwater storage and its driving factors in the YRB. Chapter 5 & 6 apply a mix of quantitative and qualitative methods to investigate the management-related reasons of groundwater storage change at the local scale and explore alternative and potentially better strategies for sustainable governance of groundwater resources in Ningxia. Chapter 7 presents a comprehensive discussion of all the findings in Chapters 2 to 6, and their implications. The body of the thesis is between Chapter 2 and Chapter 6, each of which is explained below:

Chapter 2 examines how groundwater storage changes spatially and temporally. I employed the GRACE satellite data to investigate the spatio-temporal changes of groundwater storage at multiple scales (i.e. basin, reach, provincial) during 2003 to 2016 in the YRB and identified the hotspots of the groundwater depletion within the basin.

Chapter 3 interprets the spatio-temporal information of groundwater dynamics from management angle. I innovatively applied the time stability analysis to integrate the spatial and temporal information of groundwater dynamics in the YRB and identified the clustered sub-regions that display different patterns of groundwater dynamics (i.e. different changing trends and different extents of fluctuations) and require different management strategies.

Chapter 4 investigates how socio-ecological factors influence groundwater storage change. I quantified the relationship between groundwater and main socio-ecological factors in time and space scale respectively and identified the main factors contributing to spatial and temporal changes of groundwater in the Yellow River Basin (YRB).

Chapter 5 reveals the management-related reasons for the change of groundwater storage at the local scale. I conducted interdisciplinary research (e.g. water budget analysis and interviews) to examine the possible reasons of the groundwater depletion in Ningxia.

Chapter 6 explores an improved governance for groundwater resources in the long term. I used a mix of social investigation methods (i.e. questionnaires, interviews, focus group discussions, stakeholder analysis) to analyze the weaknesses of current policy instruments for managing groundwater and proposed strategies necessary to engage the community in groundwater governance.

# 2 Spatio-temporal dynamics of groundwater storage in the Yellow River Basin

**Highlight**

- We quantified recent spatio-temporal dynamics of GRACE-based groundwater storage in the YRB.
- We analyzed groundwater dynamics and their potential causes at multiple scales.
- Groundwater showed declining pattern at all scales; provincial, reaches and basin.
- Stronger groundwater declines after 2010 at scales indicated critical need for management.
- The change in hot-spots of groundwater decline was related to human footprint.

## Abstract

Groundwater is an important source of water supply and ecosystem resilience. However, limited information on spatio-temporal dynamics makes a complete assessment of available groundwater resources difficult, impairing sustainable water management. The Gravity Recovery and Climate Experiment mission (GRACE) has recently made this possible. In this study, we used the Yellow River Basin (YRB) as a model system to explore the use of spatio-temporal dynamics information about groundwater change derived from the GRACE datasets for regional groundwater management. Results suggest that groundwater storage over the whole basin decreased significantly since 2010 (2010-2016) and showed stronger fluctuations than the time before (2003-2009). Additionally, locations which exhibited higher variabilities over time generally showed radical decrease of groundwater storage. The results indicated that groundwater depletion may reduce the aquifers' function for ecosystem resilience, thus posing risks to the ecosystem of the YRB and threatening its people to climate change and extreme events. Our hotspots analysis also indicates that human factors (e.g. groundwater consumption) become dominant in determining the groundwater change pattern over climatic variations. We therefore call for more attention to groundwater in developing sustainable water management strategies and suggest a closer cooperation of neighboring provinces in the YRB to have a reciprocal strategic plan for water regulation, protection, and management.

**Keywords:** groundwater; spatio-temporal analysis; regional management; Yellow River Basin; GRACE

## 2.1 Introduction

Groundwater is the primary reserve of freshwater available for human use (USGS, 2016). It acts as an underground reservoir for surface water bodies such as wetlands, lakes and rivers and serves the needs of >2 billion people for drinking water and irrigation (Alley, 2002; USGS, 2016). Due to slow response to the cycles of rainfall and drought than surface water, it serves as a buffer, providing extra water when surface waters dry up or extra space to store water when precipitation is excessive, thus enhancing ecological resilience (Robins & Fergusson, 2014; Rockström et al., 2014).

Despite its importance, groundwater has received less attention in scientific research and management than surface water (Sanford et al., 2006; Jha et al., 2007). Lack of accurate measures of available groundwater in any location (Gleeson et al., 2016) and its spatial and temporal changes adds on to the challenge in studying and managing groundwater (Unland et al., 2013). Without this information, it is difficult to determine the capacity of groundwater resources, and to draft appropriate management plans.

The limited understanding about the spatio-temporal dynamics of groundwater results from both the intrinsic features of groundwater as well as a lack of research investment (Sanford et al., 2006). Groundwater has traditionally been more difficult to measure and monitor than surface water, due to the expense and difficulty of drilling monitoring wells (Ireson, Makropoulos & Maksimovic, 2006; Gleeson et al., 2016). Groundwater has a complex recharge-discharge system making accurate spatially explicit monitoring difficult. In addition, the complexity and fluctuations from the seasonal changes in the precipitation and river runoff make the temporal monitoring more challenging (Chang et al., 2017). However, improved understanding of changes in groundwater storage across space and through time is critical for improving water management (Alley, 2002; Taylor & Alley, 2001).

With the launch of NASA's Gravity Recovery and Climate Experiment mission (GRACE) in 2002, groundwater changes can now be monitored with less human labor over a large area using a twin satellite (Bhanja et al., 2017). Researchers have demonstrated its promising application in monitoring groundwater at the global (Wada et al., 2010; Famiglietti, 2014; Richey et al., 2015) as well as at regional scales (Rodell et al., 2007; Voss et al., 2013). For example, Rodell, Velicogna and Famiglietti (2009) identified a significant depletion of groundwater storage in northwestern India at a mean rate of 4.0±1.0 cm/yr equivalent height of water using GRACE. More recently, Rodell et al. (2018) used the GRACE data to quantify the terrestrial water storage in 34 regions around the globe and identified 7 regions among them that have significantly lost freshwater storage in the past 14 years (March 2002~April 2016) mainly due to groundwater depletion. Other studies demonstrated the accuracy of using GRACE to measure groundwater change. For instance, Landerer and Swenson (2012) suggested that basin-scale gain factor as well as the grid-point gain factor can reduce the Root Mean Square Difference of the unscaled estimates to within 20% or less in regions like Huai River Basin, a tributary of the Yellow River Basin. Huang et al. (2015) reported that the groundwater storage anomalies estimated from GRACE data (2003–2013) was in agreement with those estimated from *in situ* observations (2005–2010) for both the Piedmont Plain ($R^2$= 0.91) and East Central Plain ($R^2$= 0.75) in North China. They have also proved that GRACE data could detect changes in both shallow and deep groundwater layers.

Despite the opportunity of quantifying spatio-temporal dynamics of groundwater change using available data from GRACE, current studies have not yet deliberately discussed the implication of groundwater changes for improving water management. Most GRACE-based groundwater studies generally summarized main aquifers around the world and compare groundwater change with precipitation, evapotranspiration or other hydraulic parameters individually (Alley et al., 2018, Khaki et al., 2018; Ndehedehe et al., 2018). Few of these studies presented some connections with management: i.e. discussed the changes based on management units, analyzed the reasons of changes with regards to both human and natural factors, or explored the implications of groundwater change for sustainable water management (Giordano et al., 2004). However, usually the water management practices are implemented through administratively-defined regions (e.g. provinces), and the water stress usually result from the synergetic effects of both human and nature (Rodell et al., 2018). Nevertheless, the upstream-downstream conflicts remain one of the barriers for sustainable management (Ray & Bijarnia, 2006; Voss et al., 2013).

While previous studies using GRACE have explored the regional groundwater changes in various river basins around the world including Mississippi River Basin (USA) (Rodell et al., 2007), Colorado River Basin (USA) (Castle et al., 2014), Canning Basin (Australia) (Munier et al., 2012), Congo basin (Africa) (Ndehedehe et al., 2018), there is seldom thorough assessment of groundwater storage changes in Yellow River Basin (YRB) of northern China (Richey et al., 2015). The YRB is one of the most important basins around the world covering nine provinces (partial or full) in China and nourishes >120 million peoples. Groundwater is a valuable resource in this region, not only serving as an increasingly important water supply for drinking and irrigation, but also as a mitigating agent that alleviates extreme events of drought and flood (Yu, 2002; Nie et al., 2015, Craddock et al., 2010; Varis et al., 2014). The average groundwater extraction is more than 13.2 billion $m^3$ per year, accounting for 26% of the total water use in the region (Giordano et al., 2004). Unfortunately, recent years have witnessed signs of groundwater stress, including reduced river base flow, declines of well levels, and land subsidence (Cai & Rosegrant, 2004; Liu & Xia, 2004). Therefore, it is imperative to examine the groundwater changes in the YRB to ensure sustainable development for the whole basin. The water management in the YRB is overseen by the Yellow River Conservancy Commission (YRCC), and detailed administrative policies are adjusted and implemented province wise. Therefore, apart from basin level studies, it is necessary to examine the spatio-temporal dynamics at provincial level to provide clear suggestions for each management unit. At the same time, the YRB are usually divided into three reaches (upper, middle and lower reaches) differing in topography, landscapes, climates, and land uses (Yu, 2002; Liu & Di, 2007). These heterogeneities in topography and geography also lead to distinct socio-economic conditions among reaches. Therefore, it is possible that the synergetic effects of human and natural factors will be different among these reaches. With this regard, it is also important to examine the spatio-temporal dynamics of groundwater in the YRB at reach level.

The objectives of this study are to employ GRACE satellite-based groundwater change data to quantify spatio-temporal dynamics at multiple spatial scales (basin, reach and provincial scales) in the YRB between 2003-2016 to better understand patterns in groundwater storage and explore their implications for regional water management.

## 2.2 Study area and data

### 2.2.1 Yellow River Basin

The YRB (0-4800m), located in the north of China, is one of the largest river basins in the world, with an estimated recharge area of 795,000 $km^2$ (Figure 2.1). Based on topographical variations (high west and low east), it is commonly divided into three reaches: upper, middle and lower reaches (Yu, 2002; Liu & Di, 2007). From an altitude around 4,800 m at the source in Tibet-Plateau (Point A in the Figure 2.1), it descends to 1,000 m at Hekou County (B), 400 m at Zhengzhou City (C), ultimately flowing to the Bohai Sea (D) (Figure 2.1). The upper reach receives water from melted glaciers on the Qinghai Tibet Plateau. Because of the high disparities in altitude from the upper reach to middle reach, the latter suffers from high water erosion with infertile lands in the loess plateau and ordos plateau. The lower reach consists of alluvial plains, which are good for growing crops, and therefore features high population density and urban areas compared with reaches upstream. However, lower reach suffers from flood events the most.

There are nine provinces along the river – Qinghai, Sichuan, Gansu, Ningxia Hui (or Ningxia), Shaanxi, Neimenggu, Shanxi, Henan, and Shandong (Figure 2.1). The river currently nourishes more than 120 million people (12 percent of China's population), waters more than 200,000 km$^2$ arable land (15 percent of China's farmland), generates nearly 8 trillion yuan per year (14 percent of China's GDP), and is an important cultural and historical icon (Hays, 2013; Yellow River Conservancy Commission, 2016).

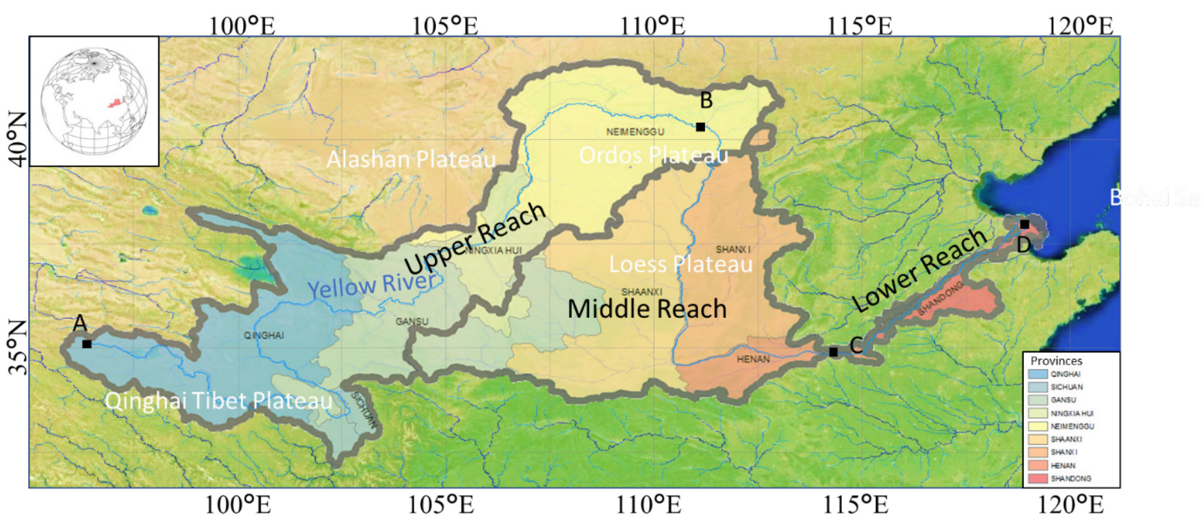



**Figure 2.1 Yellow River Basin, the study area.** The bold lines delineate three reaches (upper, middle and lower reach). The colored polygons represent nine provinces in the YRB. The blue curves represent the flow accumulation across the basin. The main flow path of the Yellow River is boldfaced by a continuous blue curve from Qinghai Tibet Plateau passing Alashan Plateau, Ordos Plateau and Loess Plateau, and ultimately meeting the Bohai Sea. Point A, B, C and D are the key

points of the Yellow River: AB is the upstream, BC is the middle stream, and CD is the downstream (revised from Gassert et al., 2013).

### 2.2.2 Data sources

Terrestrial water storage is the summation of water storage in different compartments, including groundwater, soil moisture, surface water, snow, and ice. We used the Terrestrial Water Equivalence (unit:cm) extracted from the GRACE RL-05 monthly grid data to represent the Terrestrial Water Storage (TWS). The data is available at http://grace.jpl.nasa.gov and supported by the NASA MEASUREs Program (Swenson, 2012; Landerer & Swenson, 2012; Swenson & Wahr, 2006). Matlab program was developed to extract the data within the YRB from Jan. 2003 to Dec. 2016. For the missing data in some months due to technical issues such as battery management (see http://grace.jpl.nasa.gov/data/grace-months), we interpolated the data using linear interpolation based on the neighboring months.

We obtained the remaining water compartments in the terrestrial water storage (apart from the groundwater) from GLDAS_NOAH10_M.001 (Rodell & Beaudoing, 2007), which includes a series of land surface parameters simulated from the Noah 2.7.1 model in the Global Land Data Assimilation System (GLDAS). This monthly dataset is in 1.0 degree resolution and ranges from 1979 to the present. It was acquired as part of the mission of NASA's Earth Science Division and archived and distributed by the Goddard Earth Sciences Data and Information Services Center (GESDIC: https://disc.gsfc.nasa.gov). We chose the corresponding variables (Plant Canopy Surface water, Average Soil Moisture and Accumulate Snow) from GLDAS representing changes of Surface Water Storage (△SWS), Soil Moisture (△SM) and Snow Water Equivalence (△SWE) following Rodell et al. (2004). Groundwater Storage change (△GWS) was then calculated with the equation as below (Rodell et al., 2007; Voss et al., 2013):

$$\triangle GWS = \triangle TWS - \triangle SWE - \triangle SM - \triangle SWS \qquad (1)$$

All the data are anomalies relative to the Jan. 2004- Dec. 2009 time-mean baseline. To be noticed, the GWS value derived from GRACE dataset is in the unit of cm, which is the mass change of groundwater storage represented by the equivalent water height. Readers should therefore take caution that it has a different magnitude and a different meaning from locally measured groundwater table change.

To indicate the reliability that reader could expect from GRACE-based groundwater surveys with regards to the possible measurement and leakage errors of the satellite signals, we mapped out the total error of the GRACE data (Landerer & Swenson, 2012). Further improvements for the data accuracy have also been proposed (see section 4). We estimated the errors using the following equation:

$$\sigma_G = \sqrt{\sigma_M{}^2 + \sigma_L{}^2} \tag{2}$$

Where $\sigma_M$ is the measurement error and $\sigma_L$ is the leakage error.

### 2.2.3 Data processing

For all the variables listed in the Equation (1), the spatial resolution is 1˚×1˚ and temporal resolution is month. For each variable in calculation, we first downloaded a rectangle extent (96.5E~118.5E, 32.5N~41.5N) with the time range from Jan. 2003 to Dec. 2016. Then we imported them into the ArcGIS (ESRI Inc.) and used Image Analysis to 'clip' the extent according to the irregular boundaries of the polygons in the YRB. This boundary feature layer of the YRB was obtained from Gassert et al. (2013). We then recorded the coordinates of all the grid centroids within the boundary and used MATLAB (Mathworks Inc.) to extract all the variables into Microsoft Office Excel (Microsoft Inc.) for further analysis.

We also used grid-point gain factor to reduce the error of signal attenuation in filtered GRACE time series. It is a scaling parameter derived in minimizing the misfit between the unfiltered and filtered timeseries of the monthly mean GLDAS water storage estimates (Landerer & Swenson, 2012). Since gain factors are dimensionless, the gain-corrected time series is just the arithmetic product of the TWE and gain factor. The MATLAB program for processing GRACE data including the coordinates of grid centroids in the YRB was developed accordingly.

Then, we examined groundwater timeseries in multiple spatio-temporal scales (basin, reach and provincial level) to understand groundwater dynamics in the YRB. Spatially, we averaged the 1˚×1˚ grid data at basin, reach and provincial level respectively. We also found that provinces in the similar geological locations (from west, middle to east) have similar range of groundwater changes and often exhibited similar pattern of the changing trend. We therefore presented them in three groups. Temporally, we averaged monthly timeseries at the whole study period (Jan. 2003-Dec. 2016) level and at annual level. We adopted polynomial regression analysis to estimate the trend of groundwater decrease and used ANOVA analysis to testify the mean difference between different regions in SPSS (IBM Inc.) (Quirk, 2012). To provide more direct information for management, we further categorized the values of groundwater changes. The thresholds were determined based on the range of values for all the grids in the YRB and the indication of impacts in the real life (Zhen & Routray, 2002). Detailed categorization is listed in Table 2.1.

Table 2.1 Categorization of water table and its indication.

| Thresholds of Water Table/cm | Indication of groundwater change |
|---|---|
| <-10 | Severe decline |
| -10~-5 | Minor decrease |
| -5~5 | Normal fluctuation |
| 5~10 | Minor increase |
| >10 | Abnormal increase |

Finally, we conducted Anselin Local Moran's I cluster and outlier analysis to find the hotspots of groundwater decline (Anselin, 1995). The cluster maps indicate whether a spatial clustering is more pronounced than one would expect in a random distribution. It is to identify groups of statistically significant decreases/increases of groundwater based on value and distance instead of human-defined boundaries like provinces or reaches. In this way, we could find out the scale for proper way of analyzing groundwater situation and developing management strategies.

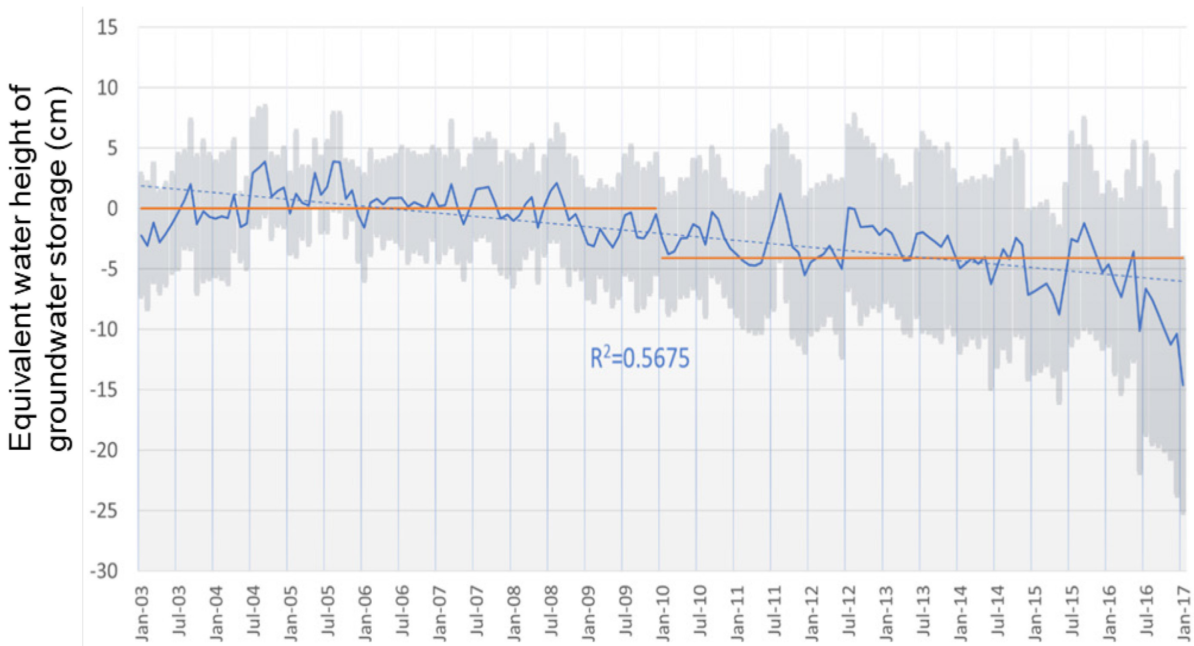
## 2.3 Results

### 2.3.1 Spatio-temporal changes of groundwater in the YRB

Spatio-temporal changes measured at basin, reach and provincial level generally showed decrease of groundwater storage over the study period (2003-2016). This decline was more pronounced after 2010. We observed a general trend: the locations with high fluctuations were usually the places with severe decline of groundwater storage. Groundwater pattern showed apparent differences in various geographical regions and have shown shifted hotspots of groundwater decline among these regions since 2010.

2.3.1.1 Spatio-temporal variability at the basin level

a.




b.

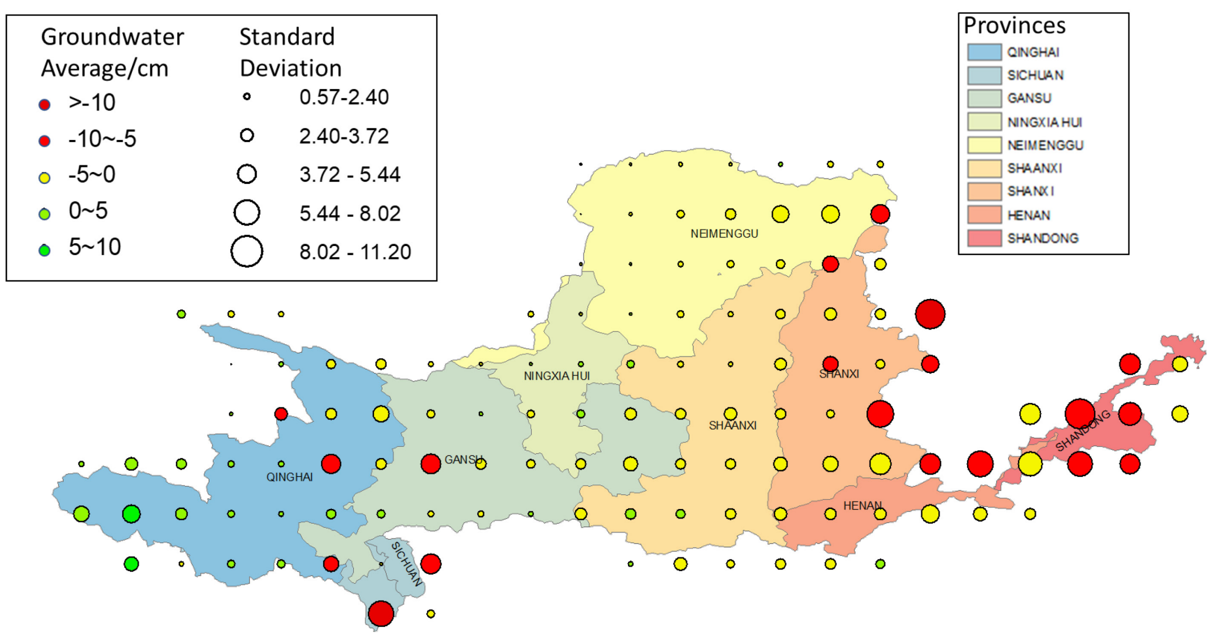


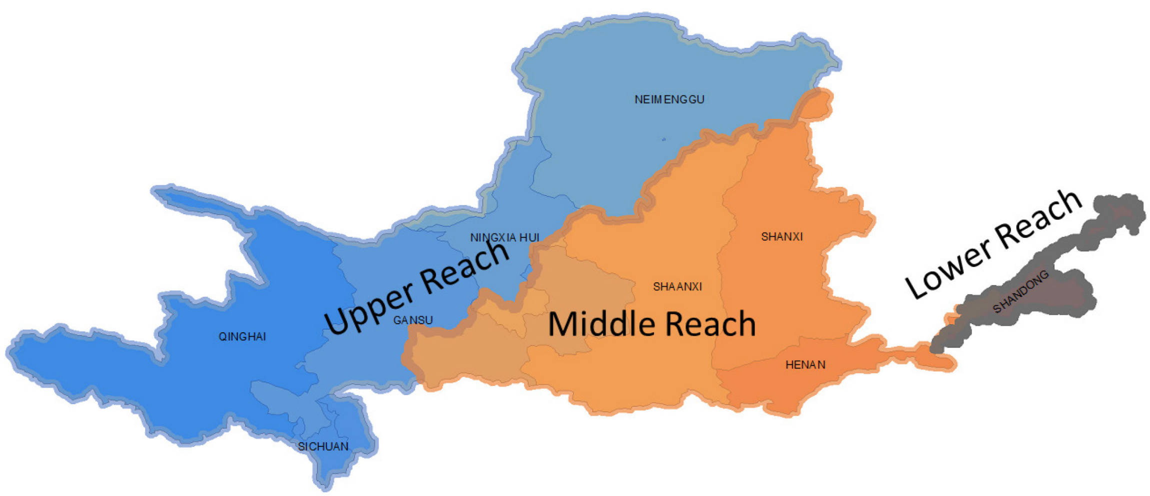
Figure 2.2 Spatial and temporal averaged groundwater storage in the YRB. a) The monthly time series displays the spatially averaged groundwater storage changes over time in the YRB (unit: cm). The shaded area shows one spatial standard deviation of the mean groundwater storage change in the YRB, suggesting that the spread-out of the values in grids changed over time. Two orange lines represent the arithmetic mean before and after 2010 (0.02cm and -4.01cm) respectively. The blue dotted curve represents the linear fitting for the whole study period. b) The point colors (red and yellow are the decrease from the baseline and green is the increase from the baseline) represent the change of the averaged groundwater storage in each grid from 2003 to 2016. The point size represents one temporal standard deviation for each grid measuring temporal fluctuations of the groundwater storage in each grid from 2003 to 2016. We included all the grids that the YRB covers, even if it just covers a fraction of the grid. The points, which are the centroids of these grids, therefore sometimes being outside of the YRB boundary. Provinces in the YRB from west to east are sequentially colored from blue to red.

Across the entire YRB basin, there were annual fluctuations, with groundwater storage typically at a relative maximum around August and relative minimum in May (Figure 2.2a). According to a linear regression ($R^2$=0.5675), groundwater decreased gradually over the 14 years. According to the paired t test, the mean groundwater storage in the first half of the study period (Jan. 2003-Dec.2009) was significantly higher than the second half of the study period (Jan. 2010-Dec. 2016) ($p<0.0001$). The annual minimum groundwater storage in April 2011 was lower than any of the months between 2003 and 2011, and this record within study period was again broken in 2015, and 2016, and reached -14.64 cm in Jan. 2017. The slope of the fitting curve became more steeply negative after 2010 (from -0.0137 cm/month to -0.0684 cm/month), indicating that groundwater has been decreasing at an accelerating rate since 2010.

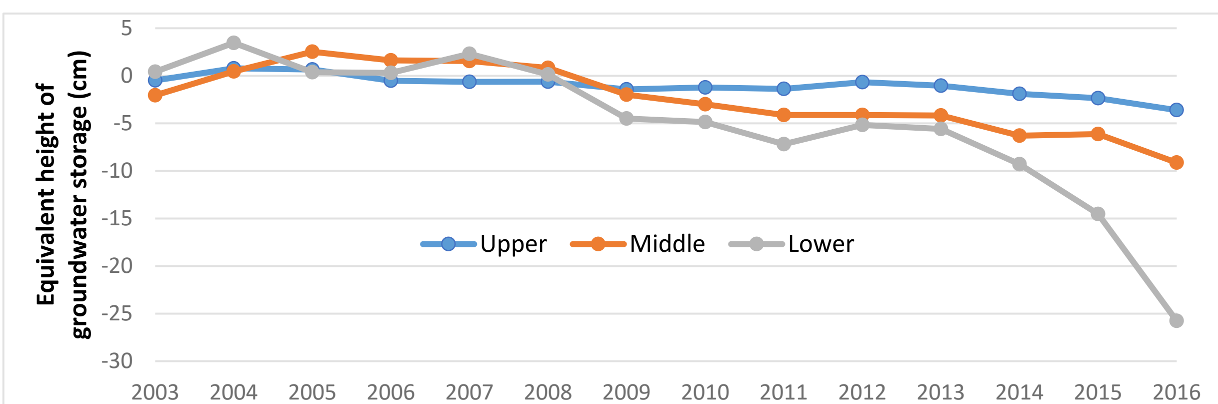
The standard deviation exhibited increasing trend especially in recent years (2010-2016) indicating that the groundwater changes in grids across the YRB showed more spatial differences over time (Figure 2.2a). Additionally, the range (maximum-minimum) of annual fluctuations in the average groundwater storage in the YRB has increased over the study period, especially after 2010 (Figure 2.2a). While groundwater storage in the YRB typically had several waves of drop and rise before reaching the annual maximum or minimum in each year, fluctuations became simpler after 2010. The storage decreased or increased directly to the annual minimum and maximum with fewer intermediate fluctuations.

Spatially, the groundwater storage showed the longitudinal zonation (Figure 2.2b). In the west where river source locates, the average groundwater storage during 2003-2016 increased compared with baseline values during 2004-2009. A strip of minor-severe groundwater decline was observed around the border between Qinghai and Gansu (Figure 2.2b, Table 2.1). In the middle of the YRB, groundwater table exhibited normal fluctuations. In the east, there was another vertical zone of minor-severe groundwater decline. Generally, the average groundwater gradually declined from west to east. The places with higher variances of groundwater table are usually the area with more groundwater decline. Specifically, the southeastern part showed more obvious groundwater decreases than other part of the YRB, and, at the same time, higher fluctuations than other area.

a.




b.



c.

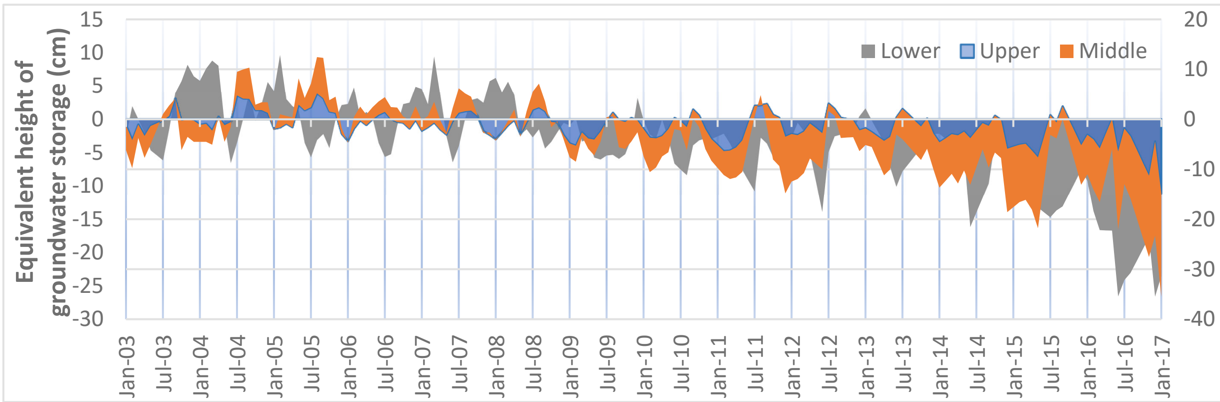



Figure 2.3 Annual and monthly time series of groundwater storage changes in the three reaches (unit: cm). a) The coverage of upper, middle and lower reaches. Blue indicates the upper reach, yellow the middle reach, and grey, the lower reach. b) The annual time series of groundwater storage for each reach. c) The monthly time series of groundwater storage for each reach. Y axis represents groundwater storage of each reach compared with 2004-2009 baseline values. The lower reach follows the y axis on the right [20, -40], while the upper and middle reaches follow the scale on the left [15, -30].

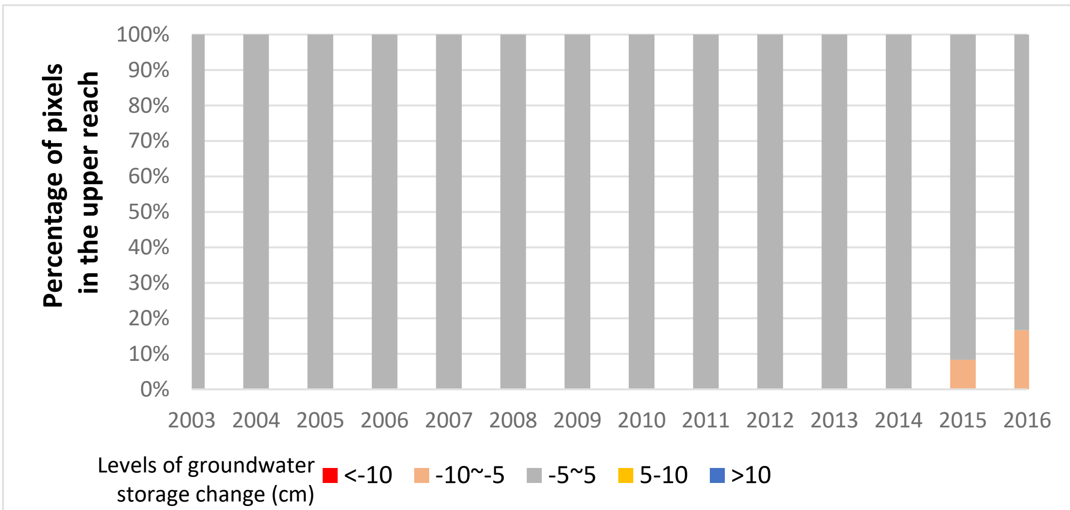
### 2.3.1.2 Spatio-temporal variability at the reach level

When analyzing the annual groundwater storage in each reach, we found that mean groundwater storage over the study period (2003-2016) were different among the three reaches of the Yellow River Basin (Figure 2.3a, $p=0.023$). Generally, the groundwater storage in upper reach was relatively higher than the middle reach while the groundwater storage in lower reach was much lower than the middle reach (Figure 2.3b).

When taking a closer look at the monthly change, we found that the upper and middle reach had more consistent fluctuation while the lower reach exhibited an opposite pattern (Figure 2.3c). In the upper and middle reach, groundwater storage were relatively high in summer (~ July) and relatively low in winter (~January). However, the lower reach showed opposite pattern, in which groundwater storage dropped in summer (~July) and returned in winter (~January).

There was a tipping point in 2010 when all the three reaches continuously exhibited negative values which indicated that the groundwater storage were continuously lower than that of 2004-2009 baseline level. Before 2010, the groundwater tables in three reaches generally showed normal fluctuation to minor changes (-10~10cm). After 2010, the declining trend of groundwater storage were more obvious, with the annual minimum values continuously broke the record-low within the study period. Also, as the value of annual groundwater minimum in the lower reach was always closer to the *previous* annual groundwater minimum in the rest two reaches, it implies that the groundwater changes in the lower reach were affected by upstream and had a time lag against the two reaches upstream (Figure 2.3c).

a.

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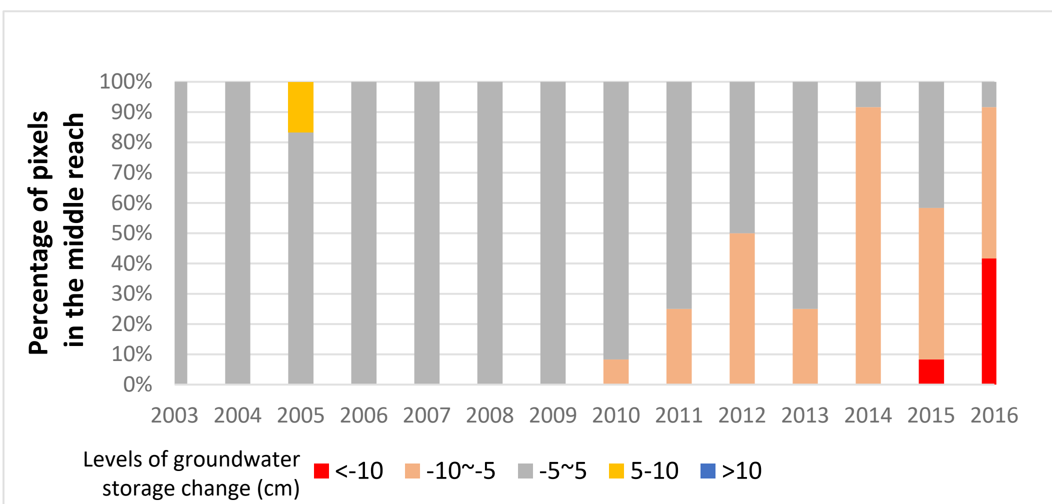
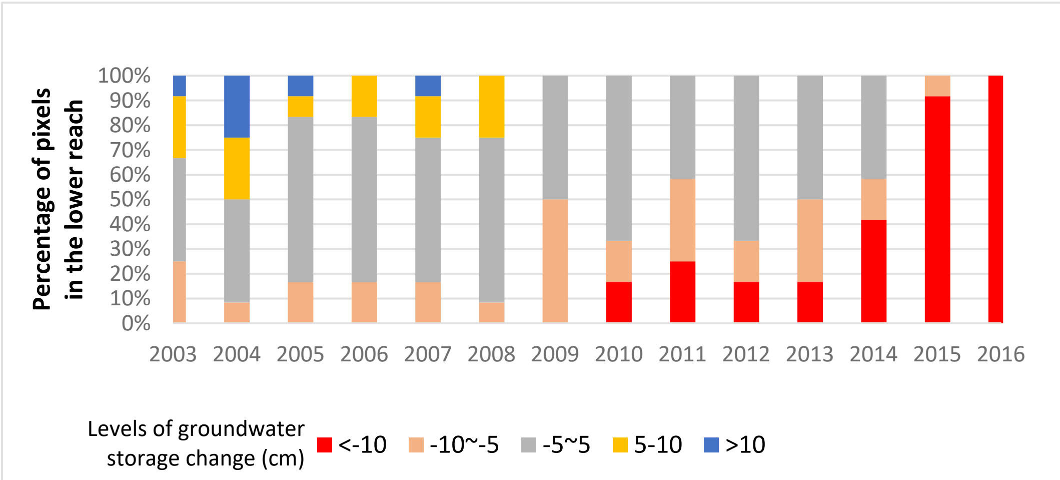


c.




d.

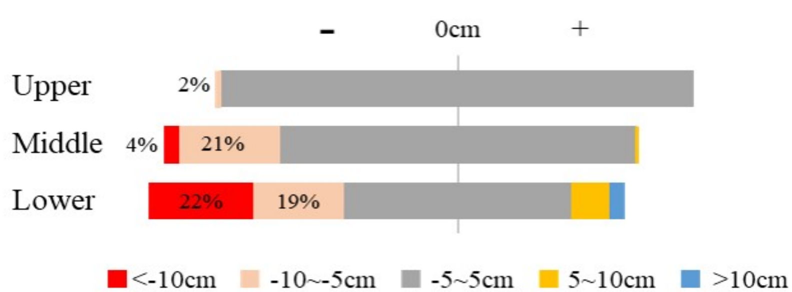
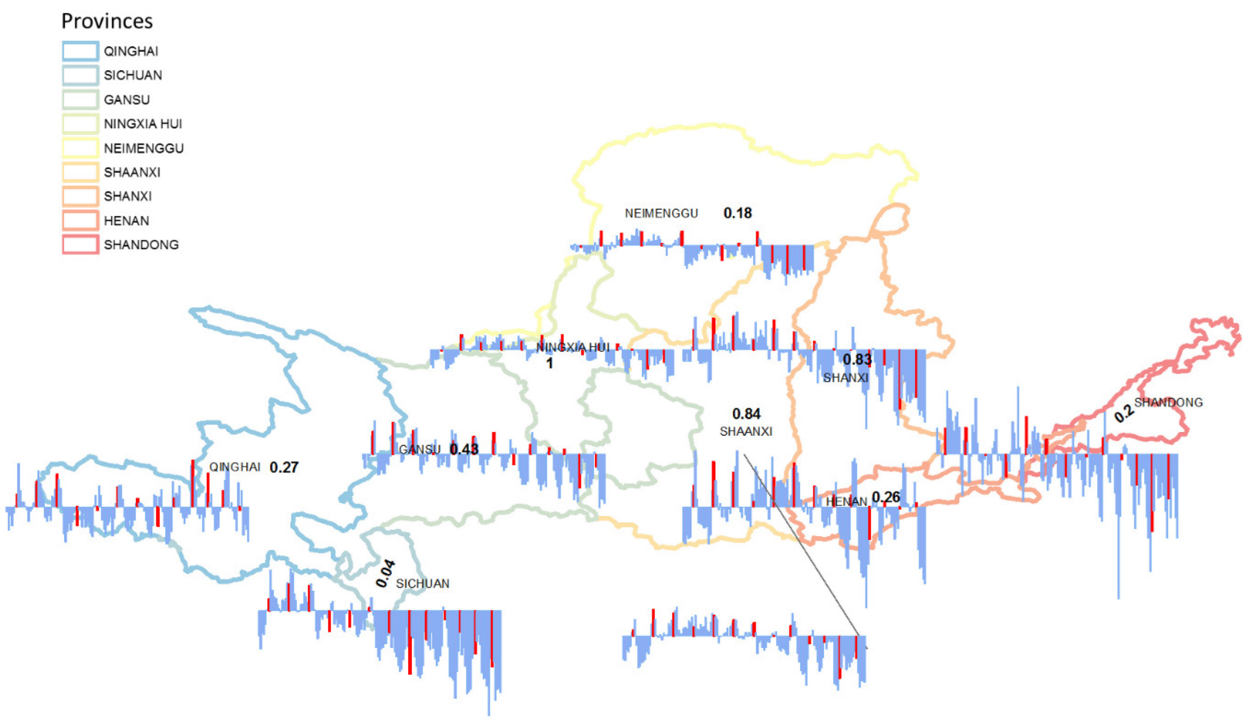



**Figure 2.4 Decline severity of monthly groundwater in three reaches of the YRB from Jan. 2003 to Dec. 2016.** Groundwater change values are categorized into five levels (Table 2.1) to examine the severity of the groundwater change, especially the groundwater decline. Vertical bar graphs show the percentage of months in each year with various levels of groundwater changes in a) upper reach b) middle reach & c) lower reach. d) Months in same categories are summed up from 2003 to 2016 to see the overall pattern in each reach. For the ease of comparison, the bars align along the 0 cm line represents the middle of the gray bar in each reach. The bars on the left of the line represent the months with groundwater decline while the parts on the right indicate the months with groundwater increase.

The most recent two years (2015-2016) witnessed the most severe signs of groundwater depletion in the YRB especially in the lower reach (Figure 2.4c). The upper reach started to show a minor decline in these two years whereas the middle reach started to show severe decline (Figure 2.4a and 2.4b). The lower reach displayed astonishing decrease and signs of depletion: severe decline continued to emerge from 2010 till most recent 2016 when all the months throughout the year presented severe declines. Overall, the lower reach had most months with severe groundwater decline compared with the other two reaches during 2003-2016 (Figure 2.4d). At the same time, the lower reach had more months with abnormal increases (> 10cm). It implies that the lower reach fluctuates more abruptly and may have a more vulnerable ecosystem.

#### 2.3.1.3 Spatio-temporal variability at the provincial level

a.

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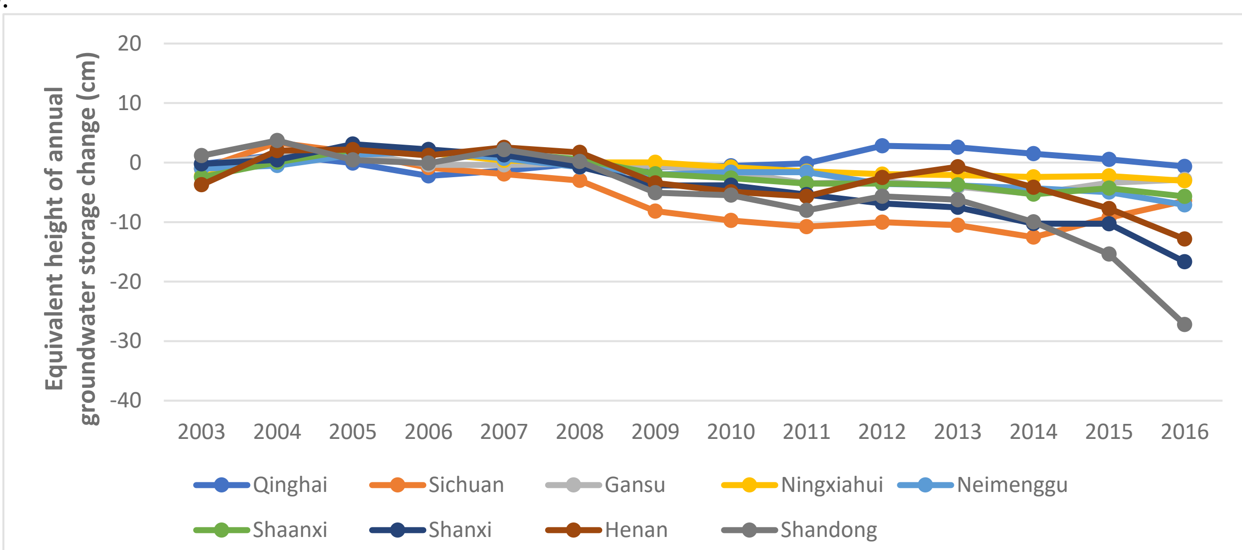

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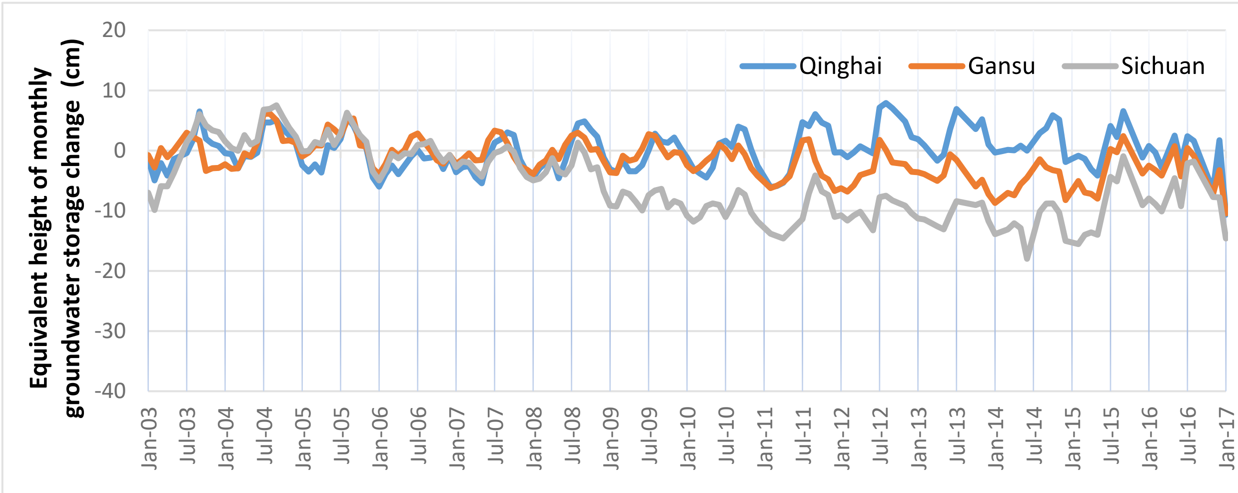

Qinghai
Gansu
Sichuan
Equivalent height of monthly groundwater storage change (cm)
20
10
0
-10
-20
-30
-40
Jan-03
Jul-03
Jan-04
Jul-04
Jan-05
Jul-05
Jan-06
Jul-06
Jan-07
Jul-07
Jan-08
Jul-08
Jan-09
Jul-09
Jan-10
Jul-10
Jan-11
Jul-11
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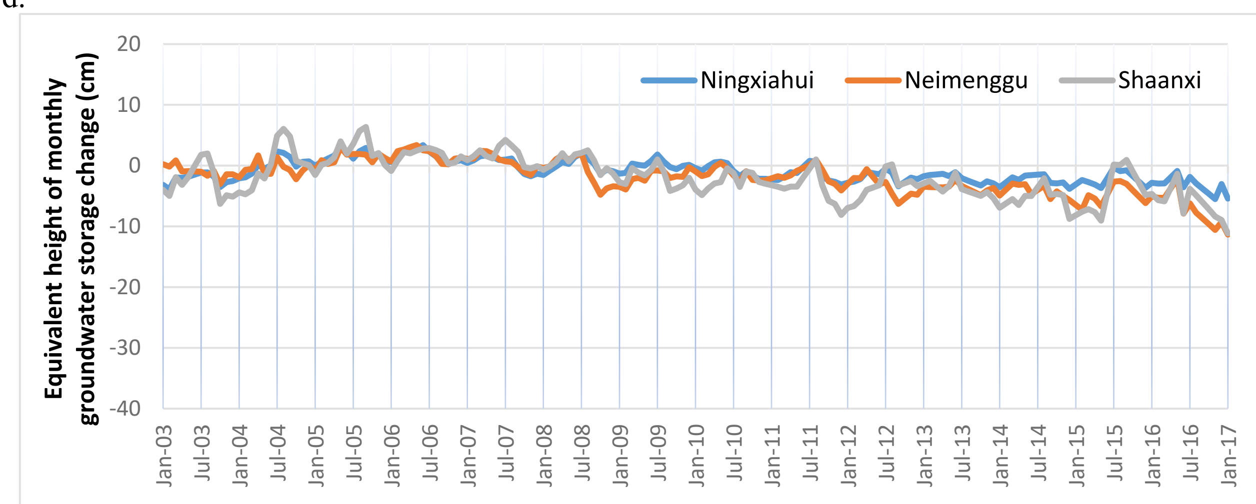
Jan-16
Jul-16
Jan-17


d.



Ningxiahui
Neimenggu
Shaanxi
Equivalent height of monthly groundwater storage change (cm)
20
10
0
-10
-20
-30
-40
Jan-03
Jul-03
Jan-04
Jul-04
Jan-05
Jul-05
Jan-06
Jul-06
Jan-07
Jul-07
Jan-08
Jul-08
Jan-09
Jul-09
Jan-10
Jul-10
Jan-11
Jul-11
Jan-12
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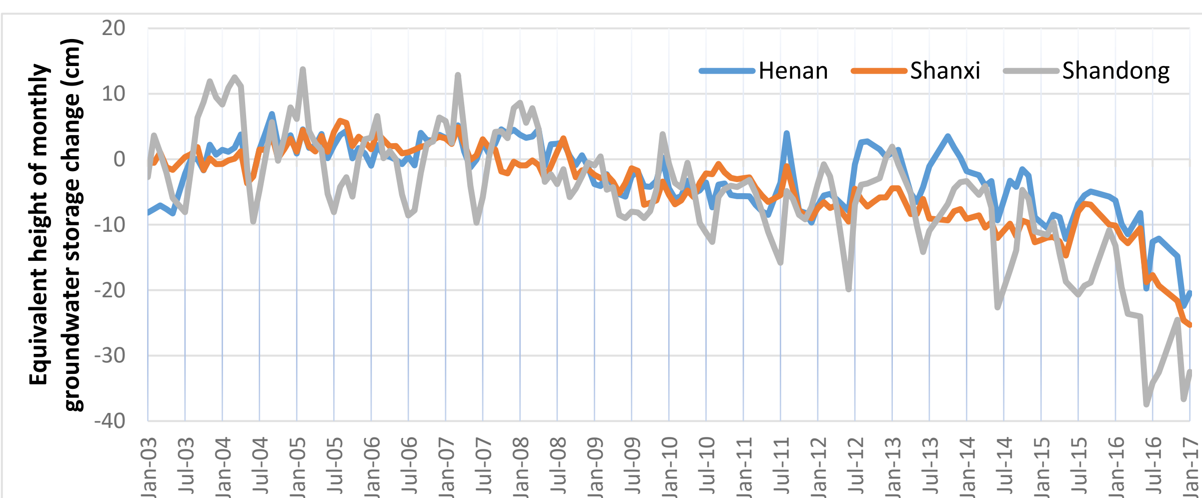
Jan-16
Jul-16
Jan-17


e.



Henan
Shanxi
Shandong
Equivalent height of monthly groundwater storage change (cm)
20
10
0
-10
-20
-30
-40
Jan-03
Jul-03
Jan-04
Jul-04
Jan-05
Jul-05
Jan-06
Jul-06
Jan-07
Jul-07
Jan-08
Jul-08
Jan-09
Jul-09
Jan-10
Jul-10
Jan-11
Jul-11
Jan-12
Jul-12
Jan-13
Jul-13
Jan-14
Jul-14
Jan-15
Jul-15
Jan-16
Jul-16
Jan-17

Figure 2.5 Annual and monthly groundwater storage changes in nine provinces. a) The monthly time series in the nine provinces in the YRB. To distinguish every year, all the bars in January are highlighted in red. The number in each color polygon represents the percentage of colored area among the total area of each province. For example, “1” in the polygon of Ningxia means 100% area of Ningxia is within the YRB. b) The respective annual averaged groundwater storage compared with 2004-2009 baseline values in nine provinces. The monthly groundwater storage compared with 2004-2009 baseline values for c) three provinces in the west (Qinghai, Sichuan, and Gansu), d) three provinces in the middle (Neimenggu, Ningxia Hui, and Shaanxi) and e) three provinces in the east (Shanxi, Henan, and Shandong).

Provinces along the Yellow River from upstream to downstream are respectively Qinghai, Sichuan, Gansu, Ningxiahui, Neimenggu, Shaanxi, Shanxi, Hennan, Shanxi and Shandong. Among them, Ningxia, Shaanxi and Shanxi are mostly covered by the YRB (Figure 2.5a).

At annual scale, all the provinces in the YRB showed obvious and continuous decreases of groundwater storage since 2009 except for Qinghai province (Figure 2.5b). Before 2009, groundwater changes were within 5 cm, while after 2009, Sichuan, Shandong, Henan, Shanxi, Shaanxi and Neimenggu successively showed apparent decreases (<-5 cm). Shandong provinces reached record-low in the last year of the study period (year 2016), indicating an emerging sign of severe groundwater decline. Despite general decreases in other provinces in the second half of the study period (2010-2016), Qinghai province was an exception: its annual groundwater storage showed apparent increase in 2012 with subsequent gradually decreased thereafter.

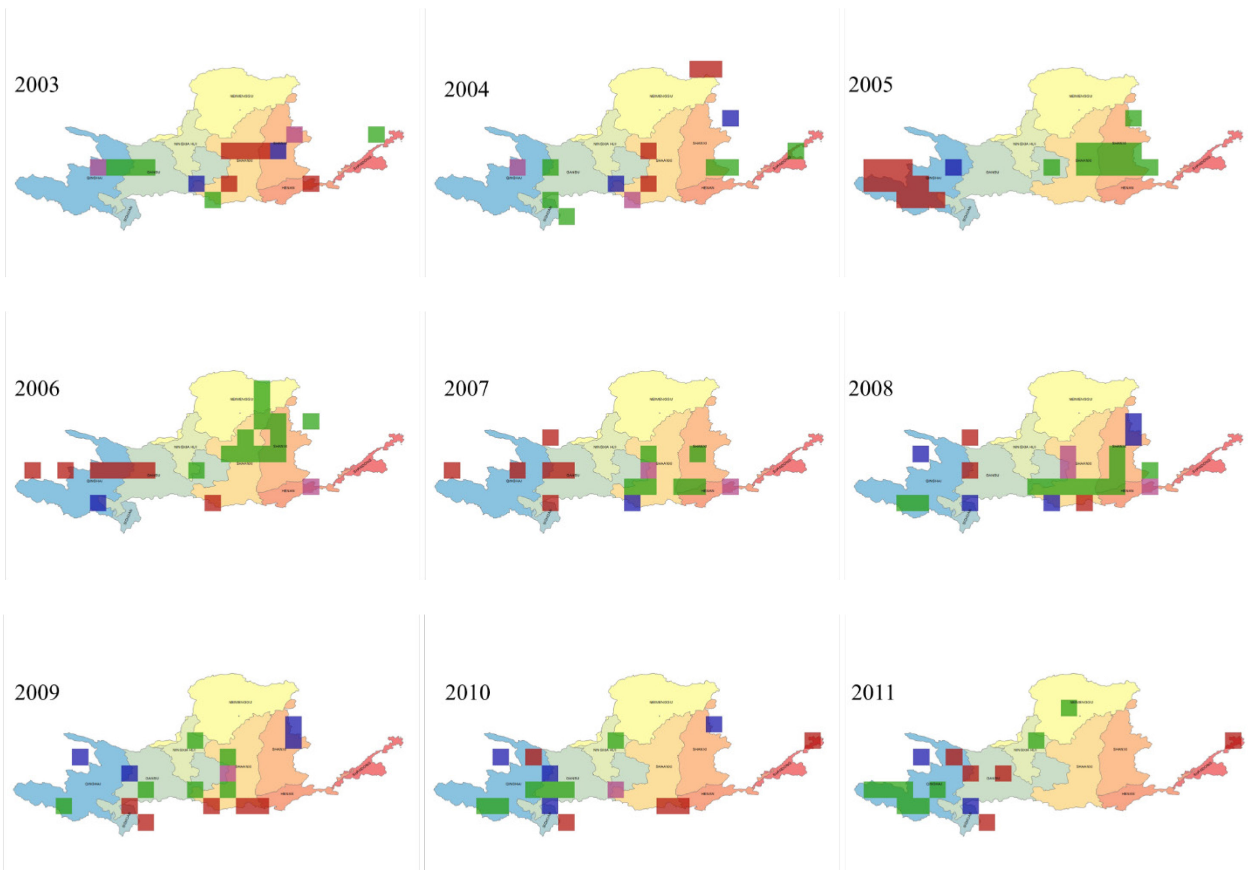
At the monthly scale, provinces exhibited different patterns between the first (2003-2009) and second half (2010-2016) of the study period. Before 2009, groundwater storage in all the provinces exhibited normal fluctuations (-5cm~5cm) except for Shandong province. After 2009, the annual range (maximum-minimum) of groundwater storage in each group was expanding, especially the lower boundary (annual minimum) (Figure 2.5c, d & e).

Qinghai, Gansu and Sichuan presented consistent and normal fluctuations before 2009, while they showed different patterns in the second half of study period (2010-2016): Qinghai showed higher annual maximum (>5cm) than before, Gansu showed lower annual minimum (<-5cm) than before, and Sichuan showed even lower annual minimum (<-10cm) than the first half period (2003-2009) (Figure 2.5c).

Ningxiahui, Neimenggu, and Shaanxi exhibited consistent and minor fluctuations (-5 cm~5 cm) before 2009, while they showed general decrease of groundwater storage after 2009: Their annual maximum was around baseline (0 cm), while their annual minimum were lower than -5 cm (Figure 2.5d).

Henan and Shanxi had minor fluctuations (-10 cm~10 cm) around baseline (0 cm) before 2009, whereas they showed increasing slope of downward trend after 2009, indicating that these two provinces were depleting groundwater storage in recent years and at an increasingly rapid rate. Shandong province exhibited abrupt changes throughout the study period (2003-2016), but apparently showed decreasing trend after 2009. The annual minimum in Shandong was reached as low as -35 cm in 2016 (Figure 2.5e).

### 2.3.2 Hotspots of groundwater decline from 2003 to 2016 in the YRB



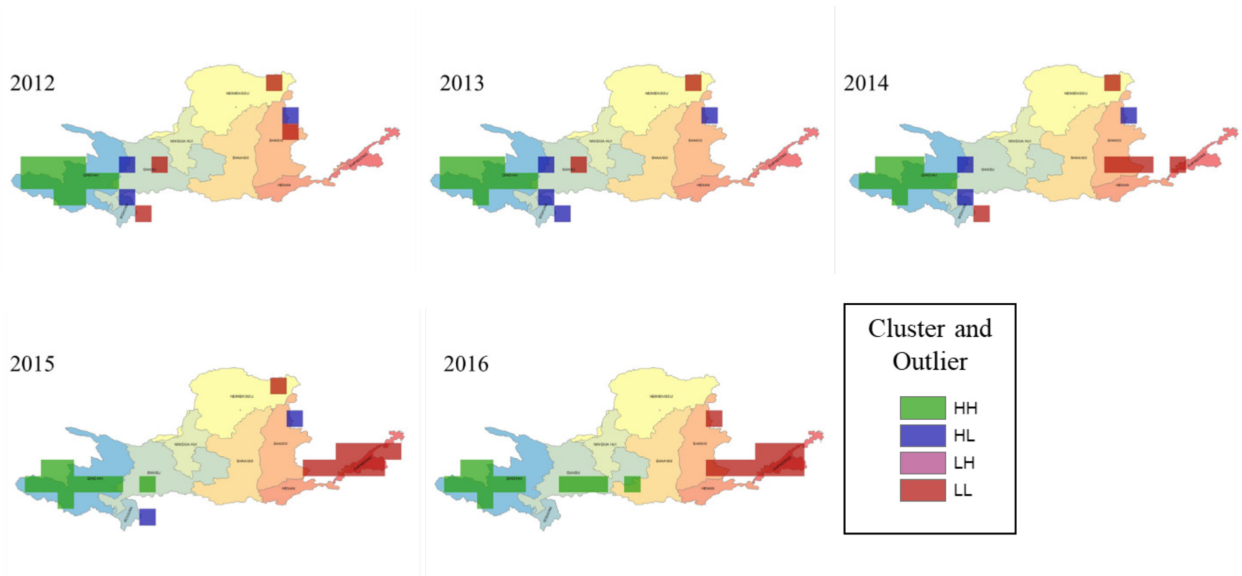



Figure 2.6 Annual clusters in the YRB from 2003 to 2016. The color polygons constitute the provincial map of the YRB following the color legend in Figure 2.5a. The cluster and outlier points are represented by pixels covering the provincial map. HH (green) is a statistically (95% confidence level) significant cluster of groundwater increases and LL (red) represents a statistically significant cluster of groundwater decreases. HL represents the abnormal point where the groundwater storage is higher than surrounding area, while LH represents the abnormal point with a lower groundwater storage than surroundings.

There was a high heterogeneity in hotspots of groundwater decline across the basin and through the time (Figure 2.6). Generally, there was a shifted pattern of the hotspots between the two halves of the study period: In earlier years (2003-2009), the hotspots of annual groundwater decrease were often located in the upper reach (in Qinghai and Gansu) and the cluster of annual groundwater increase was located in the middle reach (in Shaanxi and Shanxi). Contrarily, in later years (2010-2016), hotspots of groundwater declines concentrated in the middle and lower reach (Neimenggu, Shaanxi, Shanxi, Henan and Shandong) whereas the groundwater increase clustered in the upper reach (mostly Qinghai).

There were some abnormal years that require a closer look. In the first half of the study period (2003-2009), 2003 and 2004 witnessed relatively different patterns against other years. In these two years, there were hotspots of groundwater increase in the intersection of Qinghai and Gansu provinces, and hotspots of groundwater decrease in Shaanxi province. The pattern showed a sign of latitudinal zonation which led to more groundwater in the south and less groundwater in the north. In the latter half of the study period (2010-2016), 2011 is a special year, when most of groundwater decreases concentrated in Gansu, while groundwater storage increased both in upstream (Qinghai) and downstream (Ningxia and Neimenggu).

Even though abnormal points appeared randomly across the basin and through the time, there were some points that continuously showed abnormal high groundwater storage: the points along the intersection between Qinghai and Gansu provinces, as well as the point in the northeastern of Shanxi Province. These points require further investigation to understand potential reasons. There was also abnormal low groundwater storage in the intersection of Henan and Shandong from 2006 to 2008, but later disappeared. It may be related to same historical events during that three years. To be noticed, some abnormal points were connected with clusters. For example, some abnormal high groundwater storages were among groundwater decrease clusters, while the abnormal low groundwater storages were near groundwater increase clusters. In these cases, the abnormal points imply the disconnection of groundwater flow with surrounding aquifers.

## 2.4 Discussion

Overall, our results demonstrated that remote sensing data (GRACE), along with data assimilation products (GLDAS) can provide detailed and spatio-temporally explicit information for regional understanding of groundwater storage changes. Temporally, the general decrease of groundwater storage especially after 2010 indicates that the balance of the recharge-discharge system of the aquifers in the YRB are broken. Groundwater depletion in the YRB in recent years (2010-2016) was consistent across different spatial scales (basin, reach and province). Spatially, the hotspots of groundwater decline have shifted from the west to the east over our study period. After 2010, apart from the source region (Qinghai province) which showed signs of groundwater increase, the rest of the provinces displayed accelerated declines of groundwater storage. The lower reach had the most severe groundwater decline especially in the last two years (2015-2016), as well as the highest fluctuations. This emerging sign of decline severity implies a deteriorated situation of groundwater storage in the lower reach that needs special attention.

At the basin scale, we observed a general decreasing trend in groundwater storage from 2003 to 2016, which testifies a trend of groundwater depletion that was implied by other ground-based monitoring data (Liu & Xia, 2004). Also, the high fluctuations in groundwater changes were always found in the places where groundwater storage were low, which indicates that, with low water table, the aquifer system is more unstable, thus leading to a more vulnerable ecosystem. It implies that the area with low groundwater storage has relatively quicker processes of recharge and discharge than other places. Compared with natural discharge to lakes and rivers, the relatively direct way that groundwater leaves from the aquifers is through human extraction (Bernadez, 1993). Different from natural recharge from precipitation and river runoff, the relatively quicker way that water reenters into the aquifers is through human injection and irrigation (Vandenbohede, Van Houtte & Lebbe, 2009). With this regard, the groundwater decreases with high fluctuations suggest a human intervention of the recharge-discharge system that speeds up the interaction between surface water and groundwater.

At the provincial scale, we are more confident with the results in the provinces whose administrative area is mostly within the YRB (Figure 2.5a). Considering the limited points in Sichuan Province within the boundary of the YRB, the continuous decrease of groundwater storage in Sichuan doesn't necessarily mean that groundwater resource in Sichuan is extensively decreasing. It may be because the changed distribution of groundwater resource moving from north to south in Sichuan where we don't have data to present. However, for Ningxiahui, Shaanxi, Shanxi, which are mostly covered by the YRB, the result of significant groundwater decline after 2010 indicates that regional recharges in these provinces have difficulty in effectively compensating the groundwater discharge in the regional system. That is to say, the groundwater "account" is in debt.

This groundwater debt may result from decreases in recharge, increases in discharge, or both. Decreases in recharge may be related to reduced precipitation and surface sealing from urbanization processes (Yu, Wan & Du, 2003). Increases in discharge include withdrawals of groundwater for human use and increased evapotranspiration due to warming climate (Wegehenkel & Kersebaum, 2009). Therefore, both human and natural factors may lead to the same result of groundwater depletion. The Chinese Ministry Water Report confirmed that an extensive drought happened in 2010 in the North of China (YRCC, 2010; Duan, Wang & Feng, 2011), which may have contributed to the decreasing trend in groundwater for nearly all provinces. Zhen and Routray (2002) found groundwater over-extraction in Shandong province since the 1980s have led to well decline, land subsidence and compacted soil perceived by farmers. Meijer et al. (2006) also indicate that, by lining the canal with concrete material, the agricultural practices may reduce the groundwater recharge by approximately 50% in the irrigated areas. Rodell et al. (2018) suggested the increasing "human footprint" on the change of freshwater accessibility around the world. But they also noted that the temporal variabilities of freshwater reserve are mainly caused by inter-annual climate variabilities. For Qinghai province, the only province with increasing groundwater storage, Yang et al. (2003) detected an increase of precipitation and glacier melting there, which would increase recharge (Lutz et al., 2014). Clearer understanding on the interaction of human and natural factors and their synergistic effects on groundwater recharge-discharge balance remain to be explored in future studies.

Because the provinces located in the same geographical unit showed general consistency on spatio-temporal dynamics of groundwater, we believe it is meaningful to examine the groundwater situation in the reach level. Indeed, the spatial differences in groundwater storage among reaches within the YRB and temporal differences of groundwater time series in each reach are illuminating. Three reaches in the YRB showed quite unique features in the study period. The upper reach had relatively minor signs of groundwater decreases. This may partially result from the glacier melting and increased precipitation in the source region, which counteracts the groundwater decreases in the lower part of the upper reach (e.g. Ningxia and Neimenggu). The lower reach was relatively vulnerable, with both extreme high and low groundwater changes. This implies a more vulnerable ecosystem, thus posing more risks for human life. Middle reach acted as a transition with relatively smaller decreases than lower reach and larger decreases than the upper reach.

These differences may be the result of biophysical differences among reaches, but they may also be driven by differences in population size, economic prosperity, and urbanization (e.g. surface sealing from construction and infrastructure development) (Feng et al., 2012). For example, in the upper reach, smaller population size may lead to reduced demand for groundwater, and thus showed relatively mild change (Feng et al., 2012). In the middle reach, human exploitation and environmental degradation have contributed to the changing climate over the past 50 years (Yang et al., 2004, Alter et al., 2017), leaving peoples with water crisis (Fu et al., 2004). Nevertheless, the population remains dependent on agriculture for economic development. With little surface water, this reach may be depleting groundwater to meet needs for irrigation (Yang et al., 2004). Higher rates of erosion in the middle reach has led to higher river bed in the lower reach. This may lead to a relatively high recharge level for aquifers in the lower reach. When groundwater is extracted, the water level will return more quickly because of the high pressure thus leading to more abrupt changes of groundwater storage. At the same time, high population density with high demand for water in the lower reach leads to more excessive use of groundwater, which may be the main reason of the significant decreases in this region (Anderson et al., 2013)

Most interestingly, we found the potential hysteresis of the groundwater changes from upstream to downstream. This hysteresis suggests that aquifers are also connected between reaches, so the signs of groundwater decreases in the upper and the middle reaches may be an earlier warning for the amplified groundwater decline in the lower reach. Currently, the emergence of extreme groundwater decreases (<-10m) in the middle reaches in 2015 and 2016 along with the soar of the months with extreme groundwater decreases in the lower reach has demonstrated this possible connection.

Apart from understanding the connection and pattern of aquifers through reach level, the cluster and outlier analysis further provides information on implications for management. Despite that the pixel-based analysis may be less reliable in explaining the spatial variabilities and its potential causes, we gave a try to at least give an example of how the analysis of its kind could provide information to decision-making. First, both the spatially shifted pattern of the hotspots and temporal emergence of continuous decrease in all the reaches since 2010 suggest different recharge-discharge environments for aquifers in the YRB after 2010. Second, the hotspots of groundwater decline changing from west (source region) to southeast (lower reach) may indicate the human intervention become dominant in changing the recharge-discharge system. Also, the exceptional years that are inconsistent with general changes require further attention. For example, in 2003 and 2004, the patterns are different from the following five years. Coincidentally, the temperature of the source region has jumped from below zero to above zero in these two years (Du & Ma, 2016), which led to the increased glacier melting. This increase in glacier melting may be a probable cause of the increases of groundwater recharge in these two years. It can also be demonstrated by the increase of runoff in the Yellow River in 2003 and 2004 from the *"Water Resources Annual of the Yellow River"*. Another exceptional year is 2011. In 2011, the central government has put forward a series of water regulation policies which may temporarily restrict the excessive groundwater use. However, the following years witnessed a returning sign of the groundwater depletion which implies that human intervention by management may pale in comparison with a long-term damage on the environment.

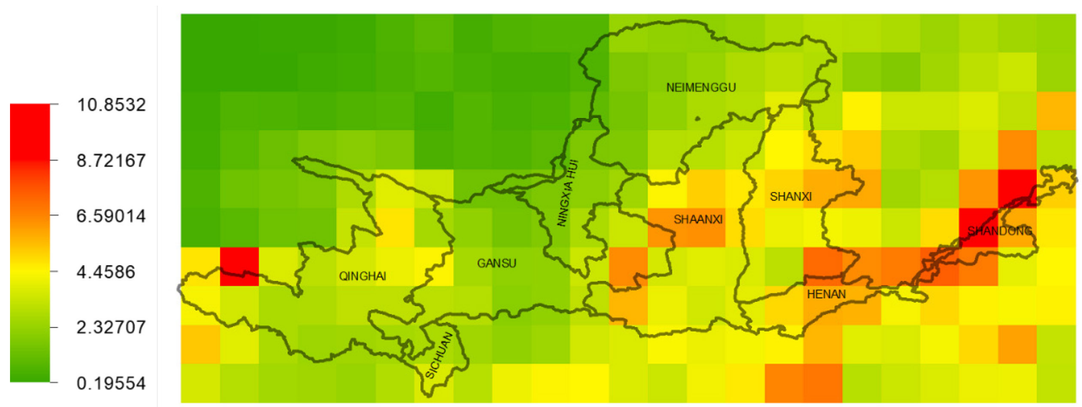



Figure 2.7 Error estimate of the GRACE datasets in the YRB-covering rectangle region (unit: cm). Green represents the lower values while the red represents the higher levels of the errors. Readers should take caution on the interpretations of the results in the red pixels.

Admittedly, current spatial resolution of the GRACE data and GLDAS is still far from satisfactory to discuss groundwater situation in local scale. On one hand, current GRACE actually is still questionable in the interpretation in pixel scale. So for the regions which consist of limited pixels (e.g. lower reach) may present more uncertainties induced by leakage errors. The total error (including both measurement and leakage errors) of the GRACE dataset in the YRB is about 3.12 cm in average and is especially evident in the southeast around the lower reach (Figure 2.7). Newly released mascon data (Save et al., 2016) may provide a better solution to reduce these errors. However, readers should take caution on its actual resolution of the information. The native resolution of the GRACE mascon solution is actually 3°, the size of a single mascon. Therefore, it is not suitable for analysis in grid point scale. On the other hand, the surface water component of GLDAS used in this study doesn't include the separate water component like lakes or reservoirs. But since lakes and reservoirs are sparsely scattered in the YRB (Yang & Lu, 2014) and groundwater is commonly viewed as spatially continuous across the region of interest (Rodell et al., 2007), the investigation of the overall spatio-temporal trend of the groundwater in the YRB would effectively eliminate the scattered or abrupt changes caused by the separate surface water components. Still, human factors like artificial dam constructions may change the temporal dynamics of the river runoff thus inducing a nonnegligible inaccuracy for the groundwater measurement (Liu, Chen, Dong, & Peng, 2012). Future studies are required to incorporate other Land Surface Models (Long, Longuevergne, & Scanlon, 2015) to improve the estimation.

Despite of the uncertainties mentioned above, it should be noted that a consistent criterion for discussing groundwater variance is necessary to understand the connections of groundwater changes between regions, thus helping to resolve the debate on trans-boundary water resource and to diminish the potential of war for water. This study provides fundamental support for further studies about socio-ecological factors of groundwater changes. Future studies should focus on the combined effects of human and nature on groundwater decreases, which may further empower the managers to incorporate groundwater use plan into overall scheme of sustainable water management.

## 2.5 Conclusions

We quantified groundwater changes in the Yellow River Basin of China and conducted spatio-temporal analysis to quantify the changes of groundwater in multiple scales. The result of the general decline in the YRB from 2003 to 2016, especially after 2010, implies that we are not on the right track in protecting groundwater. The hotspots of the groundwater decline shifted from the source region to the lower reach indicating that "human footprint" may become dominant in affecting groundwater changes. At the same time, our studies across different spatial levels indicate that geographical conditions may also play a role in determining the groundwater patterns in the YRB and a one-size-fits-all management is unlikely to be effective. This information demonstrates the need for cooperative water management across neighboring administrative regions while simultaneously designing management practices that are relevant to the local situation. Overall, our studies provide clearer message to water managers about the necessity and the direction to consider groundwater into management scheme so as to ensure a sustainable water use for future.

## Acknowledgements

The authors would like to acknowledge the Chinese Scholarship Council (CSC), Natural Sciences and Engineering Research Council (NSERC) of Canada (RGPIN-2014-4100) and Centre for Social and Cultural Data Science (CSCDS) which funded this research and NASA who provides the necessary data for this study. Special acknowledgements are also due to Dr. Lehner Bernhard, Dr. Gordon Hickey, Dr. Shuang Gao and Dr. Jesse Rieb who provide essential suggestions for this project.

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# Connecting to Chapter 3

Chapter 2 presents a detailed analysis on spatio-temporal changes of groundwater in multiple scales in the Yellow River Basin. The result suggests that the groundwater storage generally showed declining trend over the study period (2003-2016) in the YRB. This decline was more pronounced after 2010 which indicates a deteriorating situation of groundwater resource that requires better management. Within the YRB, I observed that locations with high fluctuations were usually the places with severe decline of groundwater storage which indicates the association between resilience degradation in the socio-ecological system and groundwater depletion. However, I also identified a high heterogeneity in hotspots of groundwater decline across the basin and through time which complicates the interpretation of groundwater dynamics in YRB as well as the strategies needed to control the situation. Specifically, it is not clear which part of the YRB should be prioritized for immediate control of groundwater use and which part should be equipped with more robust risk response system to enhance its resilience. In Chapter 3, I aim to answer these questions by combing out the complexity of spatio-temporal dynamics of groundwater using a new method: time stability analysis. Time stability analysis can integrate the spatial and temporal information to compare the relations of sub-regions with the whole basin. It is expected to identify representative areas that have consistent temporal variations of groundwater storage as the whole YRB (i.e. representative area), or the problematic regions that show significant decreases or frequent fluctuations of groundwater. This chapter of research takes the effort to mobilize the scientific knowledge to policy-making by interpreting spatio-temporal information of groundwater from a management angle.

# 3 Identifying hotspots and representative monitoring area of groundwater changes with time stability analysis

**Highlights:**

- Time stability of GRACE data was used for the 1st time in groundwater (GW) studies
- Spatio-temporal dynamics of GW table were quantified in Yellow River Basin, China
- Hotspots, coldspots and representative areas of GW dynamics were identified
- Clustered areas were identified for various management needs
- Potential modifications in GW management within the basin were suggested


## Abstract

Groundwater is a most accessible freshwater resource for human beings, and it is increasingly important as an alternative to surface water under the threat of climate change. However, its complex spatio-temporal dynamic remains unattended from management perspective. Past studies on groundwater management were stalled by a relative dearth of high-quality data and a lack of synthetic analysis on both spatial and temporal information. Thanks to NASA's launch of Gravity Recovery and Climate Experiment (GRACE) satellite mission, our study has solved these two problems by innovatively applying time stability analysis to GRACE-based groundwater data. Taking the Yellow River Basin (YRB) as an example, we employed GRACE satellite data to obtain monthly changes of groundwater tables from Jan. 2003 to Dec. 2016 in 1.0-degree grid of spatial resolution. Then we identified hotspots (which indicated severe groundwater declines and fluctuations over time) and representative monitoring areas (which stably represented the spatial average over time) using time stability analysis. Time stability employs multiple coefficients to identify the spatial relations between local variables and global variables overtime, thus showing the overall effect of spatial-wise and temporal-wise factors but never used in groundwater studies before. Based on this method, we further identified management categories across the YRB using multivariate cluster analysis. As a result, the YRB has been divided into five zones for different management strategies. We identified the hotspots in west-most and east-most areas of the YRB, where we suggest a strengthened groundwater protections and risk response system. The northern part of the middle reach in the YRB was also identified as the representative monitoring areas.

With this knowledge, decision-makers can have a clearer regional plan for groundwater protection, monitoring, and risk response system. This new method enables a quick decision on the prioritized areas for different groundwater management strategies while not losing the scope of spatio-temporal heterogeneity.

**Keywords:** time stability; space-time scale; groundwater resource; cluster analysis; adaptive management

## 3.1 Introduction

Groundwater is an indispensable water resource to sustain food security and increase ecosystem resilience (UNESCO, 2004; Whymap, 2008; USGS, 2016; Rodell et al., 2018). However, the pressures from climate change and increasing population have profoundly changed groundwater reserves over time (Hanjra and Qureshi, 2010). When groundwater is depleting, cities will have much less capacity in dealing with extreme climate events and will have more serious and irreversible strain on water supply (Konikow and Kendy, 2005). Therefore, it is imperative to protect and manage groundwater in a sustainable manner. Many researchers have emphasized the importance of the knowledge and information concerning groundwater resources for water management (Villholth, 2006; Ahmadi and Sedghamiz, 2007; Xiao et al., 2016). Identifying signs of abnormal decrease (hotspots) or abnormal increase (coldspots) in groundwater storage is especially necessary for managers to take proactive action to evade potential water crises. With emerging water scarcity problems around the world, more water users rely more on groundwater resources but seldom have realized its importance for sustaining future generations (Watkins, 2006; Hanjra & Qureshi, 2010; Hoestra & Mekonnen, 2011). There is an urgent need to obtain a complete and sufficient understanding of the groundwater changing trend at regional scale to construct a sustainable groundwater supply system.

Previous analyses of groundwater changes focused separately on temporal and spatial scale but have rarely synergistically examined changes across both time and space (Ahmadi & Sedghamiz, 2007; Xiao et al., 2016). For example, Cameron & Hunter (2002) used the geostatistical temporal-spatial algorithm to optimize the long-term monitoring networks. However, they processed the spatial and temporal information separately, and the method was only used for redundant points of the groundwater quality. Theodossiou and Latinopoulos (2006) analyzed the spatial variation using kriging method, however, missed the temporal information, thus being insufficient for crafting management strategies for the future. Xiao et al. (2016) separately analyzed the spatial variabilities and temporal changes of groundwater level in Beijing piedmont from 2001-2013, however, they failed to interpret the groundwater situation simultaneously. In reality, the factors in spatial and temporal scales are working together and influencing each other to contribute to the changes of groundwater. Accurately identifying hotspots of groundwater depletion and increase requires information across both time and space simultaneously.

Time stability analysis has been widely used in soil moisture studies to examine the time invariant association between spatial location and classical statistical parametric values of soil water content (Vachaud et al., 1985; Biswas & Si, 2011; Hu et al., 2009). Many studies have observed that, at certain area, the spatial pattern of soil water content remain stable over time (Comegna & Basile, 1994; Brocca et al., 2009). Moreover, the area with this characteristic of time persistence in spatial pattern can be used as a representative monitoring area for the spatial average of a given area (Grayson & Western, 1998; Hu et al., 2013). Therefore, the time stability analysis shows promise to improve understanding of the changes of soil moisture in a spatio-temporally explicit way.

There are no previous studies that have used the time stability analysis for the spatio-temporal analysis of groundwater. One main reason is the difficulty of getting satisfying datasets for the trend analysis in both spatial and temporal scale. With recently available dataset of groundwater changes from GRACE projects, it is now possible to unveil the mask of groundwater variations in a spatio-temporal explicit manner (Bhanja et al., 2016; Rodell et al., 2018). Therefore, for the first time, we adopt the time stability analysis coupled with multivariate cluster analysis to provide effective support for groundwater management.

The objective of this study is to examine spatio-temporal changes of groundwater in the Yellow River basin (YRB) to identify representative areas for monitoring and hotspots of depletion or increase that require further attention. In this study, we innovatively used the time stability analysis and cluster analysis to synergistically analyze the spatio-temporal changes of groundwater in the YRB and have accordingly provided suggestions for the management plan of groundwater preservation.

## 3.2 Material and methods

### 3.2.1 The Yellow River Basin

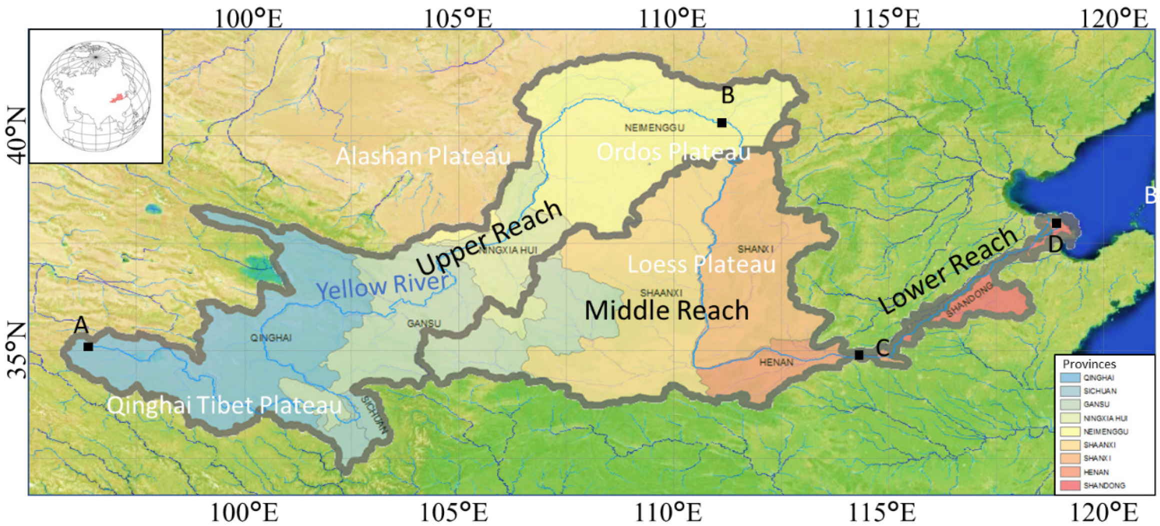



**Figure 3.1 Yellow River Basin, the study area.** (Lin et al., 2019; Gassert et al., 2013). The bold lines delineate three reaches (upper, middle and lower reach). The colored polygons represent nine provinces in the YRB. The blue curves represent the flow accumulation across the basin. The main flow path of the Yellow River is bolded by a continuous blue curve from Qinghai-Tibet Plateau passing Alashan Plateau, Ordos Plateau and Loess Plateau, then extending towards Bohai Sea. Point A, B, C and D are the key points of the Yellow River: AB is the upstream, BC is the middle stream, and CD is the downstream.

The YRB (elevation ranging between 0 and 4800 m), located in the north of China, is one of the largest river basins in the world, with an estimated recharge area of 795,000 km$^2$ (Figure 3.1). From the upstream of the Yellow River, where the Qinghai-Tibet Plateau (Point A in the Figure 3.1) locates, the river basin's elevation generally decreases until the river mouth in the East (D). (Yu, 2002; Liu & Di, 2007). Hekou County (B) and Zhenzhou City (C) are the two separated point which divides the river to three components, forming three reaches from high west to low east. Because of the high disparities in altitude from the upper reach to middle reach, the middle reach suffers from high water erosion with infertile lands in the loess and ordos plateau. The lower reach consists of alluvial plains, which are good for growing crops, and therefore features high population density and urban areas compared with reaches upstream. However, lower reach suffers from flood events the most.

There are nine provinces along the river: Qinghai, Sichuan, Gansu, Ningxia Hui, Shaanxi, Neimenggu, Shanxi, Henan, and Shandong (Figure 3.1). The river currently nourishes more than 120 million people (12 percent of China's population), waters more than 200,000 $km^2$ arable land (15 percent of China's farmland), generates nearly 8 trillion yuan per year (14 percent of China's GDP), and is an important cultural and historical icon (Gao & Yao, 2013).

### 3.2.2 Hydrogeological background of the YRB

With close interaction to the Yellow River, certain types of groundwater in the YRB have typical distributions consistent with its surface water systems. Loose sediment rock type pore water is most widely distributed in the YRB and is important water supply. Frozen-layer water mainly lies in the upper stream, the Qinghai Tibet Plateau area, flowing above or under the permafrost layer. Clastic rock type fissure and pore water is scattered in mountain piedmonts and artesian basins in the middle stream, like Ordos Plateau in Neimenggu, and Weihe Catchment in Shaanxi. Carbonate rock type fissure and pore water including karst waters mainly occur in lower stream, e.g. Lvliang Mountains in Shanxi and Liupan Mountain in Ningxia.

Because of the various landforms and complex lithology in the YRB, groundwater systems in the YRB are also intricate. Cui et al. (2004) divided the YRB into 9 groundwater systems according to surface watersheds while Eryong et al. (2009) partitioned 12 groundwater systems based on hydrogeological conditions and characteristics of recharge-runoff-discharge of groundwater. In spite of different classifications, it is commonly recognized that the main recharge resources of groundwater are precipitation, surface water (irrigation, and river water infiltration) and lateral bedrock regions, and the main discharge channels are through evapotranspiration, human abstraction, river runoff and springs (Xu et al., 2002; Eryong et al., 2009; Xu, Huang, Qu, & Pereira, 2010; Xu, Huang, Qu, & Pereira, 2011).

Although previous studies have made efforts to identify different groundwater zones in the YRB and their recharge-discharge systems, it is still hard to draft a targeted and effective groundwater plan without closer look at the changes of groundwater storage.

### 3.2.3 Data sources and data analysis

We used datasets obtained from a remote sensing data product and a data assimilation system to calculate monthly groundwater changes in the YRB for 2003-2016 at the spatial resolution of 1˚×1˚. The terrestrial water storage was obtained through the Gravity Recovery and

Climate Experiment mission (GRACE) (http://grace.jpl.nasa.gov) and the surface water equivalence, soil moisture and snow water equivalence were obtained from the Global Land Data Assimilation System (GLDAS) (https://disc.gsfc.nasa.gov). Groundwater was calculated based on the principle of mass conservation, by subtracting terrestrial water storage with the rest of abovementioned variables. The calculated groundwater changes are the groundwater storage compared with the monthly average from Jan. 2004 to Dec. 2009. For details of data processing, please refer to Lin et al. (2019).

We adopted time stability analysis to examine the spatio-temporal changes of groundwater storage. Different indices have been used to measure time stability at multiple scales (Jacobs et al., 2004; Guber et al., 2008; Schneider et al., 2008). We used the Mean Relative Difference (MRD) and the Standard Deviation of the Relative Difference (SDRD) to synergistically identifying spatial and temporal information in each grid (Tallon & Si, 2004; Brocca et al., 2009). This has previously been used in soil moisture studies to identify representative locations for regional monitoring (Brocca et al., 2009; Cosh et al., 2008). We innovatively used it here for groundwater changes in order to find both the time stable and unstable locations in the YRB. Mean Relative Differences were calculated as:

$$MRD^i = \frac{1}{k}\sum_{j=1}^{k}(GW_j^i - {}^{s}\overline{GW_j}) / {}^{s}\overline{GW_j} \ ;$$

where ${}^{s}\overline{GW_j} = \frac{1}{n}\sum_{i=1}^{n} GW_j^i$ .

$GW_j^i$ is the groundwater change in $i^{th}$ grid and $j^{th}$ month;

${}^{s}\overline{GW_j}$ is the spatial average of the groundwater values in the YRB in $j^{th}$ month; $n$ is the total number of grids in the YRB and $k$ is the total number of months during the study period. $MRD^i$ is actually the temporal mean during 2003-2016 of the relative difference of each grid compared with the spatial average of the grids in the YRB.

The Standard Deviation of the Relative Difference (SDRD) was calculated as:

$$SDRD^i = \sqrt{\frac{1}{k-1}\sum_{j=1}^{k}(\delta_j^i - {}^{t}\overline{\delta^i})^2} \ ;$$

Where

$\delta_j^i = (GW_j^i - {}^s\overline{GW_j}) / {}^s\overline{GW_j}$ ;

${}^t\overline{\delta^i} = \frac{1}{k}\sum_{j=1}^{k}\delta_j^i$ .

$\delta_j^i$ is the relative difference of groundwater change in $i^{th}$ grid compared with the spatial average of the YRB in $j^{th}$ month;

${}^t\overline{\delta^i}$ is the temporal average of the spatial relative difference for $i^{th}$ grid;

$SDRD^i$ is the sample standard deviation during 2003-2016 of the relative difference of groundwater change in $i^{th}$ grid compared with the spatial average of the YRB. In the two indices, $s$ and $t$ are used to differentiate spatial and temporal average. With these two indices, we could synergistically measure the spatial and temporal variability of each grid in a more explicit way.

Based on the MRD and SDRD values, we used the multivariate cluster analysis in ArcGIS to identify the places with time stable and unstable characteristics. The grids with minimal MRD and SDRD were defined as representative area for monitoring. Contrarily, the grids with very high absolute values of MRD and SDRD should be considered with caution. After multiple trials of the grouping strategy, we categorized the features of different grids into five groups:

Group 1 **Representative area:** the grids with minimum MRD and SDRD. This area has minimum groundwater changes and minimum groundwater fluctuations.

Group 2 **Area requires attention on resilience:** the grids with low negative value of MRD but very high SDRD. This area shows minor groundwater decrease, but with high fluctuations.

Group 3 **Area with rejuvenation:** the grids with high positive value of MRD and medium SDRD. The area shows the increase of groundwater and medium fluctuations.

Group 4 **Area requires immediate action:** the grids with very high negative value of MRD and very high SDRD. This area displays very severe groundwater decreases and very high fluctuations.

Group 5 **Potential depletion area that require further monitoring:** the grids with medium negative value of MRD and medium SDRD. This area displays medium groundwater decrease and with medium fluctuation. The detailed interpretation and respective suggestions for management will be explained in the results and discussion.

Altogether, we mapped out the time-invariant spatial pattern of groundwater distribution across the YRB based on MRD and SDRD and then divided the basin into five management zones according to the manifested change of groundwater resource over time and across space. Corresponding strategies for each zone were proposed.

## 3.3 Results

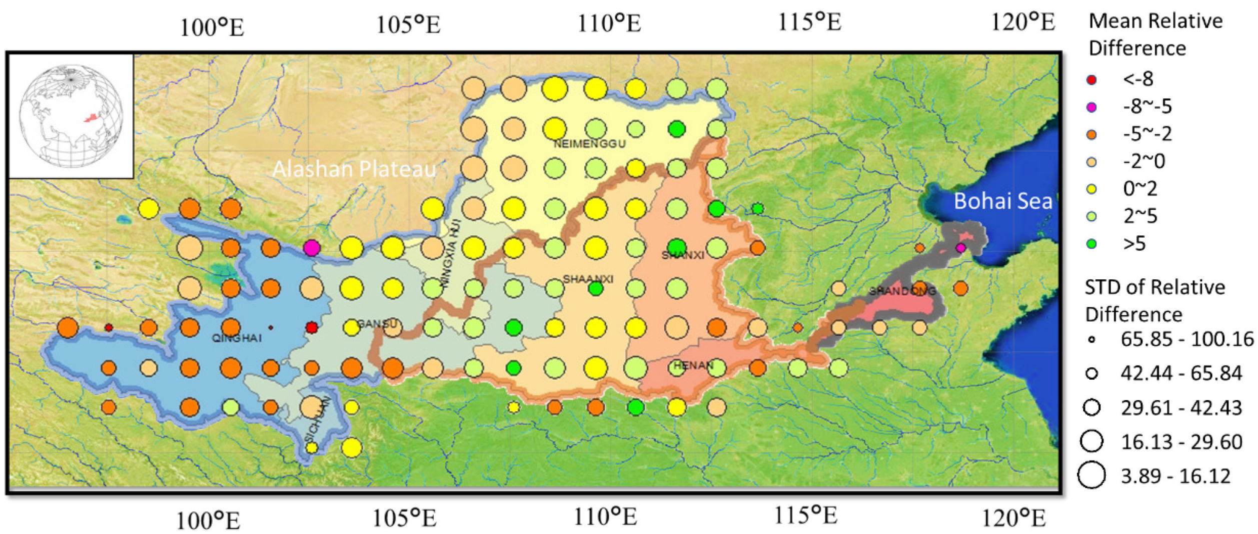



**Figure 3.2 Representative area for groundwater changes.** The color of the circle represents different ranges of values for mean relative difference. The yellow and light orange colors are the target area where mean relative difference is relatively small (-2~2). The size of the circle represents different ranges of values for standard deviation of the relative difference, which is inversely proportional to the value of size. The largest size of circle is the target area where standard deviation is the smallest. The background map is the provincial map and topography map with stream flows.

Figure 3.2 displays the general spatial relations of the groundwater tables with spatial average in the YRB over the past 14 years (2003-2016). Grids in the middle of the YRB (the eastern part of the upper reach and the western part of the middle reach) have MRDs closing to zero, which indicate that, despite variances of the spatial average over time, the groundwater tables in these places tend to be equal to the spatial average of the YRB. In the outskirt of the upper reach and the west of the middle reach, we found low SDRDs, which indicate that, despite high variances of the spatial average over time, the relations between groundwater tables in these grids and spatial average of the YRB remain stable. Combining the two indices together, the north of Ningxia and the west of Neimenggu have both close-to-zero MRDs and low SDRDs (Figure 3.2), therefore have a stable representation to the spatial average of the YRB. Accordingly, they were defined as representative monitoring areas which could be used to monitor the abnormal temporal changes of the whole YRB.

**Mean Relative Difference: $R^2$ = 0.82**

| Group | Mean | Std. Dev. | Min | Max | Share |
|---|---|---|---|---|---|
| 1 | 0.6014 | 1.3192 | -1.8541 | 3.1548 | 0.2450 |
| 2 | -2.4099 | 1.6899 | -4.7655 | 0.5950 | 0.2621 |
| 3 | 3.9846 | 1.3987 | 0.9909 | 7.5793 | 0.3222 |
| 4 | -8.8055 | 3.3057 | -12.8693 | -4.8035 | 0.3944 |
| 5 | -3.2144 | 1.3616 | -6.9115 | -0.6578 | 0.3058 |
| Total | 0.0000 | 3.5787 | -12.8693 | 7.5793 | 1.0000 |

**Stdev of Relative Difference: $R^2$ = 0.80**

| Group | Mean | Std. Dev. | Min | Max | Share |
|---|---|---|---|---|---|
| 1 | 14.8869 | 6.8372 | 3.8965 | 28.8012 | 0.2587 |
| 2 | 52.5384 | 6.7354 | 42.4488 | 65.8565 | 0.2432 |
| 3 | 34.0840 | 9.1985 | 22.3783 | 59.6265 | 0.3870 |
| 4 | 81.0200 | 15.6499 | 58.4049 | 100.1510 | 0.4337 |
| 5 | 31.0528 | 7.2505 | 19.1178 | 41.5697 | 0.2333 |
| Total | 31.4146 | 18.1376 | 3.8965 | 100.1510 | 1.0000 |

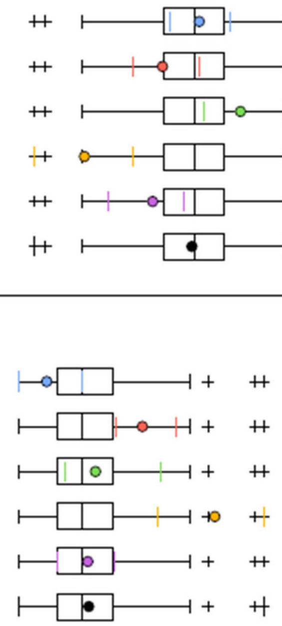


**Figure 3.3 Variable-wise summary of the multivariate cluster analysis for groundwater changes in the YRB (2003-2016).** Different colors represent different group values. In each variable (the mean relative difference and standard deviation of the relative difference), the list shows its group statistics. R2 indicates how effective the variables are in dividing the groups. The higher value represents higher effectiveness. The box plots on the right indicates the value range of the variable each group represents. The black box plots are the global statistics (including global lower whisker, global lower quartile, global median, global upper quartile, global higher whisker). The "+" represents the outliers which are the values away from the mean by 1.5 times larger than the standard deviation. The colored box plots are the group statistics (including group min, group mean, and group max).

Figure 3.3 shows the statistics of two indices for the categorized five groups. Both MRD ($R^2$=0.82) and SDRD ($R^2$=0.80) are effective in defining the five categories. The global mean of the MRD in the YRB from 2003 to 2016 is 0, and the global standard deviation of the MRD is 3.58. The global mean of the SDRD is 31.41 and the global standard deviation of the SDRD is 18.14.

Group 1 has similar mean (0.60) of MRD as the global mean of the MRD and has relatively smaller range of values (-1.85~3.15) than the global MRD. This, in another way, proves the representativeness of the groundwater tables in this area for the spatial average of the YRB. This group has smaller mean (14.89) and standard deviation (6.83) of SDRD than the global SDRD which indicates its stableness and reliance as a representative area for the YRB (Figure 3.3). The mean of MRD in the Group 2 is -2.4, which means that the groundwater tables in this area were generally lower than the spatial average but were still in the normal range (within the lower quartile of the global MRD). However, its mean of SDRD is higher than the global mean of SDRD (52.54>31.41), which indicates that the differences between the groundwater tables in this area and the spatial average of the YRB varied considerably over time. Therefore, despite that this area generally had no severe groundwater declines, it had less stable recharge-discharge system whose resilience should be taken with caution. Group 3 has a higher mean of MRD (3.98) than the global mean of the MRD. And the grid with largest increase of groundwater table (MRD=7.58) locates in this area (Figure 3.4). Group 3's mean of SDRD (34.08) is close to the global SDRD which implies that the variances in this group were driven by similar forces as in the whole YRB. Altogether, this area showed normal fluctuations of groundwater table and had relatively higher water table than the spatial average. So, the groundwater reserve in this area is gaining surplus. Group 4 (hotspots: the area with severe groundwater declines which requires immediate action) not only showed most severe declines compared with the spatial average (mean of the MRD=-8.81) but also had abnormal fluctuations of the differences over time: Its mean of the SDRD is 81.02, which is far higher than the higher whisker of the global SDRD (Figure 3.3). Let it alone its larger standard deviations for both MRD and SDRD than other four groups. It suggests that this area not only had severe groundwater decrease, but also had very unpredictable fluctuations in both time and space. Group 5 had relatively stable relations with the spatial average (mean of SDRD = 31.0528) but has the second lowest mean of MRD among the five categories (mean of MRD=-3.2144). It suggests that this area kept having lower groundwater tables than the spatial average over time. This area may have less tendency to come across abrupt changes of groundwater table in the future, but its current low status in groundwater reserve should be monitored closely in case the water levels go under the acceptable threshold.

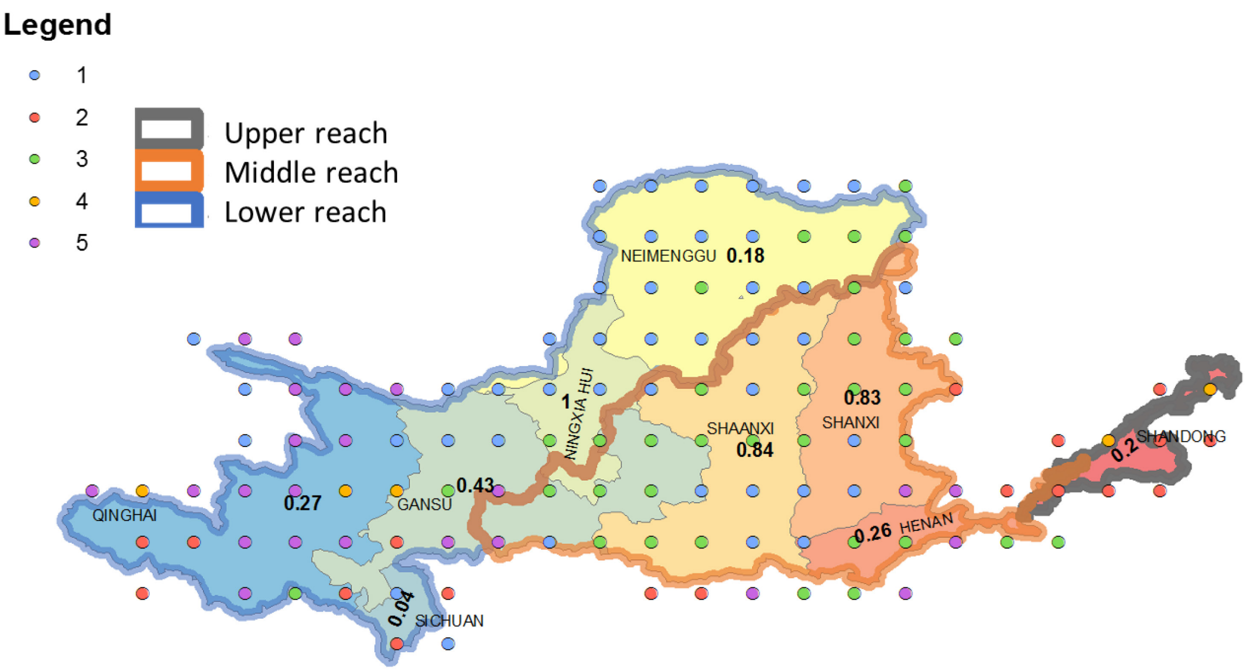



**Figure 3.4 Five management clusters categorized based on groundwater changes in the YRB 2003-2016.** The colored circles represent five different groups that we identified through multivariate cluster analysis. 1: Representative area, 2: Area requires attention on resilience, 3: Area with rejuvenation 4: Area requires immediate action, 5 Potential depletion area that require further monitoring. The colored boundaries represent the three reaches of the Yellow River. The colored polygons represent different provinces in the YRB, and the number in each province represents the percentage of the polygon in the total area of the province. For example, in Shanxi, 83% of the area is within the boundary of the YRB which is shown here while in Ningxia, 100% of the area is within the boundary of the YRB.

The Figure 3.4 mapped out the geographical distributions of these five groups. The representative monitoring area (Group 1) locates in the north of Ningxia and the west of Neimenggu as well as some scattered grids in the south of Shaanxi and Shanxi. The consistency of the Group 1 identified by the cluster analysis (Figure 3.4) with the representative monitoring areas identified by time stability analysis (Figure 3.2) mutually proved the methods' validity in identifying the area that could represent spatial average of the YRB over time. The areas that require attention on resilience (Group 2) locates in the lower reach around Shandong and in the tip of the upper reach. Their relations to spatial average vary a lot in time and space (Figure 3.4). So, the resilience of the ecosystem and society in these regions is important to prepare for the abrupt changes of the groundwater table. The areas that showed the signs of rejuvenation (Group 3) are mainly in the middle reach, including the east of Gansu and the north of Shanxi. They showed most obvious increase of groundwater storage therefore are identified as cold spots. The areas that require immediate action (Group 4), which display severe groundwater decreases, can be found in the origin of the Yellow River and at its river mouth (Figure 3.4). They are also called hotspots that should be the focus of the groundwater management in the YRB. The areas that require further monitoring (Group 5) because they show potential depletion, are the source region of the YRB and the connection part of middle and lower reaches, where it regularly showed signs of medium groundwater decrease over time (Figure 3.4). Although this area has less severe situation in terms of groundwater resource than the Group 4, it still needs close monitoring in order to evade irreversible depletion.

## 3.4 Discussion

In 2002, NASA launched the twin-satellite to measure the gravity anomalies of the Earth. Groundwater study has since opened a new way to record water table trend in the globe at a relatively fine resolution (Richey et al., 2015). This breakthrough makes many other previously inapplicable methods become available for the hydrogeology study. Time stability analysis is one of them. While it was commonly used in soil water content analysis (Brocca et al., 2009; Biswas & Si, 2011; Hu et al., 2013), it had not yet been employed in groundwater studies before our research. For the first time, we innovatively explored the time stability analysis in this study to synergistically measure the spatial and temporal information of the groundwater changes.

We identified the representative area of the YRB which could be used to overall monitor the temporal trend of the basin (Figure 3.2). They are the north of Ningxia and the west of Neimenggu which are relatively arid area across the basin, thus having relatively stable manifestation of water distribution over time. This result is consistent with the exploration of time stability in the soil water content studies by Hu et al. (2010) where drier locations have stronger time stability.

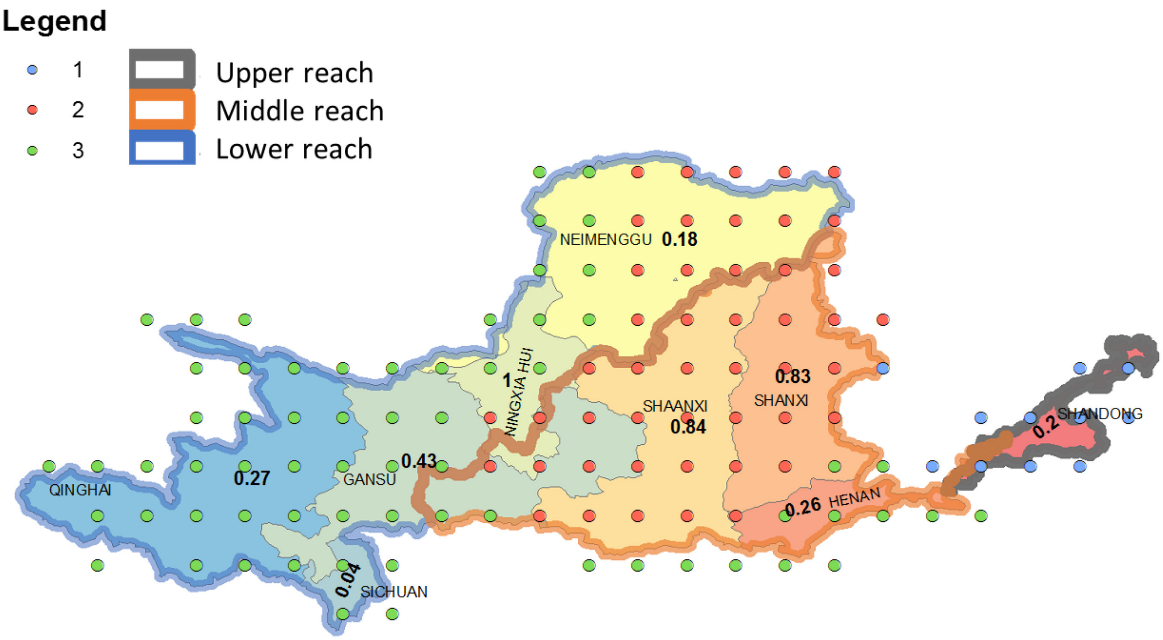
Despite the conceptual validity that measuring the representative area can capture the general trend of the whole basin over time, nonetheless, groundwater in the point scale may vary significantly due to different geological structures and various recharge-discharge systems. The more meaningful use of this method for groundwater study is to identify problematic area. Here we further employed the indices of time stability analysis to identify clusters for management. The grids in Group 4 are the places require immediate actions (Figure 3.3). It includes the source region of the Yellow River in the Qinghai province, and the river mouth in the east of the Shandong province (Figure 3.4). The significant groundwater decrease in the source region indicates the potential glacier retreat in the Qinghai Tibet Plateau (Deng & Zhang, 2018) while the decrease in the river mouth may result from the increasing water demand with soaring population (Zhang et al., 2011).

Apart from the most problematic area, other groups identified through the multivariate cluster analysis (Figure 3.3) implicate different strategies in groundwater management. For example, the area that requires attention on resilience (Group 2) mainly locates near the boundary of the YRB (Sichuan province, and the lower stream in Shandong Province). It implicates abrupt water interactions over the study period. These abrupt changes of water influx and outflow may partially result from the soil type. A higher hydraulic conductivity of the aquifers (e.g. sand and gravel) with a low permeable basement (e.g. lacustrine deposit) and a continuing slope can lead to a quickly recharged or discharged groundwater system. In the lower stream, the raised water bed is one of the main recharge of the aquifers. The change of flood and dry season may also be a reason of the fluctuations. Moreover, these frequent fluctuations of groundwater storage may indicate a less stable and resilient ecological environment, which if extreme events arrive, may lead to considerable damage, like groundwater flooding, dry wells, and even land subsidence (Konikow & Kendy, 2005; Macdonald et al., 2008; Scanlon et al., 2012). Considering the increasing threat from the climate change (Famiglietti, 2014; Hanjra & Qureshi, 2010), it is suggested to strengthen its mechanism of environmental response (e.g. reservoir and flood control system) in the area so as to increase its capacity in withholding abrupt large amount of water inflow and surviving in the drought times.

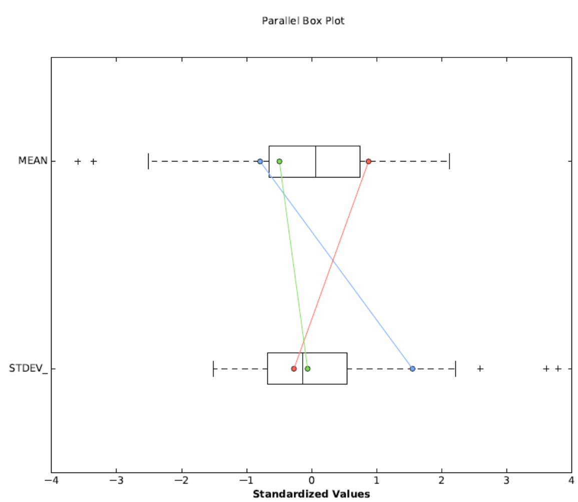
The area with rejuvenation (Group 3) were mainly found in the middle reach which indicates general increases of groundwater storage in these regions (Gansu, Shaanxi and Shanxi). It might indicate the reduced discharge and/or the increased recharge. For example, Han (2003) listed several artificial recharge schemes conducted in China including surface-spreading system and deep well injection. Cong et al. (2009) suggested that artificial water consumption was the main cause of the drying up of the Yellow River after 1950s. And they indicated that a better situation of Yellow River in the 21st century was due to the enhanced management of the water resources. However, we should take caution in interpreting these signs of rejuvenation. It doesn't necessarily mean the freshwater resource here is free of concerns and that the water management is always on the right track. According to local news and related literature, it is suspected that there are increasing human injection of groundwater under the imbalanced rigor of law between the surface water and groundwater. That is to say, the monitoring system in groundwater on both quality and quantity is incomplete, thus having less restriction to industries than the surface water. While the wastewater effluent to surface water will be charged with high fees if not being treated, it is hard to detect the discharge of untreated sewage to the wells. To reduce the cost in water disposal, some companies will illegally inject the untreated sewage into the aquifers without water treatment (Keranen et al., 2014; Yin et al., 2016)). In this case, the water quality of the groundwater may be of a concern, and an improved inspection system on the sewage to wells should be installed. Also, current water-saving constructions may have nonlinear impacts on groundwater storage changes. For example, Xu et al. (2010) testified that the groundwater storage will be reduced (water table lowered by 0.28-0.48m) with the water-saving constructions in Hetao Basin. However, later on, they use MODFLOW and GIS to refute their previous results, announcing that water-saving constructions could save groundwater by reducing evaporation (Xu et al., 2011). Their change of results may at least demonstrate that the connections between groundwater and water-saving practices are complex and may be dynamic.

The result of multivariate cluster analysis provides one way of the categorization which we think is most meaningful. However, it is also possible to divide the YRB into groups based on other categorization that may be more practical for decision-making. When using this method to other areas, researchers are suggested trying different numbers of grouping for multiple times to find the most effective way for the specific questions. In this study, we have also used three groups to identify the clusters. The clustering is very consistent with the reach's divisions, however, may have less potential than the five-group clusters for effective management (Figure 3.5).

a.




b.




c.

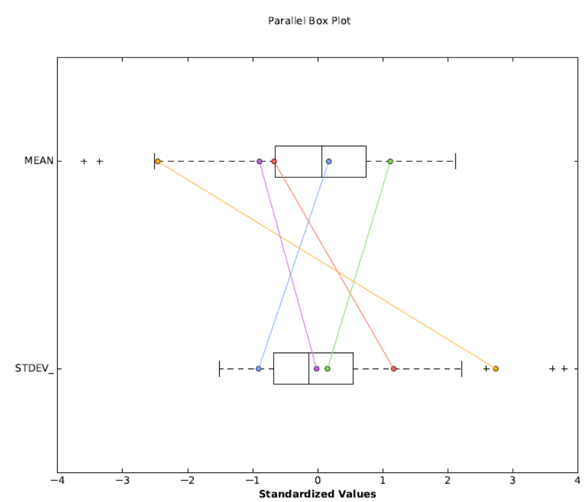



**Figure 3.5 The result comparison between different clustering strategies.** a. The cluster map of three-cluster analysis for MRD and SDRD of groundwater changes in the YRB during 2003-2016. The left box plot (b.) shows the value distribution of each group compared with global statistics in the three-cluster analysis while the right box plot (c.) is for the five-cluster analysis (also see Figure 3.3 for the cluster map of the five-cluster analysis). The black box plots are the global statistics (including global lower whisker, global lower quartile, global median, global upper quartile, global higher whisker). The "+" represents the outliers which are the values away from the mean by 1.5 times larger than the standard deviation. The colored dots in the two box plots indicate the median

of the group values for the two variables. While the five-cluster analysis identified the extreme high negative value of MRD and high SDRD in the group 4 (orange line), the three-cluster analysis failed to identify this meaningful group.

Also, our limited timeframe of study (14 years from 2003-2016) may not be sufficient to capture long-term fluctuations of groundwater which are usually the cases for deeper aquifers. As GRACE data accumulated over time, we expect to obtain longer time series of groundwater recharge data to capture changes influenced by land cover changes and climate, thus serving for long-term water plan.

Despite the uncertainty in defining the clusters and limited timeframe, both the time stability analysis and cluster analysis in this study succeeded in displaying the spatial-temporal information in a more explicit way, thus providing clearer instructions for groundwater management. Our method can be adopted in water management in other regions, and we suggested combining obtained results with groundwater quality measurements for the final decision-making.

With an increasing stress in the freshwater availability under exploding population and unpredictable climate change (Rodell et al., 2018), groundwater will play an increasingly important role as a natural reservoir in remediating extreme events and unexpected water crisis. The recent water crisis in Cape Town, Africa is one of the examples (Nel et al., 2018; Nordling et al., 2018). Under an emerging need for groundwater use, our study has provided an opportunity to have a targeted management strategy based on the spatio-temporal information of groundwater. Further studies could investigate the local groundwater use and its impacts to stakeholders' livelihoods which may help to develop a community-based strategy for the sustainable use of groundwater resource.

## 3.5 Conclusions

This study provides a holistic analysis on spatial-temporal dynamics of groundwater resource in the YRB. The middle reach of the YRB (north of Ningxia and west of Neimengu) displays the most time stable characteristics in terms of the groundwater changes, therefore can be used as a representative monitoring area to show the overall changes of the YRB overtime. Moreover, the origin of the Yellow River and its river mouth showed severe groundwater falls and high fluctuations which displayed two extreme cases respectively devastated by natural and human pressures. We suggested robust risk response systems should be installed in these two regions and more serious regulations on groundwater use should be implemented in the Yellow River Delta. The cautions and efforts put on groundwater management will not only help to satisfy the long-term needs of residents for portable water and food, but also help to strengthen the region's resilience in facing the threat of climate change and growing populations. The method of time stability analysis coupled with multivariate cluster analysis is promising for adoption to other groundwater-fed regions to build a more effective and sustainable management system for groundwater resource.

## Acknowledgements

The authors would like to acknowledge the Chinese Scholarship Council (CSC), Natural Sciences and Engineering Research Council (NSERC) of Canada (RGPIN-2014-4100) which funded this research and NASA who provides the necessary data for this study. Special acknowledgements are also due to Dr. Lehner Bernhard, Dr. Gordon Hickey, Dr. Jesse Rieb and Dr. Shuang Gao who provided essential suggestions for this project.

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# Appendix 3.1

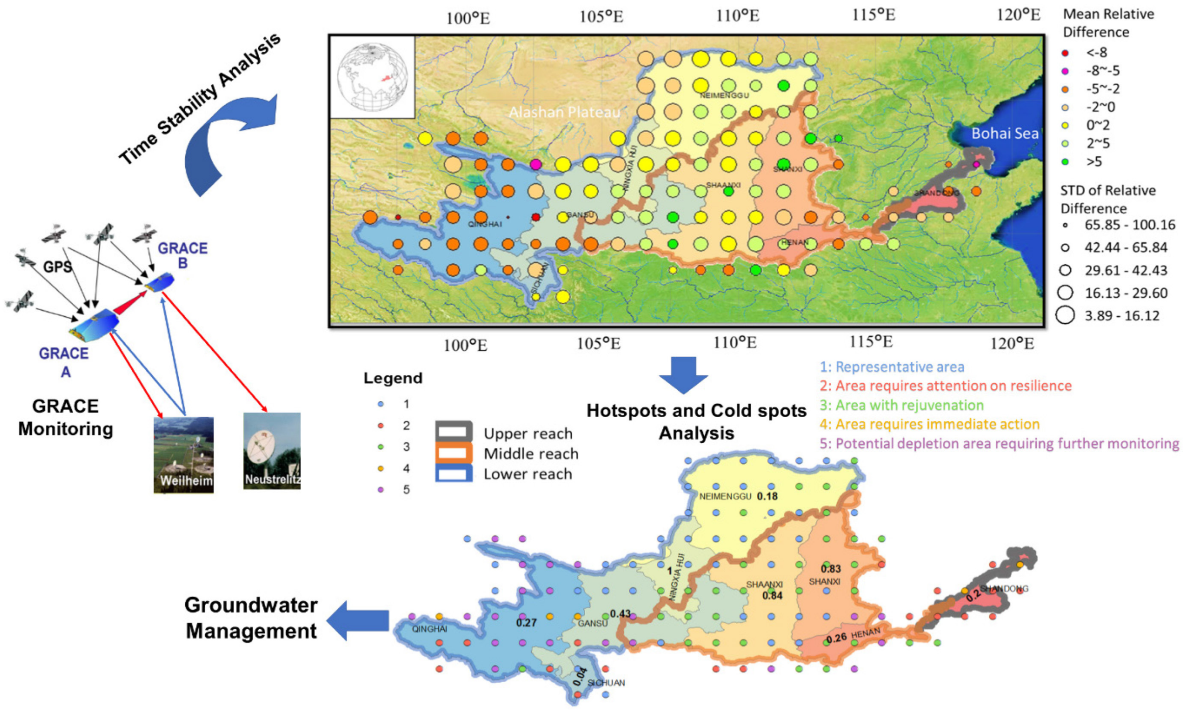



Figure S3.1 Graphic abstract for chapter 3.

# Connecting to Chapter 4

Chapter 3 provides a clearer interpretation from a management perspective of the groundwater dynamics in the YRB between 2003 and 2016 and proposes coping strategies. With the time stability analysis, I was able to use two indicators (i.e. Mean Relative Differences, and Standard Deviation of the Relative Difference) to integrate spatial and temporal information for regional management of groundwater dynamics. I identified the areas that can represent the general change of groundwater over time (middle reach around Ningxia, Neimenggu & Gansu), the areas that require an increase of the risk response system to strengthen the system's resilience (the Yellow River Delta at river mouth), and the areas that require immediate control of serious groundwater decline which has seriously affected the stability of the socio-ecological system. The knowledge on groundwater storage depletion and coping strategies learned from this chapter can assist water managers in identifying prioritized areas for groundwater management. Still, this knowledge is not enough for crafting targeted measures as it is still not clear which are the main drivers of the groundwater change in YRB.

Chapter 4 turns focus from the manifestations of groundwater dynamics to the underlining reasons for these changes. I examined the socio-ecological factors that affect the temporal and spatial changes of groundwater storage respectively. In detail, I collected data on a series of socio-ecological variables and used statistical analysis (i.e. stepwise regression analysis and principal component analysis) to identify the main determinants driving spatial and temporal changes of groundwater and quantify the relationships between the main factors (i.e. variables significantly related to groundwater) and groundwater storage. I further analyzed how the collected socio-ecological variables indicate the impacts of determinants on the spatial and temporal changes of groundwater. Specifically, given that the significant decline of groundwater storage clustered in the upstream portion of the YRB has been shifted to downstream after 2010 (result of Chapter 2), it is possible that the main drivers of groundwater decrease can be shifting over time and across the basin. In Chapter 4, I therefore investigated different correlations between groundwater storage and determinants respectively in different time periods (the periods of 2003-2009 and 2010-2016) and spatial groups (divided by different reaches or different provinces). This chapter corresponds to the second objective of the thesis to bring an improved understanding of the socio-ecological factors of groundwater change in the YRB.

# 4 Socio-ecological determinants of spatio-temporal changes of groundwater in the Yellow River Basin, China

**Highlight:**

- We identified predictors and determinants of groundwater change in the Yellow River Basin (YRB).
- We developed predictive models for spatio-temporal changes of groundwater storage in the YRB.
- Anthropogenic factors dominated temporal changes of groundwater in the YRB between 2003 and 2016.
- Nature and human collectively determined the spatial changes of groundwater in the YRB.


## Abstract

The spatio-temporal complexity of groundwater storage change is a result of interconnected impact of socio-ecological factors. Previous research indicates several socio-ecological factors (e.g. human extraction, land cover change, and climate change) that may result in groundwater depletion. However, we seldom have empirical studies that provide spatio-temporally explicit information on the main drivers among these factors that determine regional groundwater change. This research explored a spatio-temporally explicit understanding on the socio-ecological determinants of the changes of groundwater storage in the Yellow River Basin (YRB) of north China. We selected this basin because its spatial heterogeneity complicates the relationship between socio-ecological factors and groundwater resources. We collected annual (time resolution) data between 2003 and 2016 (time scope) with 1°× 1° grid (space resolution) on about 18 social-ecological factors that might affect groundwater storage change in the YRB (space scope). Using this data and groundwater storage information from Gravity Recovery and Climate Experiment database, we determined key predictors, highly performed predictive models, and dominant drivers for temporal and spatial changes of groundwater storage. Temporal changes of groundwater in the YRB between 2003 and 2016 were mainly contributed by anthropogenic factors, including population density, plantation, and irrigation water consumption over time. The spatial groundwater changes across the YRB were determined by both the geographical location

(e.g. indicated by longitude) and urbanization level (e.g. indicated by the domestic and industrial water consumption). The knowledge about the role of socio-ecological determinants of groundwater dynamics in space and time in the YRB can help determine main levers controlling regional change of groundwater storage and assist in a sustainable use of groundwater resources.

**Keywords:** groundwater management; socio-ecological factors; stepwise regression; principal component analysis; GRACE

## 4.1 Introduction

Groundwater depletion has become a global phenomenon that requires immediate attention in management (Wada et al., 2010). Estimates of changes in groundwater storage from the Gravity Recovery and Climate Experiment (GRACE) project have shown an astonishing decrease of groundwater storage globally (Rodell et al.. 2018), including Australia (-18 ± 1.3 mm/year), North India (-40 ± 10 mm/year), California (-20.4 ± 3.9 mm/year), and North China (- 22 ± 3mm/year) (Leblanc et al., 2011; Tregoning et al., 2012; Rodell et al., 2009; Famiglietti et al., 2011; Scanlon et al., 2012; Feng et al., 2013; Huang, et al, 2015). The worldwide depletion of groundwater has already given rise to a series of environmental problems, including wetland shrinkage, land subsidence, ecosystem degradation, and sea water intrusion (Chai, et al, 2004; Ergil, 2000; Griebler & Avramov, 2015). Even though we have developed knowledge about groundwater depletion, the groundwater stress continues to expand around the world (Aeschbach-Hertig & Gleeson, 2012; Rodell et al., 2018).

Regional studies have indicated that both anthropogenic and biophysical factors can play important roles in changing groundwater storage (Foster & Chilton, 2003; Aeschbach-Hertig & Gleeson, 2012). Anthropogenic factors that influence groundwater storage include drinking water supply, irrigation, dam construction, and other human activities (Xu et al., 2010; Hayashi et al., 2009). Biophysical conditions such as elevation, temperature, soil water content, latitude and longitude can also profoundly impact groundwater storage changes (Taylor et al., 2013; Scanlon et al., 2005; Wang et al., 2019). These socio-ecological factors may be coupled (Smerdon, 2017). For example, groundwater overuse (anthropogenic) can be a result of a long-lasting drought (biophysical), and the lack of precipitation during the drought would further stimulate excessive withdrawal of groundwater, which accelerates groundwater depletion (Scanlon et al., 2005; Smerdon, 2017).

These socio-ecological factors can affect spatial and temporal changes of groundwater storage in different ways, which requires more empirical studies. For example, Taylor et al. (2013) suggested that the change of groundwater storage over time can be closely related to the occurrence of climate extremes, but Li et al. (2014) identified that groundwater exploitation can influence the temporal changes of groundwater storage more than precipitation and evapotranspiration. While some studies have found that the spatial distribution of groundwater recharge on the Earth may be related primarily to the general distribution of global precipitation (Taylor et al., 2013), others indicated that soil and land attributes can be the most significant factors for groundwater storage (Fu et al., 2019). Comprehensive knowledge of the contribution of each factor to the spatio-temporal changes of regional groundwater storage is still scattered, and lacks quantitative analysis (Taylor et al., 2013; Fu et al., 2019).

Further, effective groundwater management needs information about the main drivers that dominate the change of groundwater storage, which requires a clearer interpretation. While there is a series of studies examining relationships between individual socio-ecological factors (e.g. precipitation, temperature, land use changes, and groundwater withdrawal) and groundwater dynamics, we find limited studies that examine these factors in a spatio-temporally explicit way or discuss their synergies (Javi et al., 2014; Li et al., 2014; Ainiwaer et al., 2019; Taylor et al., 2013). These synergies can be represented by dominant drivers which represent collective impacts of a series of measured socio-ecological factors. By identifying these drivers and quantifying their spatial and temporal relationship with groundwater storage, we can understand which factors are more responsible for regional groundwater change and their synergetic impacts on the groundwater resource, thus determining possible levers to control groundwater storage change (Fu et al., 2019).

Our research aims to have deeper understanding about the impacts of socio-ecological factors on the spatio-temporal changes of groundwater storage by 1) identifying best predictors among the collected socio-ecological factors for the spatio-temporal changes of groundwater storage, 2) presenting best regression models to quantify the impacts of these predictors on groundwater storage and 3) determining the dominant drivers that these factors collectively contribute to. We selected the Yellow River Basin (YRB) in north China as study area. The YRB is an important river basin supporting millions of people and a challenging river basin for environmental studies with complex socio-ecological background and high spatial heterogeneity

(Gassert et al., 2013). Our research is expected to untangle the complexity of multi-facet impacts of socio-ecological factors and assist in effective groundwater management.

## 4.2 Materials and methods

### 4.2.1 Study area

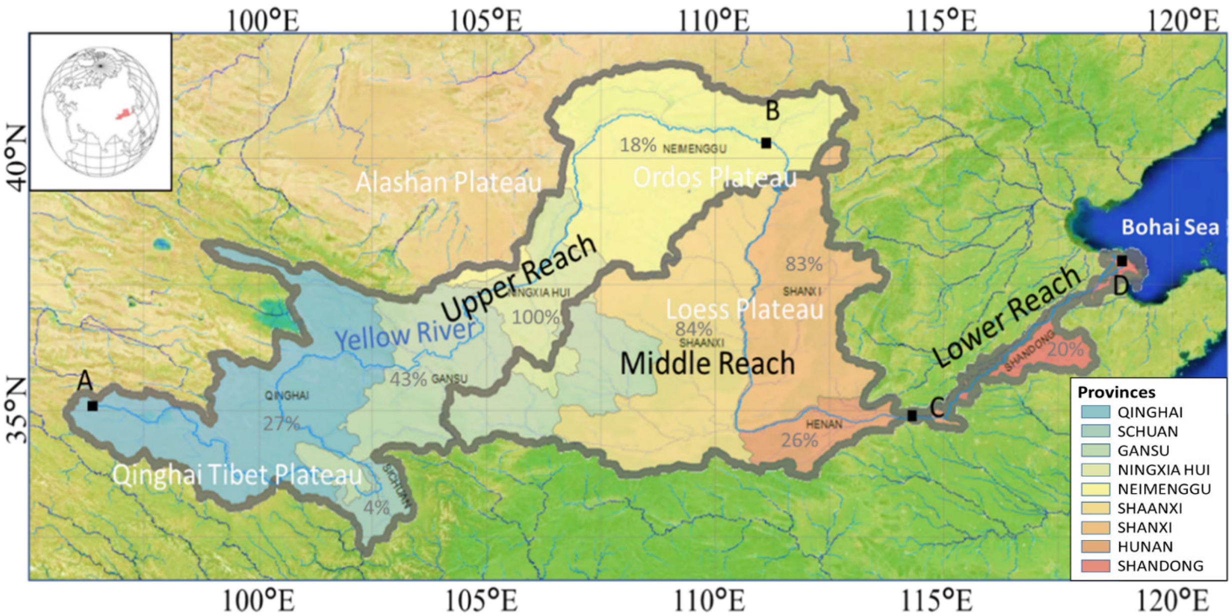



**Figure 4.1 Map of the Yellow River Basin.** (Revised from Lin et al., 2019a; Gassert et al., 2013, Chapter 2). The main flow path of the Yellow River is blue bolded, flowing from Qinghai Tibet Plateau, passing Alashan Plateau, Ordos Plateau and Loess Plateau, and ending in the Bohai Sea. A-B is upper stream, B-C is middle stream and C-D is lower stream. The grey-bolded lines delineate three reaches (upper, middle and lower). Within the three reaches, the colored polygons represent nine provinces in the YRB. Adjacent value is the area percentage of each province that is within the river basin.

The YRB is located in the north of China with the area of 795,000 km$^2$. Nine provinces are along the Yellow river, each of which has a different percentage of land within the Yellow River Basin (Figure 4.1). Both the river and river-fed aquifers collectively feed more than 120 million people in these provinces (Liu et al., 2008). Groundwater has close connections to the surface water and is mainly recharged by the Yellow River and discharged by river runoff, human extraction, and evapotranspiration (Xu et al., 2010). The river basin can be divided into three main parts according to distinct topographical differences: a) the mountainous upper reach (4600m-

500m, 2m/km downward slope), b) the middle reach across the plateau (500m-100m, 9cm/km downward slope), and c) the lower reach across a flat plain (100m-0m, 20cm/km downward slope) (Popov & Greer, 2019). The basin mainly consists of loose sediment rock layers but with several distinctions in different reaches: in the upper reach where the Qinghai Tibet Plateau locates, there are permafrost with underlining frozen layers; in the middle reach where Ordos Plateau and Weihe Catchment locate, clastic rock type fissure and pore waters are scattered; in the lower reach where Lvliang Mountain and Liupan Mountain sit, karst waters are prevalent (Xu et al., 2002; Eryong et al., 2009; Xu et al., 2010; Xu et al., 2011). The level of economic development in the Yellow River Basin is analogous to the geographic elevation as indicated by GDP increases from the upper reach to lower reach (Gassert et al., 2013).

Being one of the largest and populated river basins in the world, the YRB is the most challenging region in China for water management. It has a very heterogeneous landscape with three topographical stages from northwest to southeast. Water use regulation and related constructions (e.g. dams) have also brought impacts on the distribution of water resource in this watershed (Wang et al., 2006; Yang et al., 2008). The spatio-temporal examination of the factors of groundwater change is essential for the diversified development and adaptive management of this area.

### 4.2.2 Data collection and pre-processing

Table 4.1 Data list on groundwater storage and its related factors. The variables with the "*" are static variables (only one snapshot) while others are dynamic variables (time series from 2003-2016).

| **Abbreviation (Time frame)** | **Explanation** | **Unit** | **Key pre-process** | **Reference** |
|---|---|---|---|---|
| **GW (2003-2016)** | Groundwater storage change | cm | Extracting and scaling | Swenson, 2012; Lin et al., 2019a |
| **SW (2003-2016)** | Soil water content | mm | Spatial Upscale | Ven de Dool et al., 2003 |
| **PEV (2003-2016)** | Potential Evapo-transpiration | mm/day | Spatial Upscale | Harris et al., 2014 |
| **PRE (2003-2016)** | Precipitation | mm/month | Spatial Upscale | Harris et al., 2014 |
| **TEM (2003-2016)** | Temperature | Celsius degree | Spatial Upscale | Fan & Van den Dool, 2008 |

| | | | | |
|---|---|---|---|---|
| **NDVI (2003-2016)** | Normalized Difference Vegetation Index | vegetation index | Temporal forecast after 2010. Extract values for each grid. | Wang & Chen, 2016 |
| **DEM* (2017)** | Digital elevation model | m | Spatial Upscale | China data center, 2017 |
| **POP (2003-2016)** | Population density | number of persons/$km^2$ | Time interpolation between 2005, 2010, and 2015, regression towards 2016 | Center for International Earth Science Information Network of Columbia University, 2018 |
| **IRRC (2003-2016)** | Irrigation water use | mm/month | Temporal forecast from 2010 up to 2016. | Huang et al., 2018 |
| **DOMC (2003-2016)** | Domestic Water Consumption | mm/month | Temporal forecast | Huang et al., 2018 |
| **INDC (2003-2016)** | Industrial Water Consumption | mm/month | Temporal forecast | Huang et al., 2018 |
| **LIVC (2003-2016)** | Livestock Water Consumption | mm/month | Temporal forecast | Huang et al., 2018 |
| **IRRW (2003-2016)** | Irrigation Water Withdrawal | mm/month | Temporal forecast | Huang et al., 2018 |
| **DOMW (2003-2016)** | Domestic Water Withdrawal | mm/month | Temporal forecast | Huang et al., 2018 |
| **INDW (2003-2016)** | Industrial Water Withdrawal | mm/month | Temporal forecast | Huang et al., 2018 |
| **LIVW (2003-2016)** | Livestock Water Withdrawal | mm/month | Temporal forecast | Huang et al., 2018 |
| **IRRAREA* (2018)** | Irrigated area% | % | Spatially upscale (use the mean) | Rodell et al., 2018 |
| **DAM* (2011)** | Representative maximum storage capacity of the dam | million $m^3$ | Convert to raster | Lehner et al., 2011 |
| **BWS* (2013)** | Baseline water stress (total water withdrawal / total available water resource) | % | Convert to raster | Gassert et al., 2013 |

We applied the GRACE data in this research to represent the groundwater storage change (Table 4.1). The data is available at http://grace.jpl.nasa.gov and is supported by the NASA MEASUREs Program (Swenson, 2012; Landerer & Swenson, 2012; Swenson & Wahr, 2006). More details on the collection and processing of the GRACE data can be found in Lin et al. (2019a) (also see Chapter 2).

Previous studies have indicated that groundwater storage can be affected by biophysical factors like soil water content, potential evapotranspiration, precipitation, temperature, vegetation growth, and anthropogenic factors like population density, water use, irrigation and dam construction (Chaussard et al., 2013; Rahm & Riha, 2012; Hellegers, Zilberman & Van, 2001; Scanlon et al., 2005; Shah, 2007; Foster, 1990; Naik et al., 2008). Based on this knowledge, we collected available data on 18 socio-ecological factors relating to groundwater change (Table 4.1).

We extracted and processed the data to a consistent scope and resolution: 1°× 1° grid data (spatial) within the Yellow River Basin (96.5-118.5E 32.5-41.5N) and annual time series (temporal) from 2003 to 2016. For data available at a finer grid (e.g. 0.5°/ 0.25° resolution), we upscaled to 1° resolution using ArcGIS (main functions include "Extract value by points" and "Zonal statistics"). For the shapefile data, we used the similar functions in ArcGIS to convert them to a raster, and then calculated the average values for each 1°×1° grid. For the data with finer time series (e.g. monthly data), we averaged them to obtain annual time series. The population density data is available for the years 2000, 2005, 2010, 2015, and predicted for 2020. We therefore interpolated the data using linear interpolation to obtain the time series from 2003 to 2016. The available water use data is from 2003-2010, so we used an advanced machine learning method (Exponential Triple Smoothing algorithm) to forecast the values of water use between 2011 and 2016 (Excel function "FORECAST.ETS") (Kalekar, 2004; De Livera et al., 2011). With the abovementioned pre-processing, we obtained 14 dynamic variables (SW, PEV, PRE, TEM, NDVI, POP, IRRC, IRRW, INDC, INDW, DOMC, DOMW, LIVC, LIVW) and four static variables (DEM, BWS, IRRAREA, DAM). The static variables each have one gridded map (125 pixels) and the dynamic variables each have 14 gridded maps from year 2003 to 2016 (Table 4.1).

To provide required data for spatial and temporal analysis, we further averaged the pre-processed data in space and time scale separately. For temporal analysis, we used the 14 dynamic variables. We averaged grid values across the YRB in each year to represent temporal changes of socio-ecological factors at basin scale between 2003 and 2016. For spatial analysis, we collected an 18-layer map for the YRB. Each grid of those layers includes annual average value of 18 factor variables. In order to investigate the impact of geographical location on the spatial change of groundwater resource, we also included latitude (Lat) and longitude (Lon). In this paper, we referred to the processed average time series as temporal variables and the averaged gridded map as spatial variables for ease of explanation.

### 4.2.3 Data analysis

We conducted data analysis mainly using R programming (packages include “leaps”, “mass”, and “factoextra”, R core team, 2013). We first identified the key predictors for groundwater storage changes in time and space using the regression subset selection method (Fu et al., 2019). Then we applied stepwise regression analysis to present the best regression models respectively for temporal and spatial changes of groundwater storage (Ripley, 2019). Finally, we used Principal Component Analysis (PCA) to identify the key dimensions from the 18 collected factors (Abdi & Williams, 2010), indicating the dominant drivers for the spatial and temporal changes of groundwater storage.

A good predictor in this study means that its changes have a high probability to be significantly correlated with the changes in the response variable (i.e. groundwater storage changes) in the multiple regression models (Fu et al., 2019; Lumley, 2013). To identify the best predictors among the 18 socio-ecological factors, we applied the regression subset selection method (*regsubsets* function in R package “leaps”). This method could exhaustively generate multiple regression models from the 18 socio-ecological factors and rank them by adjusted $R^2$ (Lumley, 2013; Kvålseth, 1985). We used the significance percentage to measure the predictability of each factor: the number of models in which the factor is significant divided by the total number of models that include the factor (Fu et al., 2019). This indicator (i.e. significance percentage) shows the probability that the factor is impacting groundwater change. The higher percentage represents a stronger ability in predicting groundwater (GW in Table 4.1) in time or space. This method outperforms the marginal correlation coefficient because it can consider the suppressor variables which may not correlate with groundwater storage separately but may show significant correlation in multiple regression models when being put together with other factor variables (Woolley, 1997) (Figure 4.2).

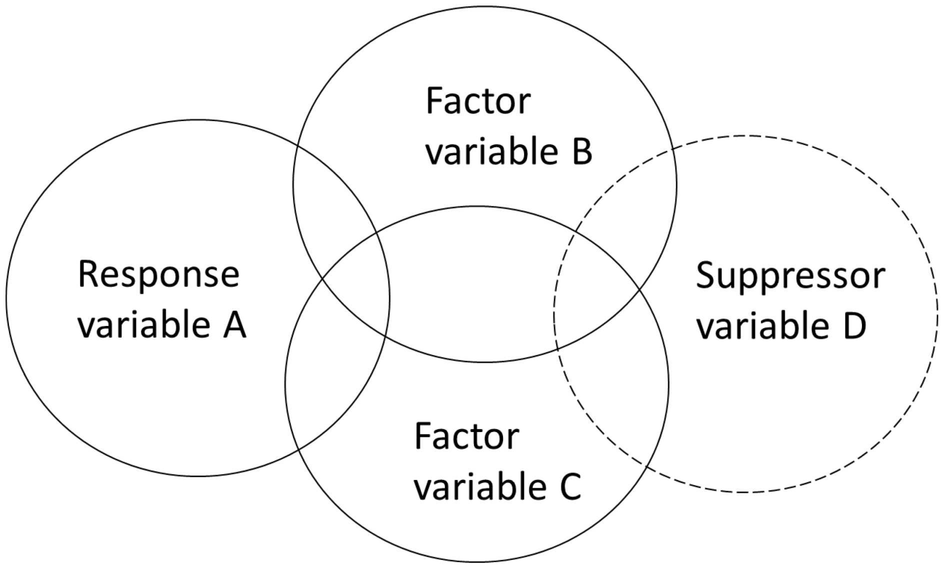



**Figure 4.2. Conceptual diagram for suppressor variable.** A is the response variable, B and C are correlated factor variables. Suppressor (factor) variable D is not correlated with A, but has indispensable impact on the variance of A through indirect impact of B and C. So, D may not show significant correlation with A in marginal correlation coefficient but can have important impact on the variances of A and may indicate a high significance percentage in candidate regression models.

To quantify the relationship between main predictors and groundwater change, we selected the regression model with highest adjusted $R^2$ among all candidate models. The quantification was done with the stepwise regression (*steps* function in R package "mass"). Respective regression coefficients for each predicting variable were provided (Fu et al., 2019; Ripley, 2019).

To understand the key driving mechanisms of groundwater change, we applied PCA (*fviz_pca* function in R package "factoextra") (Kassambara & Mundt, 2017). It can reduce the dimensions we need to consider when managing groundwater while not losing important information (Abdi & Williams, 2010; Helena et al., 2000). This information helps us to know how factors collectively impact the change of groundwater. To do so, we first examined the slope of the Scree plot which shows the contributions of each underlining dimensions to the total variances of all variables. The major dimensions were identified from the first to the break point where the slope was changed. The total variances of groundwater storage change were represented by these major dimensions (Abdi & Williams, 2010). We analyzed the relations between each factor and the major dimensions based on biplot. Each observation was also pinpointed in the biplot.

To further examine the change of key dimensions across time and space, we grouped the observations into sub-levels of time and space scales respectively and analyzed how they were positioned in the biplot. The way we divided the time and space scale was based on our previous research on the spatio-temporal changes of groundwater storage within the YRB which displayed different patterns at specific sub-levels (Lin et al., 2019a; Lin et al., 2019b; Chapter 2 & 3). In temporal scale, we grouped them into two half time period 2003-2009 and 2010-2016 to see if the key driving dimensions changed between earlier and later time periods. In spatial scale, we grouped them into reach level, and provincial level respectively to see how the driving mechanisms of groundwater change differed in sub-areas.

## 4.3 Results

### 4.3.1 Factors determining temporal change of groundwater storage

#### 4.3.1.1 Predictors for temporal changes

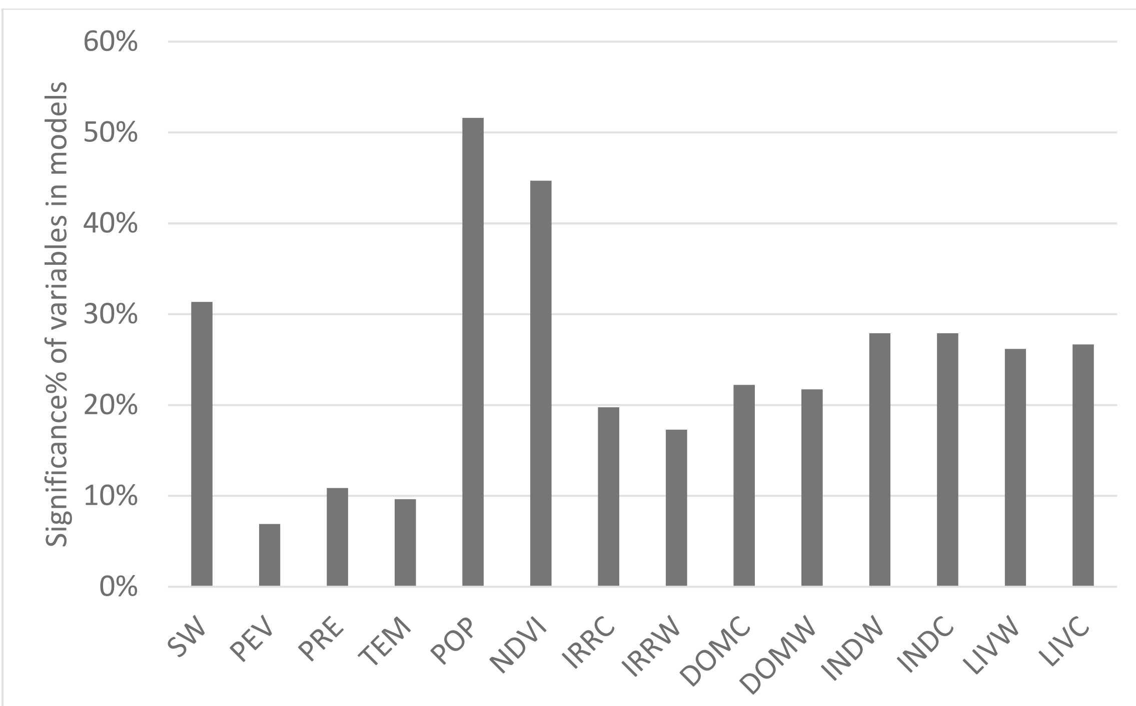



**Figure 4.3 Significantly correlated factors for the temporal changes of groundwater storage.** The y axis shows the significance of the variable as a predictor for temporal groundwater change. The x axis includes the 14 temporal variables.

The population density (POP) had highest percentage of significant correlation with groundwater storage (GW), followed by vegetation growth (NDVI) and soil water content (SW) (Figure 4.3). This result indicates that population density, vegetation growth and soil water content were the most reliable predictors for the temporal change of groundwater. The least relevant factors for the temporal groundwater change in the YRB included potential evapotranspiration (PEV), precipitation (PRE) and temperature (TEM), but they still showed some significant correlations with groundwater storage in some regression models (Figure 4.3). Also, we found that water consumptions by sectors usually had a better predictability than water withdrawals for the temporal changes of groundwater storage (e.g. the significance percentage of irrigation water consumption was larger than irrigation water withdrawal).

#### 4.3.1.2 Predicting temporal changes in groundwater storage

Table 4.2 Selected linear regression model for temporal groundwater (Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1).

| **Model 1: GW ~ Intercept*- NDVI*** - IRRC *+ DOMC* - INDC* + LIVC*** | | | | | **Adj. $R^2$=0.97** |
|---|---|---|---|---|---|
| | Estimate | Std. Error | t value | Pr(>\|t\|) | Significance |
| **(Intercept)** | 1.91E+03 | 6.32E+02 | 3.022 | 0.016509 | * |
| **NDVI** | -1.30E+01 | 2.06E+00 | -6.277 | 0.000239 | *** |
| **IRRC** | -1.11E+01 | 3.72E+00 | -2.975 | 0.017723 | * |
| **DOMC** | 1.78E+05 | 5.60E+04 | 3.183 | 0.012937 | * |
| **INDC** | -2.51E+06 | 8.20E+05 | -3.054 | 0.015714 | * |
| **LIVC** | 2.62E+06 | 8.61E+05 | 3.042 | 0.016007 | * |

Temporal Model 1 had the highest adjusted $R^2$ among all candidate regression models, which indicates the best possible linear relationships between collected socio-ecological factors and temporal changes of groundwater (Table 4.2). Vegetation growth (NDVI), industrial water consumption (INDC) and irrigation consumption (IRRC) had statistically significant negative relationship with groundwater storage (GW), while domestic water consumption (DOMC) and livestock water consumption (LIVC) had a statistically significant positive relationship with groundwater storage. Altogether, this model explained 97% of the differences in temporal change of groundwater storage.

#### 4.3.1.3 Dominant drivers of temporal change in groundwater storage

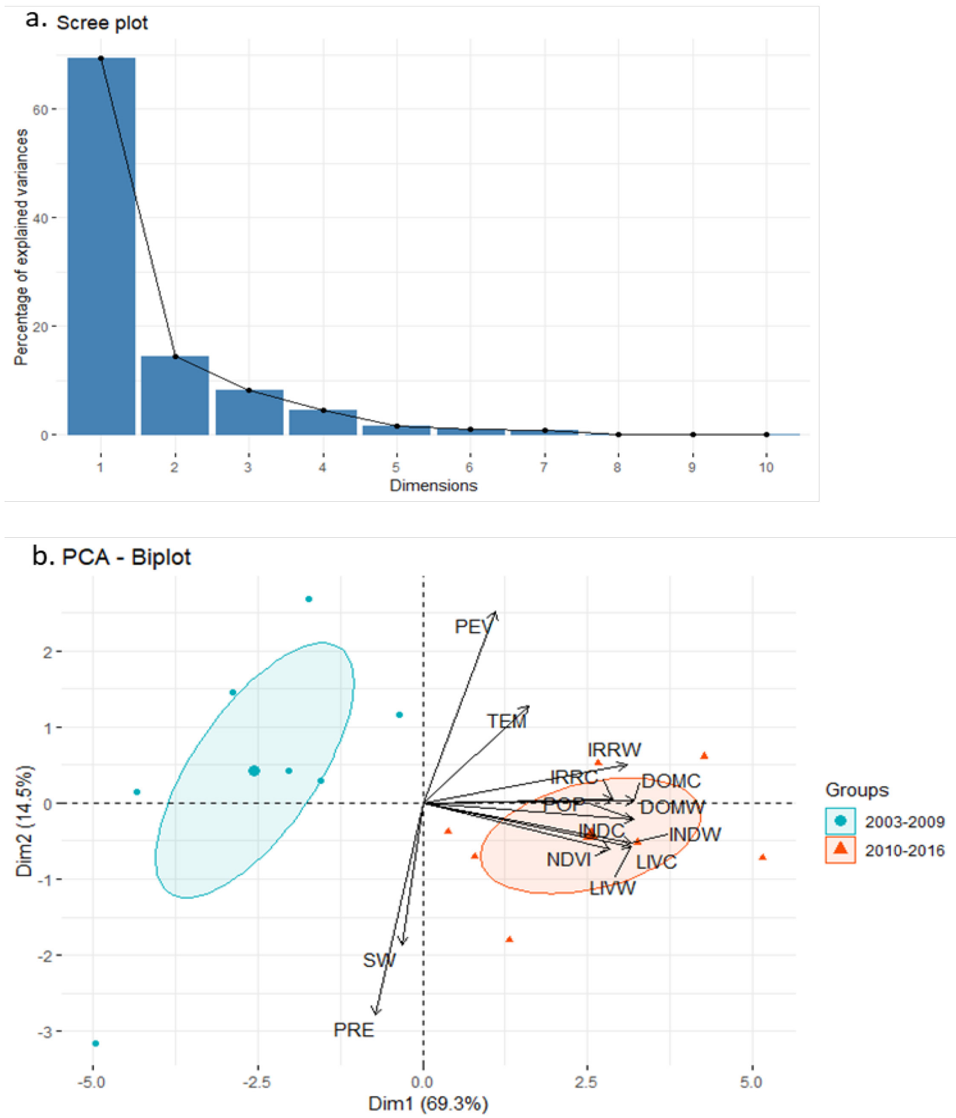



**Figure 4.4 Main dimensions that represent most variances of temporal variables in the YRB.** a. Scree plot b. Biplot of the PCA for 14 variables. The points are observations and were grouped in two time period (2003-2009 and 2010-2016). The text in the matrix are the 14 temporal variables. The coordinates of the observation points/the variable text are the correlations between the individual observation/variable and the dimensions (X is the correlation with dimension 1, and Y is the correlation with dimension 2). The arrow points to the coordinate of each variable. Its direction indicates the variables' correlations: positively correlated variables point to the same side of the plot, while negatively correlated variables point to opposite sides. Variables perpendicular to each other have minimal correlations. The coordinates for a given group (two larger dots) is calculated

as the mean coordinates of the individuals in the group, and the ellipse were drawn based on the 95% of confidence level of the mean coordinate.

Temporal variables can be mainly grouped into two dimensions in PCA which altogether explained over 80% of total variances (Figure 4.4a). Dimension 1 (69.3%) represented anthropogenic changes (e.g. DOMC, DOMW, IRRC, IRRW, INDC, INDW, LIVC, LIVW, POP and NDVI). These factors all showed positive correlations with dimension 1. Here NDVI represents vegetation growth which was usually counted as biophysical changes in the literature. But in the YRB, vegetation growth can be also a result of human plantation (Li et al., 2001; Wang et al., 2010), thus can be counted as anthropogenic changes. Dimension 2 (14.5%) represented biophysical changes (i.e. SW, PRE, and PEV) (Figure 4.4b). Among them, soil water content and precipitation were positively correlated with dimension 2 while potential evaporation had negative correlation with dimension 2.

The impact of the dimensions (dominant drivers) on groundwater storage change displayed different patterns between the earlier (2003-2009) and the later (2010-2016) period. Before 2010, dimension 1 was negatively correlated with the observations of groundwater storage change while the relationship shifted to a positive correlation after 2010. Also, the observations of groundwater storage before 2010 had a relatively broader range of correlation coefficients with dimension 2 indicating that natural dynamics had diverse and complicated impacts on groundwater storage change.

## 4.3.2 Factors determining spatial groundwater storage change

### 4.3.2.1 Predictors for spatial changes

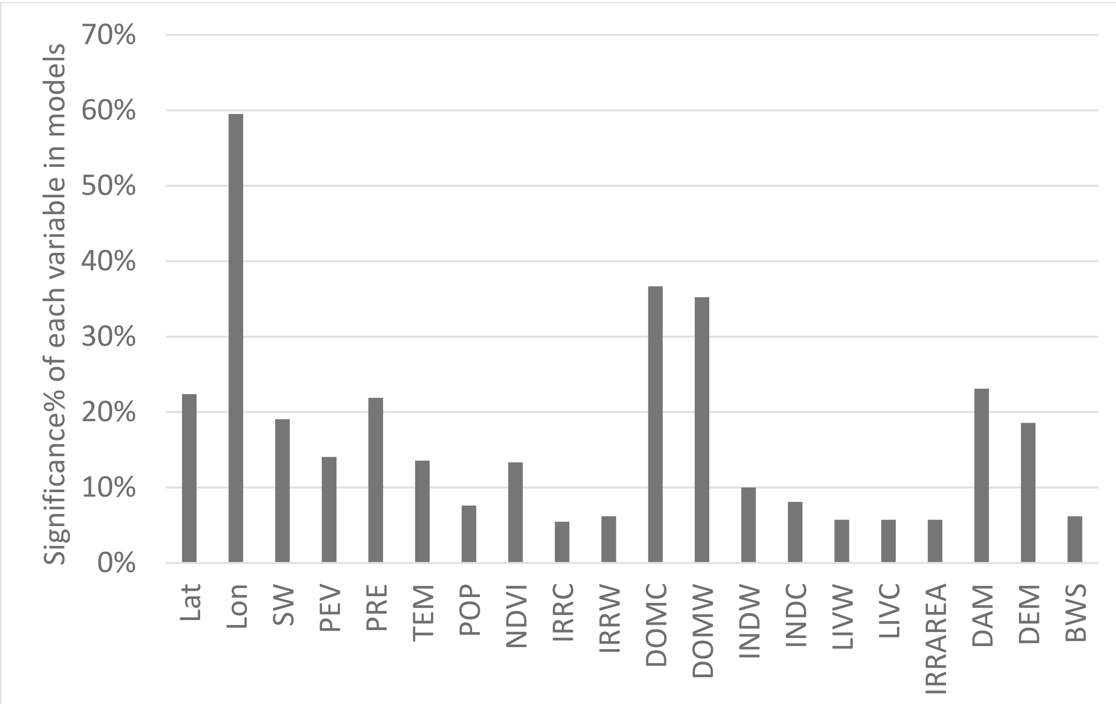



**Figure 4.5 Significantly correlated factors for the spatial changes of groundwater storage.** The y axis shows the significance percentage of the variable in all candidate linear regression models for spatial changes of groundwater storage. The x axis includes 20 spatial variables, from left to right is Latitude, longitude, soil water content, potential evapotranspiration, precipitation, temperature, population density, normalized difference vegetation index, irrigation water consumption, irrigation water withdrawal, domestic water consumption, domestic water withdrawal, industrial water withdrawal, industrial water consumption, livestock water withdrawal, livestock water consumption, irrigated area, representative maximum storage capacity of the dam, digital elevation model, and baseline water stress.

Among the socio-ecological factors we investigated in space scale, Longitude (Lon) had the highest probability of significant correlation with spatial changes of groundwater storage (GW), followed by domestic water consumption (DOMC), and domestic water withdrawal (DOMW) (Figure 4.5). While population (POP) had better predictability for temporal groundwater storage change, it had relatively low predictability for spatial changes of groundwater storage, which indicates that the population mainly affected the groundwater storage change in time (e.g. population increase or decline in the same place) instead of space (e.g. migration).

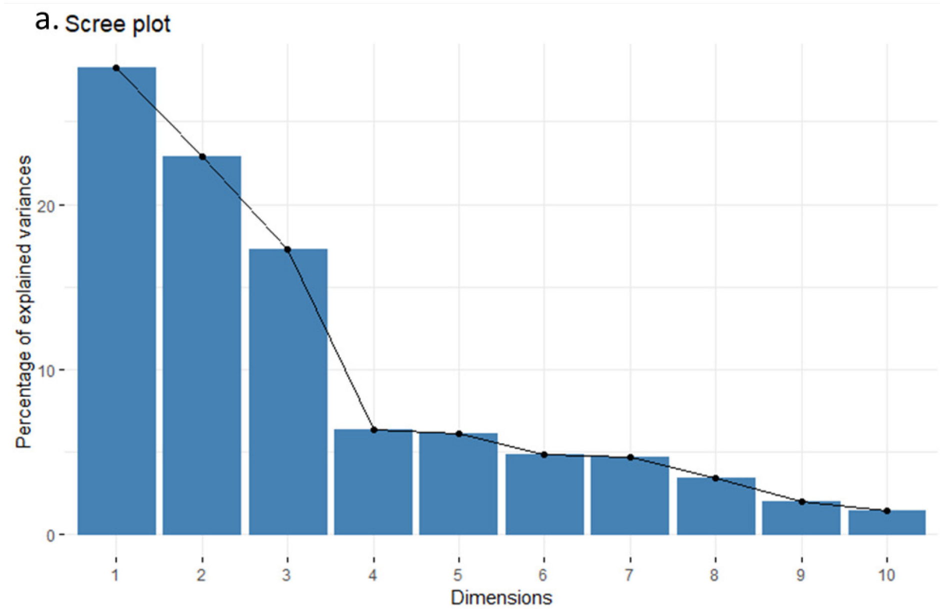
#### 4.3.2.2 Predicting spatial changes in groundwater storage

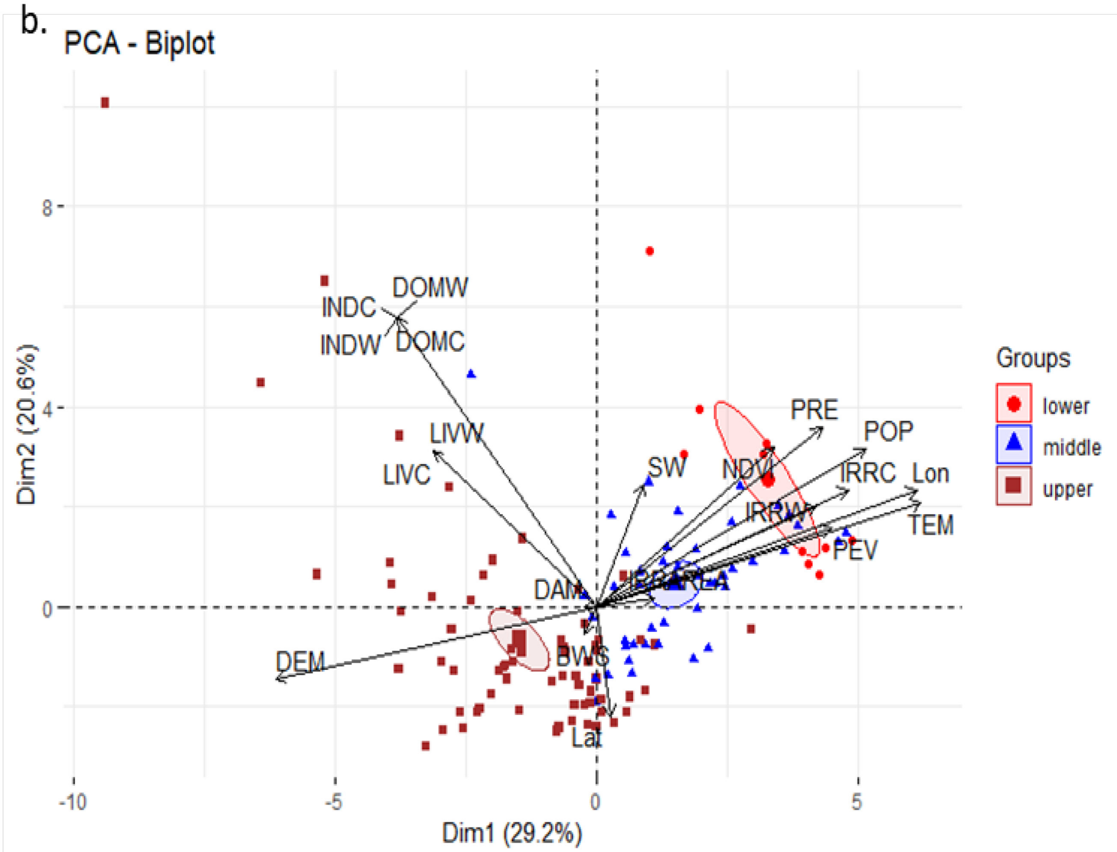
Table 4.3 Selected linear regression model for spatial groundwater change (Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1).

| **Model 1:** GW ~ Intercept***- Lat***- PRE***+ DOMC***- DOMW***- DAM** | | | | | **Adj. $R^2$=0.41** |
|---|---|---|---|---|---|
| | Estimate | Std. Error | t value | Pr(>\|t\|) | Significance |
| (Intercept) | 3.30E+01 | 5.01E+00 | 6.594 | 1.24E-09 | *** |
| Lat | -7.99E-01 | 1.22E-01 | -6.527 | 1.72E-09 | *** |
| PRE | -1.52E-01 | 1.94E-02 | -7.85 | 2.03E-12 | *** |
| DOMC | 3.43E+05 | 7.51E+04 | 4.561 | 1.24E-05 | *** |
| DOMW | -2.16E+04 | 4.74E+03 | -4.561 | 1.24E-05 | *** |
| DAM | -2.18E-04 | 7.25E-05 | -3.01 | 0.00319 | ** |

Spatial Model 1 had the highest adjusted $R^2$ among all candidate regression models, which indicates the best possible linear connections between factor variables and spatial changes of groundwater storage (Table 4.3). Precipitation (PRE), latitude (Lat), domestic water withdrawal (DOMW) and dam capacity (DAM) had statistically signicant negative relationships with spatial change of groundwater storage (GW), while domestic water consumption (DOMC) had a statistically significant positive relationship with GW. Altogether, this model explained 41% of groundwater differences in space.

#### 4.3.2.3 Dominant drivers of spatial change in groundwater storage



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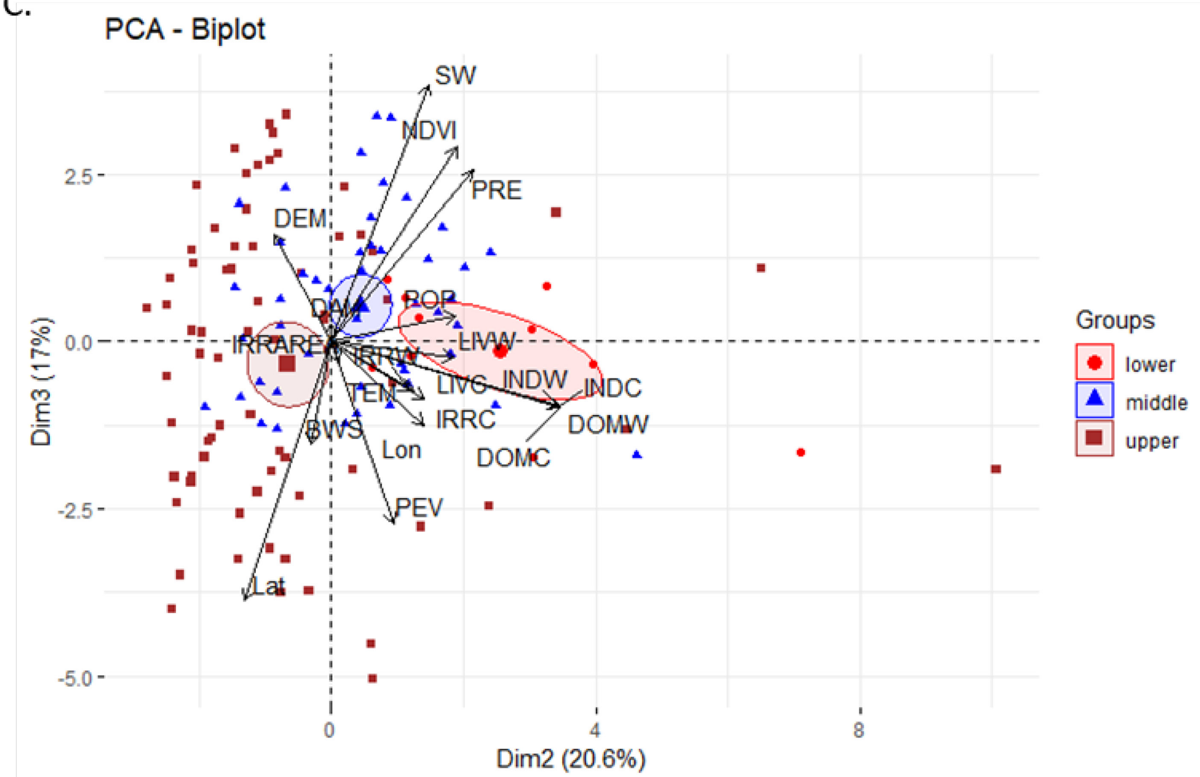
PCA - Biplot
SW
NDVI
PRE
DEM
DAM
POP
IRRAREA
IRRW
LIVW
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INDW
INDC
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Dim3 (17%)
Dim2 (20.6%)
Groups
lower
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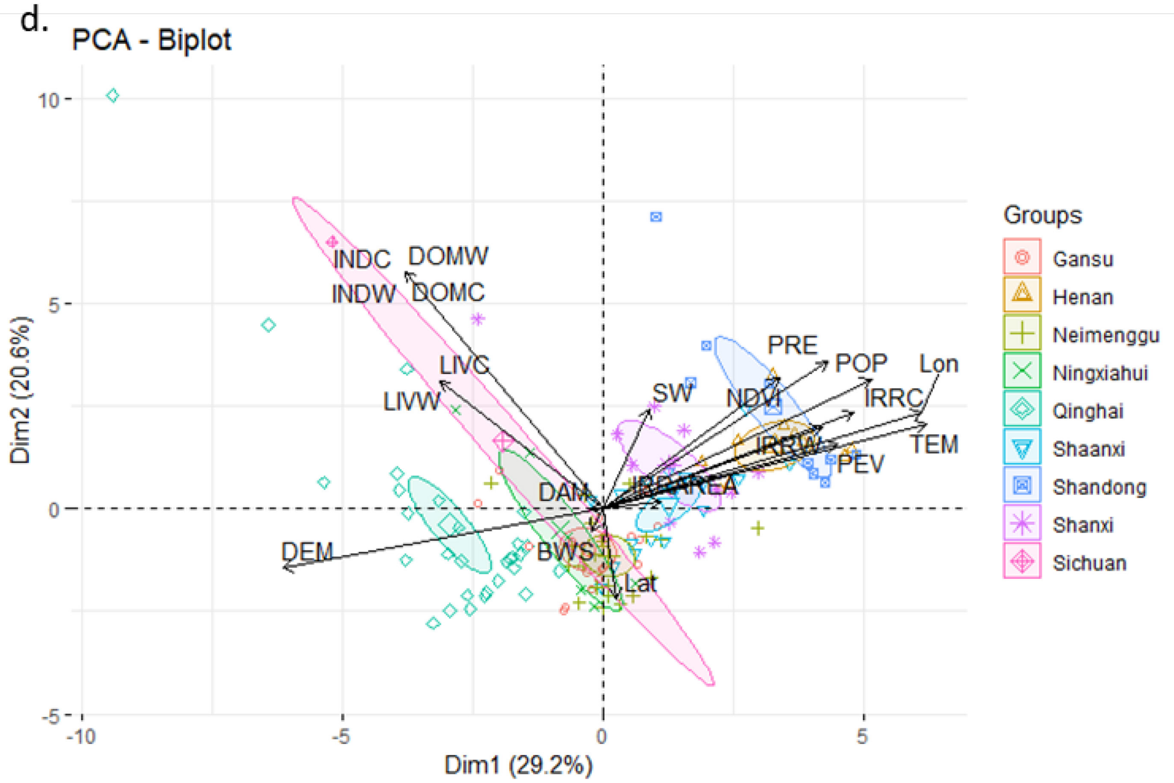
d.


PCA - Biplot
INDC
DOMW
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PEV
DAM
IRRAREA
DEM
BWS
Lat
Dim2 (20.6%)
Dim1 (29.2%)
Groups
Gansu
Henan
Neimenggu
Ningxiahui
Qinghai
Shaanxi
Shandong
Shanxi
Sichuan

e.

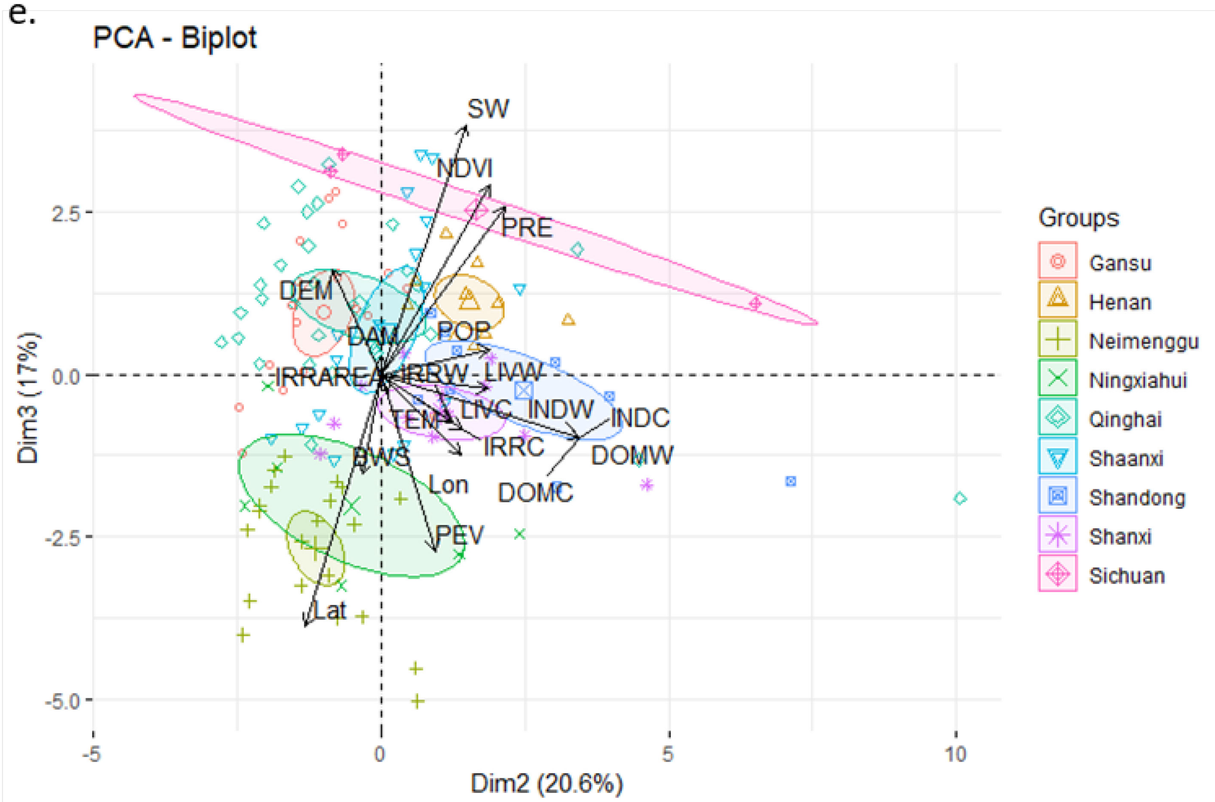


**Figure 4.6 Main dimensions that represent most variances of spatial variables during the period of 2003 - 2016. a.** Scree plot. Y axis represents the percentage of variances explained by each dimension (principal component). **b.** Biplot for dimension 1 & 2 grouped in reaches. The points are observations and were grouped in three reaches (upper, middle and lower). The variable names in the matrix are the 20 spatial variables. The coordinates of the observation points/the variable names are the correlations between the individual observation/variable and the dimensions (principal components). X is the correlation with dimension 1, and Y is the correlation with dimension 2. Larger dots were the mean coordinates of the individuals in the group and the ellipse were drawn based on the 95% of confidence level of the mean coordinate. **c.** Biplot for dimension 2 & 3 grouped in reaches. X axis is the correlation with dimension 2, and Y is the correlation with dimension 3. **d.** Biplot for dimension 1 & 2 grouped in provinces. X axis is the correlation with dimension 1, and Y is the correlation with dimension 2. The points are observations and were grouped in nine provinces in the YRB e. Biplot for dimension 2 & 3 grouped in provinces. X axis is the correlation with dimension 2, and Y is the correlation with dimension 3.

Spatial variables can be mainly grouped into three dimensions in PCA which altogether could explain over 65% of the total variances (Figure 4.6a). Dimension 1 (representing 29.2% of total variances) represented east-west differences which mainly consisted of longitude (Lon), precipitation (PRE), population (POP), temperature (TEM), elevation (DEM), potential evapotranspiration (PEV), irrigation water consumption (IRRC) and irrigation water withdrawal (IRRW). We found that the observations of these factors showed distinct differences between east and west. Dimension 2 (20.6%) represented developmental differences which mainly consisted of industrial water consumption (INDC) and withdrawal (INDW), domestic water consumption (DOMC) and withdrawal (DOMW), and livestock consumption (LIVC) and withdrawal (LIVW). Dimension 3 (17%) represented south-north differences which mainly consisted of latitude (Lat), soil water content (SW), potential evapotranspiration (PEV), vegetation (NDVI), and precipitation (PRE). The observations of these factors mainly varied between south and north.

Observations displayed different patterns in different reaches and provinces (Figure 4.6 b-e). The lower reach had the strongest correlation with dimension 1 (east-west changes) and dimension 2 (developmental changes) compared with the middle reach and the upper reach. The middle reach had near-to-zero correlation to either dimension. The ascending sequence of the mean correlation of provincial groundwater storage with dimension 1 (east-west changes) can mirror their geographical location from west to east (Qinghai, Gansu, Sichuan, Ningxiahui, Neimenggu, Shaanxi, Shanxi, Henan, and Shandong). Similarly, the ascending sequence of the mean correlation of provincial groundwater storage with dimension 3 can mirror their locations from north to south (Neimenggu, Ningxiahui, Shanxi, Shaanxi, Gansu, Qinghai, Shandong, Henan, Sichuan).

## 4.4 Discussion

Our study showed that both anthropogenic changes (dimension 1, 69.3%) and biophysical changes (dimension 2, 14.5%) drove temporal changes of groundwater storage in the YRB between 2003 and 2016, and anthropogenic factors had more influence. Predictor analysis showed that population density, vegetation growth and soil water content can predict temporal groundwater storage changes well. Among them, vegetation growth (plantation) and population density show synergetic impacts from human activities (dimension 1, anthropogenic changes) while the soil water content shows the impact from nature itself (dimension 2, biophysical changes). While the above-mentioned predictors (population density, vegetation growth, and soil water content) always have significant relationships with the changes of groundwater storage , the best regression model for temporal groundwater change between 2003-2016 include the measures of vegetation growth and water consumption by sectors (including agriculture, domestic, industrial and livestock sectors). It would need at least the information of the vegetation growth and water consumption by sectors to have a relatively accurate prediction on groundwater change over time (Adjusted $R^2$=0.97).

In terms of the spatial groundwater change, longitude, domestic water consumption and domestic water withdrawal have proven to be the most reliable predictors among the socio-ecological factors collected in this study. Among them, the longitude indicates the east-west differences (dimension 1), and the domestic water consumption and domestic water withdrawal indicate the differences of urbanization level (dimension 2). The three main dimensions for spatial groundwater change have relatively similar level of influence (east-west differences 29.2%, developmental differences 20.6%, and north-south differences 17%), indicating that spatial change of groundwater storage in the YRB was determined by both the different characteristics of geography and urbanization level at the same time. Further, the spatial regression model suggested that domestic water consumption, domestic water withdrawal, latitude, precipitation and dam capacity can best predict the spatial changes of groundwater storage in the YRB. The composition of this regression model again manifested the collective impacts of geography (indicated by latitude and precipitation) and urbanization (indicated by domestic water consumption and withdrawal) on spatial variances of groundwater resource. In particular, dam capacity has relatively low correlation with either of the three dimensions but is a significant predictor in the regression model. It is possible that aquifers around the dam constructions can receive a considerable amount of recharge from dams, thus having a significant increase of groundwater resource or hydrologic alteration (Kim et al., 2014; Yang et al., 2008). This factor represents the importance of contextual impacts on groundwater changes other than the identified three dimensions.

Admittedly, there may be other factors that may impact the spatio-temporal changes of groundwater, but the information in this research is helpful to provide targeted management strategies. For example, using vegetation growth and sectoral water consumption, we can have a relatively accurate prediction on temporal changes of groundwater using the provided regression model (Adjusted $R^2$ =0.97). But the provided spatial regression model may not represent all the variances (Adjusted $R^2$ =0.41) due to the limit of the linear regression analysis. Still, the analysis in this paper provides a clear comparison between time and space relationship which worth noting. It also points out the importance of precipitation, dam construction and domestic water use on affecting spatial changes of groundwater storage which showed consistent results with other previous research (Wang et al., 2006; Yang et al., 2008; Fan et al., 2014). Specifically, we understood that the spatial groundwater change was mainly shown as east-west differences, which were correlated with irrigation water withdrawal, precipitation, population, and temperature.

Further studies may be required to investigate multi-scale factors, especially finer-scale factors that may show different impacts on groundwater storage changes. In PCA, the connection between sub-level groups and key dimensions indicated that sub-level variances of groundwater storage can provide further information on how factors are affecting groundwater changes. For example, we found that the temporal variances of groundwater storage after 2010 were more driven by anthropogenic factors. There requires further exploration on a finer-scale data of factor variables (e.g. daily data with finer spatial resolution) and investigation on additional socio-ecological factors affecting local-scale water cycles (e.g. local management practices affecting provincial groundwater storage change). Further analysis can apply geographically weighted regression to consider more local-scale contextual factors (Javi, et al, 2014).

## 4.5 Conclusions

This study provided spatio-temporally explicit information about the impacts of socio-ecological factors on groundwater change. We found that anthropogenic variables were the dominant drivers of groundwater change over time, and this impact was deepened in recent period (2010-2016). The spatial differences of groundwater were an outcome of the intertwined effects of socio-ecological factors and were more pronounced by east-west differences in the YRB. This research disentangled the complex impacts of multiple factors on spatio-temporal changes of groundwater storage and provided evidence support in targeted groundwater management. The method used in this study can be applied to other areas to understand the spatio-temporal impact of socio-ecological factors on groundwater availability.

## Acknowledgement

The authors would like to acknowledge the Chinese Scholarship Council (CSC), Natural Sciences and Engineering Research Council (NSERC) of Canada (RGPIN-2014-4100) and Centre for Social and Cultural Data Science (CSCDS) which funded this research and NASA who provides the necessary data for this study. Special acknowledgements are also due to Mr. Gregory Wilson who provides essential supportive work on the data analysis and Dr. Lehner Bernhard and

Dr. Gordon Hickey who provide essential suggestions for this project. We also thank Dr. Kate Reilly for her friendly review which helped us to improve the manuscript.

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## Connecting to Chapter 5

Chapter 4 performs a comprehensive examination of the socio-ecological factors driving the change of groundwater system. I identified the main determinants that drive the groundwater changes between 2003 and 2016 in the YRB and the main factors that can predict the spatio-temporal changes of groundwater in the future. Result suggests that the changes of population density and vegetation index were significantly correlated with the change of groundwater storage over time. The longitude, domestic consumption and domestic withdrawal were significantly correlated with the change of groundwater storage over space. Anthropogenic factors dominated the temporal changes of groundwater storage, whereas both anthropogenic factors (e.g. industrial consumption, and livestock consumption) and biophysical factors (e.g. precipitation and soil water content) synergistically impacted the spatial changes of groundwater storage. One thing to note is that the relationship between human activities and groundwater is not always negative. In particular, I found that domestic water use consumption is positively related to both spatial and temporal change of groundwater, which is different from past literature that indicated a negative relation between groundwater use and storage. This unusual relation might be due to a management interference. It is possible that a governmental restriction on groundwater use has contributed to the decline of domestic water use but fails to reverse the decreasing trend of total groundwater storage. This potential effect of management on groundwater depletion may not be easily revealed by biophysical method. It is therefore necessary to go across disciplines using a combination of natural and social methods to examine the management-related factors for groundwater change. Considering that the management practices are different across provinces, I focused on the center province of the YRB, (i.e. Ningxia) in Chapter 5 to further examine management-related reasons for groundwater change. This smaller-scale focus of study also makes the results of social investigation more reliable and meaningful (Evans et al., 2002). Ningxia is a representative region of the YRB for groundwater dynamics (result in Chapter 3), and at the same time there is a new water management scheme (i.e. Water Rights Transfers system) implemented during the past 14 years that can be examined with GRACE-based data available over the same time period. The research in Chapter 5 is expected to provide a new way of examining factors of groundwater change at a finer scale (provincial scale) in addition to the factor exploration at the basin scale in Chapter 4. The two chapters together could provide multi-scale understanding of socio-ecological factors of groundwater storage changes.

# 5 Management-related reasons for groundwater storage change in Ningxia

**Highlights:**

- Remote sensing data show that groundwater storage in Ningxia decreased significantly between 2006 and 2016.
- Groundwater consumption was not a major reason for the groundwater decrease in Ningxia.
- Reduction in groundwater recharge may relate to management practices that intend to reduce surface water loss, such as drip irrigation and canal lining.


## Abstract

Groundwater is the largest accessible source of freshwater in the world, but recently available data indicate a depletion of groundwater resources globally. The reasons for this global groundwater depletion are not entirely clear, but most research has attributed declines to increased groundwater consumption. However, evidence to confirm the role of increased consumption in groundwater depletion remains incomplete. In this chapter, we examined the potential causes of groundwater change in Ningxia, China. We first calculated change in groundwater storage between 2003 and 2016 based on the Gravity Recovery and Climate Experiment (GRACE) data. Then we conducted a water budget analysis to investigate potential drivers of groundwater decrease in this region, including decreased recharge (i.e. human-induced surface recharge, precipitation recharge, and lateral recharge) and increased discharge (i.e. evapotranspiration and human consumption). Further, we conducted interviews of 22 decision-makers to better understand specific regional management practices related to groundwater storage change. Our results indicated that groundwater storage decreased significantly in Ningxia during the period from 2003 to 2016. While increased groundwater use is often blamed for declines in groundwater storage, we could find no significant relationship between groundwater use and the decline in groundwater storage in Ningxia over the studied time period. Instead, the main contributor to groundwater decrease appears to be a reduction in surface recharge to groundwater, which may be related to changes in water management practices designed to reduce surface water use, such as canal lining and drip irrigation. Interviewees acknowledged that the Water Rights Transfer system (WRT) introduced in this region in 2003 focused on the restriction of river water use and did not carefully consider

groundwater in the system planning. These results may provide important lessons to other regions facing groundwater decline; namely, that managers should not assume that increased groundwater consumption is the only reason to blame.

**Keywords:** groundwater management, GRACE, water budget, sustainability, interdisciplinary

## 5.1 Introduction

Of all freshwater on the Earth, nearly 30 percent is stored as groundwater (Natural Resources Canada, 2017). Groundwater is a widespread underground reservoir sustaining ecosystem resilience and human livelihoods for the long term (Boulton et al., 2008; Gleeson et al., 2012; Mukherji & Shah, 2005; Everard, 2015). Groundwater is an especially important source of freshwater in arid areas, sustaining around two billion people and providing an indispensable water supply for crops (UN Environment Management Group, 2011). Today, half of the world's irrigated crops rely on groundwater (Famiglietti, 2014). Increasing demand for water resulting from population growth, urbanization, and industrialization has boosted groundwater use, sometimes surpassing the amount of annual recharge of regional aquifer systems (Mukherji, 2004; Pereira et al., 2009). Increasingly, dry regions, which are becoming drier due to climate change and land use change, have had to resort to using non-renewable groundwater to address short-term emergency water shortages, leading to groundwater depletion (Hu et al., 2019). For example, in Sub-Saharan Africa, rapid development has increased the need for water, which has been satisfied by abstracting groundwater, sometimes by drilling wells as deep as 100 meters (MacDonald et al., 2012).

With the aid of the Gravity Recovery and Climate Experiment (GRACE) that allows us to see changes in groundwater storage easily across wide areas, it is becoming apparent that groundwater depletion is a global crisis (Famiglietti, 2014; Richey et al., 2015). The GRACE satellites were launched by NASA on March 17, 2002. Since then, GRACE satellites have recorded gravity anomalies around the Earth, and the data have been used to investigate groundwater storage (represented by the monthly equivalent height of groundwater) in groundwater basins worldwide (Swenson and Wahr, 2006). GRACE-based studies show that major aquifers in the arid and semi-arid areas of the Earth (e.g. western and central USA, northwestern India, northern Middle East, Australia, and north China) are experiencing rapid depletion of groundwater stocks, and that the depleted area is expanding (Rodell et al., 2009; Tregoning et al., 2012; Famiglietti, 2014; Gleeson et al., 2012). For example, in northern China, a prolonged drought from 1999 to 2010 limited recharge to aquifers and prompted the construction of emergency well fields, which had the combined effect of decreasing groundwater levels 20 to 40 m over the 11-year period (Treidel et al., 2011). The detrimental effects of such groundwater depletion (e.g. land subsidence, ecosystem degradation) in northern China are vast, and are felt by local people over an area more than four times larger than the actual area of aquifers (Gleeson et al., 2012).

Resolving this global groundwater crisis requires a careful examination of the reasons behind groundwater decline, which, other than groundwater overexploitation, are rarely discussed in detail in the literature (Rodell et al., 2009; Zelm et al., 2010; Aeschbach-Hertig & Gleeson, 2012). Groundwater depletion is usually attributed to overexploitation or overuse (Gleeson et al., 2012; Rodell et al., 2018; Kumar et al., 2011), but there is evidence that human activities can also affect groundwater storage by changing recharge. For example, the increased intensity of some agricultural activities such as expanding irrigated land, can increase the groundwater recharge from irrigation (Foster & Chilton, 2003). And a change of irrigation method from flood irrigation to sprinkler or drip irrigation can reduce the recharge from irrigation to aquifers (Kendy, 2004). In the process of urbanization, building construction and road hardening can obstruct the surface water recharge to aquifers (Sharp, 2010). Such human-driven changes in groundwater are also complicated by the strong influence of climate conditions such as precipitation and climate extremes (Taylor et al., 2013; Döll & Fiedler, 2007; Wada et al., 2010).

A basic method used to understand the drivers of changes in groundwater storage is water budget analysis. Such budgets list, and then quantify, all sources of groundwater recharge and discharge. As shown in the stock-flow diagram (Figure 5.1), the change of the groundwater storage (stock), in essence, was controlled by the inflow (recharge) rate and outflow (discharge) rate (Sterman, 2000; Qureshi et al., 2010).

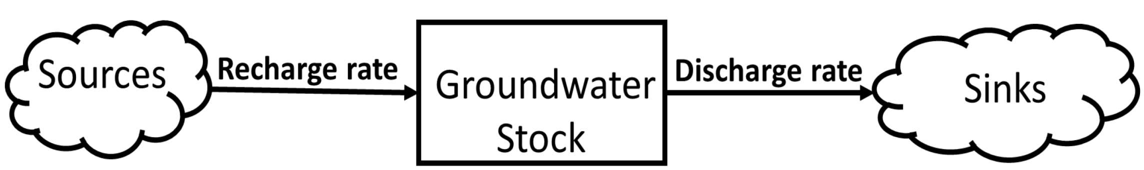



Figure 5.1 An example stock-flow diagram of the groundwater system. The clouds represent the sources and sinks, which are surface water in this system. The rectangle is the stock of groundwater and the solid arrows represent inflow and outflow (to the groundwater stock), thus

measuring the rates of changes. Over a period of time, the change of stock can be represented as the inflows minus outflows.

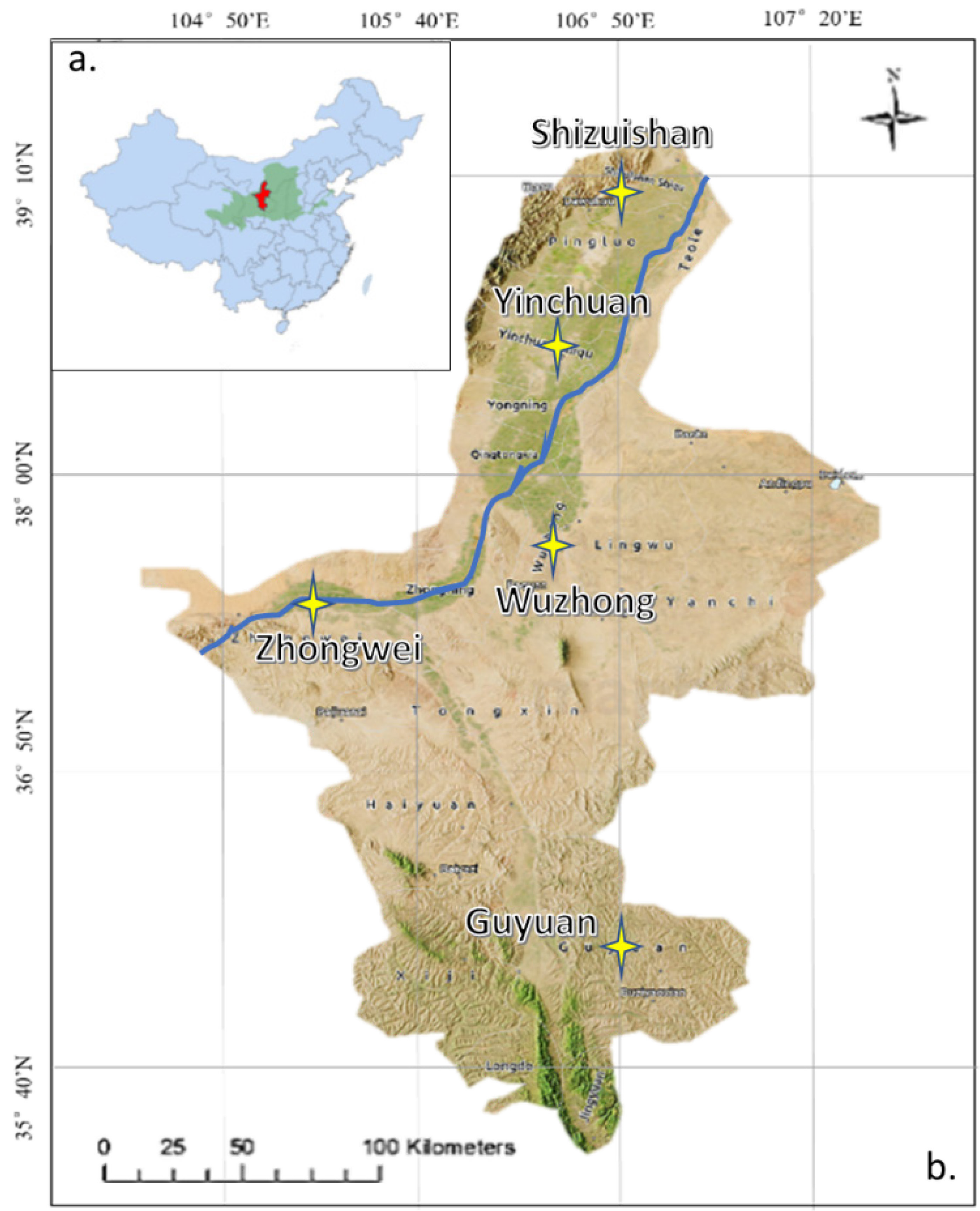
In this study, our objective is to understand the drivers of groundwater storage change in the Ningxia Hui Autonomous Region (Ningxia) of China. This region is one of the most water-stressed areas in China with less than 500 $m^3$ of annual water consumption per capita (Chan, 2014), which is only half of the World bank water poverty line (Wong et al., 2018). Groundwater has been extensively used as drinking water in Ningxia. Here we conducted water budget analysis and interview to explore the main reasons of groundwater storage change, especially to understand the role of groundwater overexploitation relative to other important drivers of change in groundwater storage, including local management practices.

Ningxia is interesting to study because the government has put in place a new policy system, namely the Water Rights Transfer (WRT) system, whose management practices we anticipate would impact groundwater storage, but have not yet been fully explored. These management practices including promotions of water-efficient irrigation methods and canal lining have been changing human footprints on groundwater resource in this region since 2003. Specifically, this WRT system in Ningxia may be promoted to the rest of China as it was approved as a model system in 2014 by the Chinese government. However, one feature that has been thus far overlooked is how these management strategies aimed at surface water efficiency might affect groundwater use and recharge.

## 5.2 Place and Context

### 5.2.1 Study area

Ningxia (66400 $km^2$) is located in the middle of the Yellow River Basin in northern China, with a population of 6.3 million (Figure 5.2a). About 44% of the population lives in rural areas, and the region has a relatively low level of economic development compared with southeastern China (China Statistical Information Network, 2018). The agricultural sector is the main water user, with irrigation adopted primarily along the Yellow River in the north in the Qingtongxia Irrigation Region (5504 $km^2$, near Yinchuan) and the Weining Irrigation Region (922 $km^2$, near Zhongwei) (Figure 5.2b).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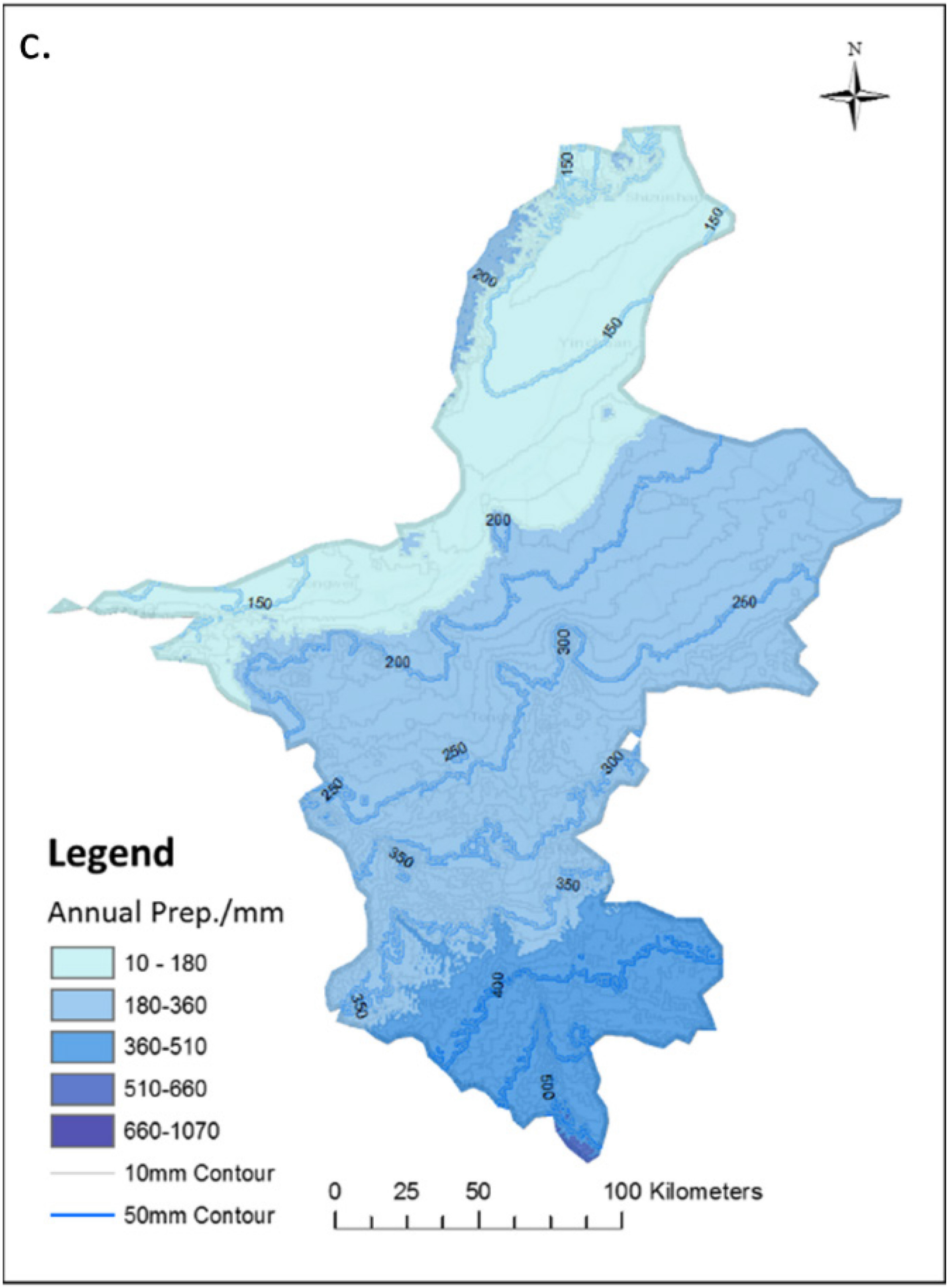
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**Figure 5.2 Topological and precipitation map of Ningxia.** a) Location of the yellow river basin (green polygon) and Ningxia (red polygon) within China (blue area). b) Topological map of Ningxia. Ningxia is in the middle of the Yellow River Basin with the Yellow River flowing across the north (blue line). It contains 5 prefecture-level municipalities (stars). The elevation increases from 1,100 m in the south to 2,000 m in the north. The highest point is 3,556 m at Helan Mountain, which is located in the north near Shizuishan (the dark brown part). There are two main plains (green) along the Yellow River near Yinchuan city (Yinchuan Plain) and Zhongwei city (Weining Plain). c) Precipitation map of Ningxia. Precipitation decreases from south to north (blue shading). The thick blue line represents an interval of 50 mm, and the thin blue line represents an interval of 10 mm.

Ningxia is a typical continental area with a temperate semi-arid to arid climate and very limited water resources. The region receives around 289 mm of precipitation annually, which is less than the half of national average, and has an average of 1250 mm of evaporation per year (Li et al., 2008). Within the region, there is a precipitation gradient, with relatively more precipitation falling in the south and relatively less in the north (Figure 5.2c). At the same time, population growth, urbanization and industrialization are changing land use and increasing pressure on water resources in Ningxia. (Quan et al., 2008).

One of the major water resources in Ningxia is the Yellow River. The Yellow River, which is the second longest river in China and the sixth longest river in the world (Ongley, 2000), flows through Ningxia and eight other provinces. A considerable amount of the river water used for irrigation infiltrates to the aquifers in Ningxia, approximately 30,000-50,000 $m^3/km^2$ per year (NWRB, pers. comm., 2018). In addition to supplying water to Ningxia, the remaining Yellow River water flows downstream, sustaining lives for more than 100 million people on its way to the ocean (OECD, 2015). To avoid upstream-downstream conflicts over water use, the Yellow River Conservancy Commission (YRCC) has allocated a certain amount of water to each of the nine provinces through which the river flows (Shao et al., 2009). In this scheme, Ningxia is allocated 4 billion $m^3$ of allowable annual withdrawal from the Yellow River, which makes up less than 11% of the total river flux. Because of its restricted surface water resources and dry climate, along with the increasing water demands, Ningxia is facing an unprecedented challenge in water management.

### 5.2.2 Water Rights Transfer system

To maintain economic development despite the limited water supplies, the government of Ningxia launched the WRT system in 2003 as a pilot project to increase water use efficiency. This project established a water trading system in which each sector (e.g., industry, agriculture) is given the rights to a certain amount of water use, which can then be traded with other sectors. Such trade happens primarily between agriculture and industry, where water-saving technologies, such as canal lining and drip irrigation, are used to help reduce agricultural water use, and the "extra" unused water is bought by industry. This structural transformation of water use is viewed as an increase in water use efficiency. That is, because the profit from industry (57.9 yuan/$m^3$ water) is 50 times higher than that from agriculture (0.97 yuan/$m^3$water) for same amount of water (NWRB, 2016), water used by industry generates relatively more profit than water used by agriculture.

This system has led to fairly dramatic changes in water use, and potentially in groundwater recharge, especially in agricultural regions. Before 1998, most agricultural canals in Ningxia were earth-lined (Japan International Cooperation Agency, 2006). Canal lining with concrete was promoted as a water-saving technique in the WRT system in 2003. With less loss to soils due to the concrete lining of the canal, agriculture uses less water per unit of production, allowing industry to use more water while not significantly increasing the total water consumption of Ningxia. By 2016, nearly 70% of canals in Ningxia had been lined with concrete, reducing water loss through seepage from over 40% to just 5-20% (NWRB, pers. comm., 2018). At the same time, the High Efficiency Irrigation (HEI) area was developed, where traditional irrigation methods (e.g. flood irrigation) have been changed to more water-efficient irrigation methods (e.g. drip irrigation, sprinkler irrigation). Of the 6047 $km^2$ of irrigated land in Ningxia, about 30% had been transformed to HEI by 2016 (NWRB, 2017). This land transformation to HEI has also led to declines in water use to about half of that used in traditional flooding irrigation (Gao & Bao, 2017; Yang, 2012). There is a reason to believe that the WRT system might change groundwater recharge (Figure 5.3). Canal lining and the installation of water-efficient irrigation technologies both resulted in less water use, but perhaps also in less water available for aquifer recharge (Porhemmat et al., 2018; Ebrahimi et al., 2016)

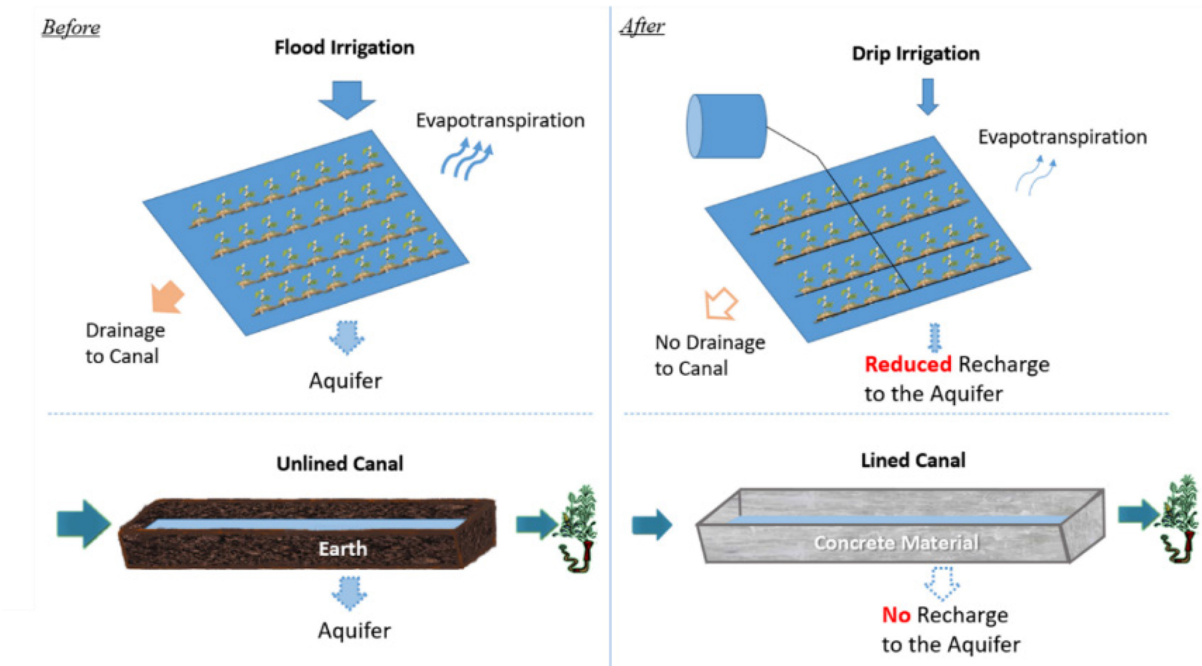



Figure 5.3 Illustration of hypothesized impact of water management practices on aquifers. The left column displays the main groundwater recharge and discharges before the management system was constructed (with flood irrigation and unlined canal) while the right column shows the change of groundwater balance after the management system (with drip irrigation and lined canal). The arrows represent the water movement. The red words highlight the reduced recharge to the aquifers after the management practices were implemented.

## 5.3 Data sources and analysis

To identify the potential causes of groundwater change in Ningxia, we first examined the change in groundwater storage between 2003 and 2016 using the GRACE data analyzed with linear regression and Mann-Kendall analysis. Then we conducted a groundwater budget analysis using a mass balance model to compare the groundwater budget between 2003 and 2016. Based on the budget analysis, we investigated potential contributors to groundwater change, which include groundwater consumption and surface recharge to groundwater stocks, and their correlations with groundwater storage. Finally, we interviewed related water managers to have a deeper understanding of the water management system in Ningxia and its potential relationship to groundwater change.

### 5.3.1 Groundwater time series and trend analysis

To quantify change in groundwater storage in Ningxia over time, we extracted the monthly change in terrestrial water storage (including surface water and groundwater) from GRACE data at http://grace.jpl.nasa.gov and removed the surface water components (i.e. the surface water equivalence, soil moisture and snow water equivalence) using the data from the Global Land Data Assimilation System (GLDAS) at https://disc.gsfc.nasa.gov. The datasets are in netCDF format and were processed (including scaling, and interpolation) through the self-developed program in Matlab (Lin et al., 2019a; Landerer & Swenson, 2012). All these data are at 1 arc degree spatial resolution and use equivalent water height in centimeters to represent the water storage (Swenson, 2012). We used 2003 to 2016 as a study period, each full (January – December) year for which GRACE data is available. We clipped all 1-degree grid data to the Ningxia region and then calculated groundwater change following commonly used methods described in the literature (Swenson, 2012; Landerer and Swenson, 2012; Lin et al., 2019a). We then averaged the grid data to get a monthly time series of groundwater storage from 2003 to 2016 for the whole region. The data do not give an absolute volume of groundwater storage, but rather a relative volume with respect to the commonly-used baseline from Jan. 2004 to Dec. 2009 (see details at https://grace.jpl.nasa.gov/about/faq/). These data therefore represent changes in the groundwater stock over space and time, but not the actual amount of groundwater. For details of data processing, please refer to Lin et al. (2019a).

To assess whether changes in groundwater storage were significant and to determine the trend, we used linear regression (Excel software, Microsoft Inc.), and Mann-Kendall analysis ("Kendall" package in R software, McLeod, 2005). The $p$ value indicates the significance level of the trend/correlation (Mann 1945, Kendall 1975, Gilbert 1987). Mann-Kendall analysis is suitable for nonlinear timeseries and has been used in hydrological series to detect monotonic trends and correlations (Yue et al., 2002) which may identify the general change of groundwater storage over years, if there is any. It generally neglects the seasonal fluctuations which may be of importance for short-term management practices but not a key focus in this paper. We then used the median slope of all pairs of observations (i.e. Sen's slope) to represent overall trend. ("Trend" package in R software, Sen, 1968; Helsel & Hirsch, 1992).

### 5.3.2 Mass balance model

To identify which factors might be contributing to changes in groundwater storage, we first identified all the recharge and discharge components that could cause changes. The mass balance equation of groundwater storage change in Ningxia is shown by the equation:

$$\Delta GW = \Delta S + \Delta P + \Delta L - \Delta E - \Delta C \quad (1)$$

Where Δ represents the change between two years (here we calculated the change of each variable between 2003 and 2016). ΔGW is change in groundwater stock. Changes in recharge of the aquifer over 14 years consist of surface recharge change (ΔS, including river/canal recharge and irrigation infiltration), precipitation recharge change (ΔP), and lateral recharge change from mountain aquifers (ΔL). Changes in discharge consist of evapotranspiration change (ΔE, including phreatic evaporation, plant transpiration, and other discharge to surface) and water consumption change (ΔC). The units of all listed variables can be converted to centimeter.

We conducted a budget analysis based on the mass balance equation and compared the water budget between 2003 and 2016. The groundwater stock change (Δ GW) was calculated using the area of Ningxia multiplied by the change of equivalent height obtained from GRACE data. The groundwater consumption was obtained from NWRB who estimated consumption based on local surveys (available at www.nxsl.gov.cn). The groundwater recharge data (including ΔS, ΔP, & ΔL) was measured by the local hydrological stations and collected by NWRB (available at http://slt.nx.gov.cn) (He et al., 2009). We then calculated the change of each variable between year 2016 and year 2003. Data on evapotranspiration (Δ E) was not available in collected data or government reports, so it was calculated based on the mass balance equation. For the main reasons of groundwater change identified in the water budget analysis, we further conducted a Kendall correlation analysis investigating their relationship with groundwater storage (Kendall 1975; McLeod, 2005).

### 5.3.3 Assessing the impact of management practices

To develop a more detailed understanding of the water management system in Ningxia and its potential relationship to groundwater change, we conducted 22 semi-structured interviews with officials and managers in Ningxia whose jobs are related to water management (e.g. water policy-makers, hydrogeological engineers, village heads of irrigation associations, groundwater monitors, and employees of the agricultural water office and water companies) (See interview guide 1 in

Text S5.1). To identify interviewees, we first drafted a list of stakeholders based on a preliminary investigation and then used the snowball method (Biernacki & Waldorf, 1981; Noy, 2008) to find other categories of stakeholders that were not initially identified. Saturation was reached for stakeholders' opinions of the WRT system and perspectives on the groundwater situation when there were no new statements or opinions on these topics in an interview (Saunders et al., 2018). We audio-recorded all interviews so that we could check our notes; in cases where interviewees refused audio recording, we had multiple people taking notes. Oral consents were obtained. The questions in the interviews aimed at understanding stakeholders' interpretations of the WRT system and its impact on the water situation in Ningxia. Specifically, we collected the interviewees' comments on suspected impacts on groundwater (Figure 5.3) to understand their reasoning for the management plans and other important concerns in the WRT scheme. (Also see Text S5.2).

To statistically test the impact of the WRT system on groundwater change, we investigated the relationship of two indicators to the annual change in groundwater storage: the area of HEI regions and the length of lined canal. Limited data on these two indicators were available at www.nxsl.gov.cn (NWRB, 2017). The area of HEI were available from 2005 to 2016, representing the progress of installing water-saving infrastructure in Ningxia. The length of lined canal length were available from 2013 to 2016. We calculated correlations of the indicators with groundwater storage change using Kendall correlation analysis (Kendall 1975; McLeod, 2005).

## 5.4 Results

### 5.4.1 Change in groundwater storage

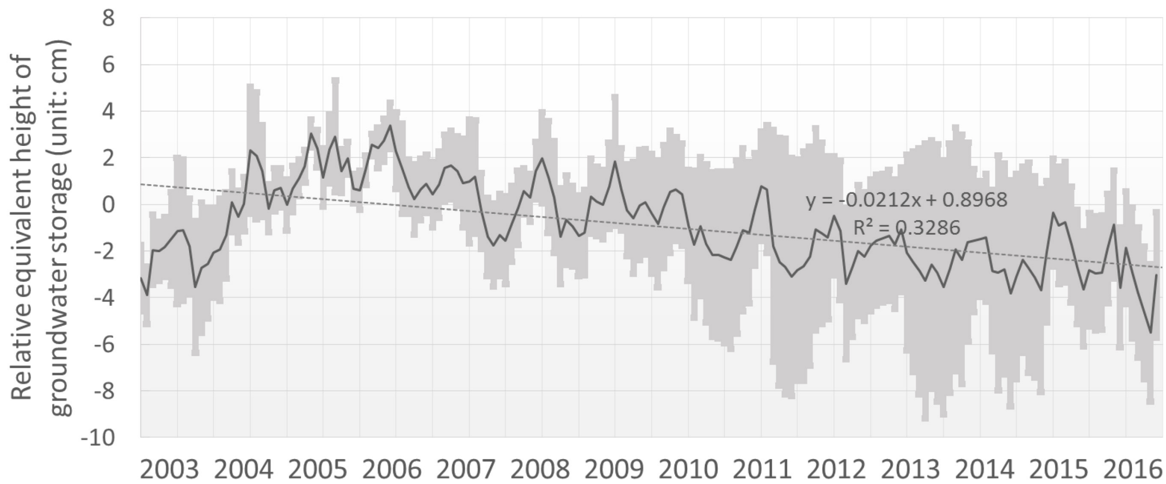



**Figure 5.4 Time series of groundwater storage in Ningxia from GRACE data between 2003 and 2016** (Unit: cm). The solid line represents a time series of monthly averaged groundwater storage, relative to the baseline average for the period of 2004-2009. The light grey shadow shows the error (±1σ). The dotted line shows the linear regression trend.

Generally, groundwater storage in Ningxia decreased significantly between 2003 and 2016 ($p < 0.005$). Sen's slope indicated that the groundwater equivalent height declined at a rate of 0.015cm/month, indicating a loss of 10 million $m^3$ of groundwater per month. Relative groundwater storage showed an increase from 2003 to 2006, from a minimum of -3.89 cm below the baseline to a maximum of 3.37 cm above the baseline. It then decreased until the end of our data collection in 2016, reaching a new lowest point of -5.50 cm. Additionally, variance increased fairly dramatically after 2010, indicating increasing spatial heterogeneity in groundwater decline across Ningxia (Figure 5.4).

Government data from NWRB showed a trend of groundwater depletion that was consistent with what we observed using satellite data (Wang & Chen, 2016). Currently, five depleted areas have been identified by the Ningxia groundwater assessment (NWRB, pers. comm., 2018), all of which were in the north of the Yinchuan plain, which included Yinchuan city and Shizuishan City. Compared with the groundwater level in 1980s (1.35 m below surface level), the average groundwater level in the north of the Yinchuan plain had dropped over 1 meter by 2016 (2.19 m below surface level), which corresponds to a 0.11 billion $m^3$ decrease in groundwater.

## 5.4.2 Groundwater budget analysis

**Table 5.1 Budget analysis for groundwater between 2003 and 2016.** All values are expressed as billion $m^3$. Data for evapotranspiration (E) was not available but the change in evapotranspiration could be calculated based on the mass balance equation (Equation 1). Grey shaded rows are discharge and white rows are recharge. The rightmost column shows the net difference of groundwater storage between 2003 and 2016 (Δ). Negative recharge values lead to a decrease in groundwater stock while negative discharge values (grey area) lead to an increase in groundwater stock. △GW (bottom right) shows the net difference of groundwater stock between 2003 and 2016.

| Signal | Explanation | 2003 | 2016 | △ |
|---|---|---|---|---|
| S | Surface recharge | 1.99 | 1.42 | -0.57 |
| P | Precipitation recharge | 0.13 | 0.08 | -0.05 |
| L | Lateral recharge | 0.42 | 0.36 | -0.06 |
| C | Groundwater consumption | 0.65 | 0.53 | -0.12 |
| E | Evapo-transpiration | | | -0.03 |
| GW | Relative groundwater storage | -1.51 | -2.04 | -0.53 |

Our water budget analysis illustrates the contribution of each component of the system to the groundwater storage (Table 5.1). The change in groundwater storage (-0.53 billion $m^3$) was primarily due to a decrease in surface recharge (-0.57 billion $m^3$). The reduction in groundwater use (-0.12) partially compensated for reductions in groundwater storage due to reduced recharge (-0.68 billion $m^3$ in total). More detailed analyses on the change of groundwater in consumption and surface recharge over time are as below.

#### 5.4.2.1 Change in groundwater consumption

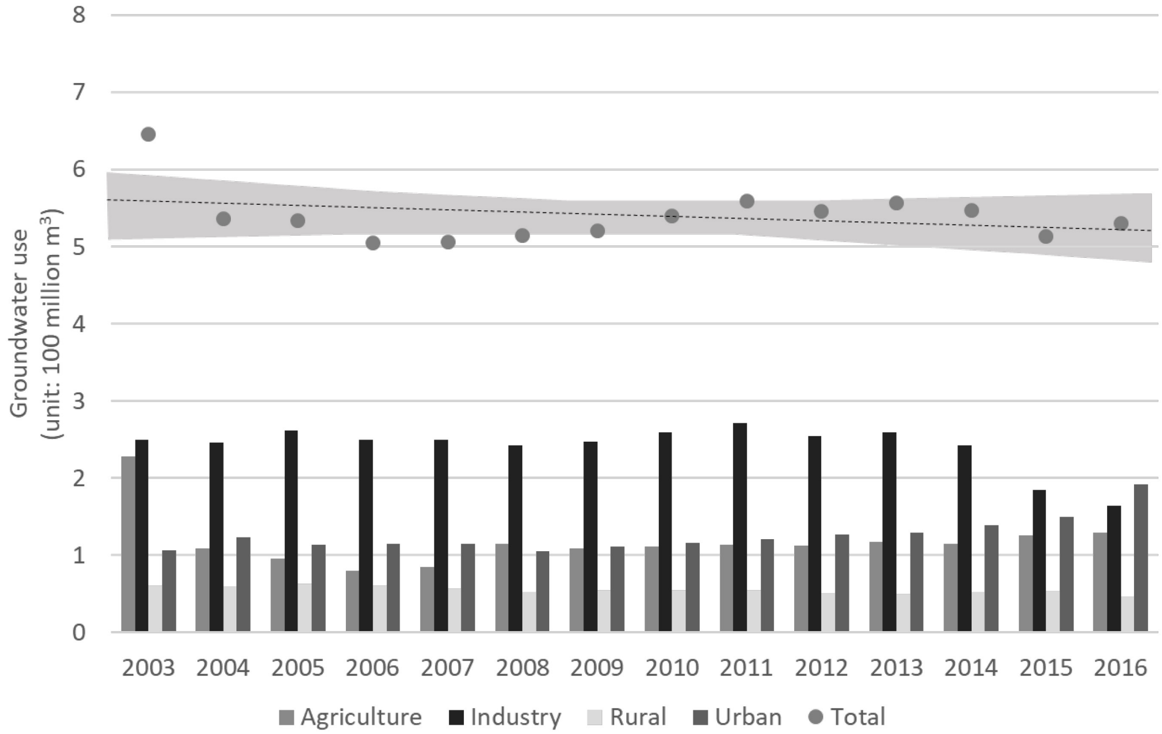



**Figure 5.5 Total groundwater use and sectoral groundwater use from 2003 to 2016.** (unit: 100 million m$^3$). The dotted line is the linear regression of the total groundwater use, and the grey shadow is the 95% confidence band of the linear regression model (p=0.4136).

Groundwater consumption in Ningxia did not change significantly between 2003 and 2016 (Figure 5.5). In fact, our analyses show that groundwater consumption was not significantly related to change in groundwater storage (p=0.079). Total usage was high in 2003 (645.3 million m$^3$), and then dropped to around 550 million m$^3$ in following years. There was a slight rise, but statistically insignificant, in the annual total from 2009 to 2011 along with the increase of industrial groundwater use (Figure 5.5). Then the total groundwater use returned to its previous level of around 550 million m$^3$ per year while industrial water use dropped quickly.

The sectoral groundwater use pattern did change over this time period. Specifically, the proportion of groundwater consumed by urban areas increased from 129.5 million m$^3$ in 2013 to 191.6 million m$^3$ in 2016 (Figure 5.5). Groundwater use by the industrial sector dropped abruptly from 259.4 million m$^3$ in 2013 to 163.8 million m$^3$ in 2016. Agricultural use of groundwater was very high in 2003 (228.2 million m$^3$) but dropped sharply in 2004 (108.0 million m$^3$) and then increased gradually until 2016, when it reached 129.6 million m$^3$ (Figure 5.5). In the most recent four years (2013-2016), industrial and rural groundwater use decreased while the agricultural and urban use increased, indicating a transformation of water use structure.

#### 5.4.2.2 Change in surface recharge of groundwater

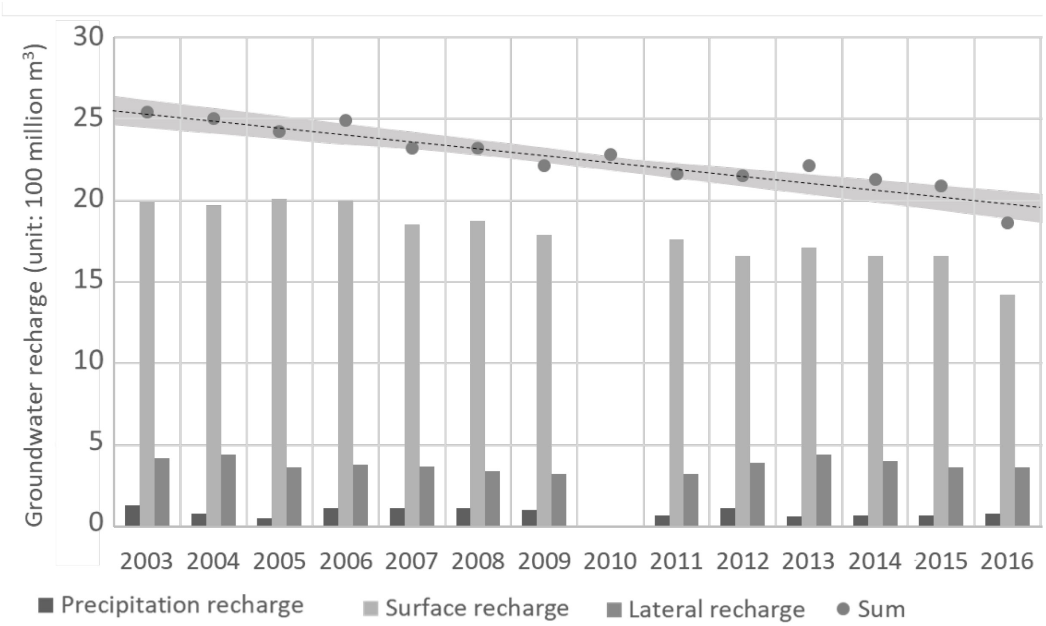



**Figure 5.6 Time series of groundwater recharge from 2003 to 2016 in Ningxia.** Groundwater recharge in Ningxia includes precipitation recharge, surface recharge (from canals, rivers and irrigation), and lateral recharge (from mountain aquifers). The data in 2010 is missing. The dotted line is the linear regression of the total groundwater recharge, and the grey shadow is the 95% confidence band of the linear regression model ($p<0.001$).

Groundwater recharge in this region comes nearly entirely from surface recharge, which includes seepage from canals and rivers and infiltration from irrigation (Figure 5.6). In fact, surface recharge accounted for over 75% of the total groundwater recharge. Surface recharge decreased significantly over the years analyzed ($p<0.001$). The change in the surface recharge was significantly correlated with groundwater storage ($p=0.0015$). Neither precipitation nor lateral recharge changed significantly over the time period analyzed.

### 5.4.3 Impact of management practices on change of groundwater storage

In interviews, the water planners had few concerns about groundwater. Only three of 22 interviewees initially mentioned groundwater when talking about the WRT system. Instead, most of the interviewees mentioned the strict limit set by the YRCC, which capped Yellow River surface water use by Ningxia at 4.0 billion $m^3$/year. They explained that more water-saving management practices in the WRT system could effectively reduce the need for irrigation water, in part through an expected reduction in canal seepage. That is, most water managers that we interviewed were focused on meeting the targets set for them, which revolved around surface water, rather than groundwater.

However, when we brought up the potential connections between canal seepage, irrigation water, and groundwater recharge, 75% of interviewees acknowledged the possible impacts of the WRT system on groundwater depletion (Figure S1). Most interviewees acknowledged that they didn't address groundwater in the WRT plan, while some others believed that, "Conserving surface water will also conserve groundwater."

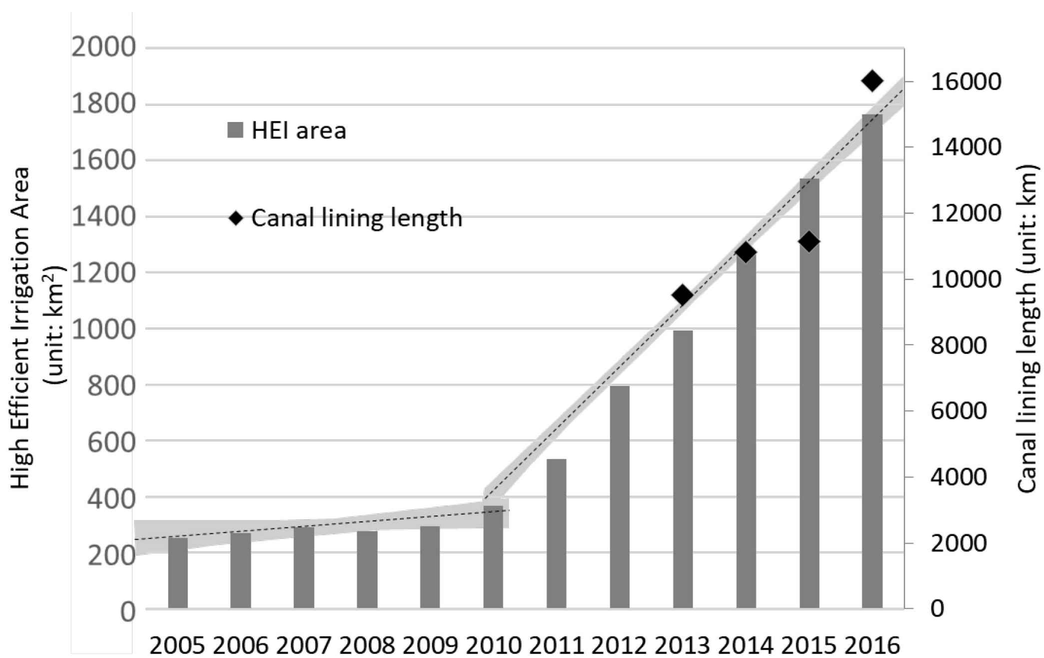
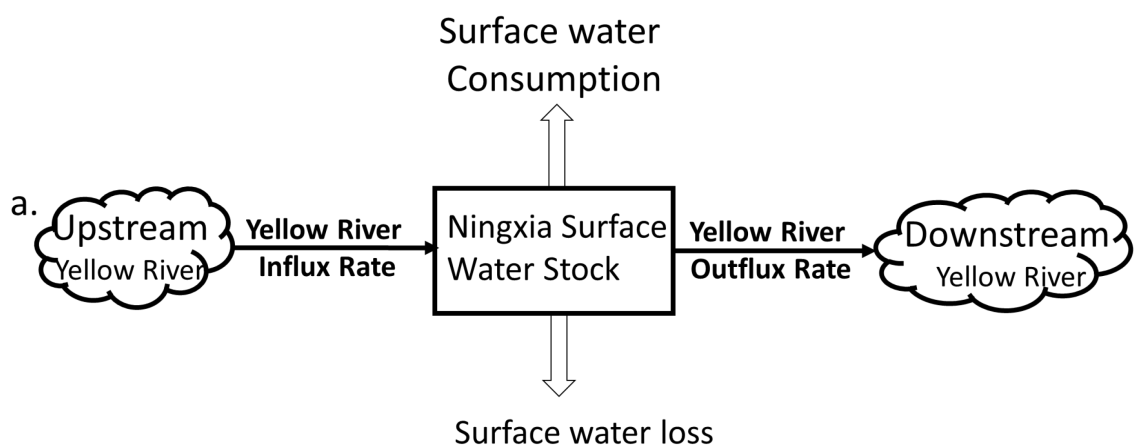



**Figure 5.7 Implementation of water-saving infrastructure in the WRT system since 2005.** The bars show the area of the HEI following the y axis on the left, and the black squares show the length of lined canals following the y axis on the right. The data is missing for HEI before 2005, and for canal lining length before 2013. The dotted lines are the linear regression of the HEI area (unit: $km^2$) for 2005-2010 ($p=0.037$) and 2010-2016 ($p<0.001$) respectively, and the grey shadows are the 95% confidence bands of the two linear regression models.

While the water-saving infrastructure was being implemented, the surface recharge of groundwater was decreasing (Figure 5.6 & 5.7). According to the government data (NWRB, 2017), over 1700 $km^2$ of land has become HEI area (29.2% of total irrigation area), and over 16,000 km canals have been lined (68.68% of the total length of canals) since the advent of the WRT system (Figure 5.7). The growth of the HEI area accelerated after 2010 (Figure 5.7), with a significant relationship between surface recharge and the area of the HEI ($p<0.001$), indicating that water management in the WRT system was significantly negatively correlated with the surface recharge between 2010 and 2016 (Figure 5.6 & 5.7).

## 5.5 Discussion

Our results showed the significant decrease in groundwater stock in Ningxia from 2003 to 2016. We further showed that increased consumption of groundwater cannot numerically be responsible for this decline. Instead, it appears that the main driver of declines in groundwater storage in this time period is likely the reduction of surface recharge that accompanied the water-saving infrastructures of the WRT scheme.



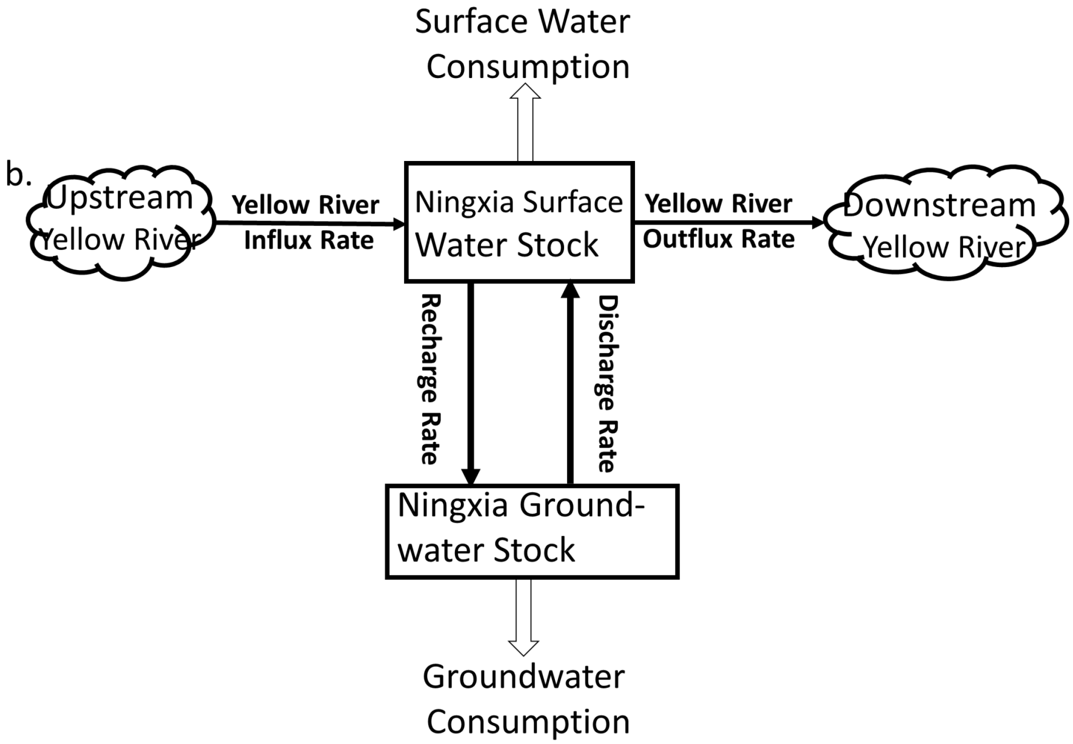



**Figure 5.8 Stock flow diagram of two conceptual models of groundwater in Ningxia**. Rectangles represent stocks. The clouds represent sources and sinks of the Ningxia water system. The solid arrows represent the flow direction, and the hollow arrows represent the auxiliary variables. a) Simplified stock-flow diagram of water flow in Ningxia. *Yellow River Influx Rate* is the volume of Yellow River water flows into Ningxia per year; *Yellow River Outflux Rate* is the volume of Yellow River water flows out of Ningxia per year. The canal seepage and infiltration from irrigation that was not captured by the crops were treated as "lost" surface water. b) Alternative stock-flow that includes the connections between surface and ground water. *Recharge Rate* is the net recharge from the surface water stock to the aquifers per year (the sum of surface water irrigation, lateral recharge and precipitation subtracting the groundwater irrigation). *Discharge Rate* is the net discharge per year from aquifers to the land surface (the sum of evapotranspiration and water discharge to canals). Surface water consumption and groundwater consumption are the auxillary variables controlled by management and use practices.

We found that the surface water "saved" by the WRT in the form of reduced demand for surface water system came at the cost of a similar reduction in the amount of groundwater recharge (Figure 5.8). As most interviewees indicated, water management measures in the WRT scheme reduced surface water loss from agricultural irrigation, thus keeping sufficient Yellow River flow headed downstream as the YRCC required (Figure 5.8a). However, this reasoning of management practices did not consider the connection between surface water and groundwater. However, the "lost" surface water from inefficient use before the WRT system was in place was an important source of groundwater recharge (Figure 5.8b). In Ningxia's case, this part of recharge constitutes over 75% of the total recharge of groundwater. Thus, water-saving infrastructure actually limited the amount of recharge from surface water used in agricultural sector to groundwater. As a result, while more water on the surface was available to use, the stock of groundwater was decreasing. Still, this reduction in surface recharge might not have resulted in groundwater depletion if groundwater discharge (use) was also reduced at the same pace. Although groundwater consumption has declined due to managerial control (including shutting down illegally-drilled industrial wells (Ministry of Ecology and Environment, 2011)), the discharge rate has nevertheless decreased at a slower pace than the recharge rate, leading to the ultimate decrease in groundwater stocks.

An important lesson of this research is that groundwater consumption is not always the only culprit of groundwater depletion. Even though overexploitation is indeed responsible for groundwater depletion in many places (Mukherji, 2004), assuming this to be the case may reduce managers' ability to identify, and control, other potential causes (Kendy et al., 2003; Walzberg et al., 2019). In Ningxia, we found that groundwater consumption was likely not an important contributor to the decline in groundwater. However, by assuming this to be the main cause of their problem, and by focusing primarily on surface water, managers reduced their attention to other possible factors, and missed opportunities for improved management.

Related to this issue is the need for carefully defined system boundaries for management. Difficulties in solving problems may not be the result of an insufficiently strong response from managers, but, rather, the wrong type of response due to managers overlooking an important system component (Scheffer & Carpenter, 2003; Sekhri, 2014; Closas & Villholth, 2019; Doukas & Nikas, 2019). In Ningxia, in part due to strong pressure from the government, managers were focused on the surface water, often ignoring the groundwater part of the system, which we show has ultimately led to a failure to adequately protect interconnected groundwater resources. Arguably, it is hard, or perhaps even impossible, to identify all components of every management system. Indeed, the literature suggests that system boundaries must change depending on the problem identified and the issue to be addressed (Lodge, 2002; Brkić et al., 2019), suggesting that system boundaries should change with the question at hand (Suh et al., 2004; Nemecek & Gaillard, 2010). Here, we identified one missing component of the system, but the intrinsic complexity of social-ecological systems means that there will likely always be something unknown or missing (Biggs et al., 2012). Still, policies focused on a single target are more likely to miss essential system components (White, 1995; Pikitch et al., 2004): managers driven by meeting the requirements of a single-target often have no time and energy to care or think about other components (Levine, 2016). This type of problem frequently occurs in systems with slowly-changing variables, where long term sustainability can be neglected in the face of more immediately pressing challenges, even though this focus on the near-term may result in even greater challenges in the future (Folke, 2004; Farazmand, 2007; Gunderson et al., 2012).

In this regard, the problems we identified with groundwater management in Ningxia are similar to those seen in the process of pursuing society's long-term sustainability goals (United Nations World Water Assessment Programme, 2018). Because groundwater has much slower velocity than surface water and has broader coverage, impacts of groundwater depletion are manifested across longer timespans and across a larger spatial extent which is hard to control (Theesfeld, 2010). These impacts include land subsidence, wetland shrinkage, reduced capacity for streamflow regulation during climate extremes, and loss of water supplies for future generations (Rockström et al., 2014). Yet it is deceptively easy to overlook the slow underlying changes that lead to these often unanticipated and irreversible impacts of groundwater decline (Walker et al., 2012; Scheffer et al., 2009; Haacker et al., 2019; Green et al., 2011)

## 5.6 Conclusions

Groundwater depletion is a crisis happening around the world, with global consequences which require immediate attentions, but causes of the groundwater depletion beyond groundwater consumption are rarely discussed, leaving society in a position with overly limited management options. Our study draws from a case in Ningxia, China to investigate the management-related drivers of groundwater storage change. Results indicated that reduced recharge associated with management practices, rather than groundwater consumption, were the most important contributors to the decrease of groundwater in Ningxia between 2003 and 2016. This research highlights the importance of appropriate system boundaries for resource management, and the necessity of incorporating groundwater and other slow variables into sustainable resource management systems.

## Acknowledgements

The authors would like to acknowledge the Chinese Scholarship Council (CSC), Natural Sciences and Engineering Research Council (NSERC) of Canada (RGPIN-2014-4100) and Centre for Social and Cultural Data Science (CSCDS) which funded this research, and NASA which provided the necessary data for this study. A big thank to Quebec Centre for Biodiversity Science (QCBS) and CWRA (Canadian water resources association) which provide necessary platform and financial support for the discussion of the ideas. Special acknowledgements are due to the community in Ningxia, including NGOers (Mr. Hu Yanqin, Mr. Wang Yuxiao, Mr. Chenxu, Mr. Gancao etc.) and water managers who provide essential contact for the interviews. Gratitude are given towards students and teachers in Ningxia university including Fan Qi, Wang Junhui, Liu Peng, Wang Hong, Wang Jiaxing, Ma Jinlong, Zhangjun, Cao Lanzhou, Jin Anni, Wang Hengheng, Mian Haikun, Wukailong, Ma Xiaomei and professor Wang Huihui & Zhu Zhiling who voluntarily helped with the field work and provided necessary information for the understanding of Ningxia's situation. The authors are also grateful for Dr. Jesse Rieb for careful review and great suggestions on refining the manuscript, Dr. Lehner Bernhard and Dr. Gordon Hickey for their insightful suggestions for this project, and Ms. Jiahua Chen for her critical support in the survey process.

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# Appendix 5.1

## Text S5.1 Semi-structured interview guide 1

We are students from McGill University and Ningxia University doing research on water. We wish to know more about the water situation in Ningixia to find out the key problems we can contribute to with our knowledge. Therefore, we wish you could spare one hour discuss with us about the water situation and water management in Ningxia. The interview will be within one hour. To ensure the accuracy of the information, we need to record during the interviewing process to concentrate our focus on following your talk. These record materials will be kept safely and secretly and will be destroyed once the research has been finished. The description of the result will be anonymous. If you want to stop recording, you are free to say so any time during the interview.

1. Your work unit? The work content? How long have you worked here? Your self-assessment for your work?

2. Please talk about your view on the water situation in Ningxia from the professional and personal perspective respectively. (water quality, water quantity, surface water, groundwater).

3. Your knowledge about water-saving infrastructures and measures, any relations to your own work?

4. Will you come across any difficulties relating to water management? Please give 2~3 examples if you have any.

5. Since 2003, Ningxia starts to implement water rights transfers system (WRT). Could you discuss about the effect of the WRT system generally, the impacts on yourself and your aspiration?

6. Will you connect with other stakeholders, could you share their reflection on the WRT system?

7. Have you ever come across some difficulties in the process of implementation, or could predict any in the future?

8. Do you have other new ideas on water management? Or have you heard others mentioning any? What is it?

Thank you very much for your support! We will have a transcription of the interview based on the audio record. Please leave your contact information if you wish to have a look. We will mute your personal information in the research report and will respect your other concerns if there are any. Wish you a very enjoyable life!

### Text S5.2 Semi-structured interview guide 2

We are students from McGill University and Ningxia University doing research on water. We wish to know more about the water situation in Ningixia to find out the key problems we can contribute to with our knowledge. Therefore, we wish you could spare one hour discuss with us about the water situation and water management in Ningxia. The interview will be within one hour. To ensure the accuracy of the information, we need to record during the interviewing process to concentrate our focus on following your talk. These record materials will be kept safely and secretly and will be destroyed once the research has been finished. The description of the result will be anonymous. If you want to stop recording, you are free to say so any time during the interview.

Name_________ Position__________ Work length__________ Contact Info_________

1.Could you describe your work briefly? How do you think it plays a role in the water resource management system? Who you will meet during the work? Are there your influences on them or their influences on you?

2.Groundwater, or well water, is the main drinking water resources. What do you know about current situation of groundwater in Ningxia? (E.g. The volume? Could it satisfy the needs? The connection of groundwater and surface water? The change of groundwater with policy making and climate change? Where are the regions that require more attention? Where in the management work could manifest the consideration on the sustainable use of groundwater?)

3.According to our knowledge, current Water Rights Transfers (WRT) system has efficiently increased the surface water use efficiency while keep the economic growth. Can you discuss the impacts of this system on your work?

4. According to our knowledge, current WRT system include drip irrigation, canal lining, etc. Could you share your knowledge/ data on that (about the change of these practices over 2003-2016)?

5. We believe that WRT system has brought new vitality to Ningxia. But at the same time, we have concerns from the perspective of groundwater. As shown in the figure below, groundwater seems to be neglected in the water-saving constructions. A considerable amount of so-called saved water is the original recharge to aquifers. What are your thoughts after reviewing the picture?

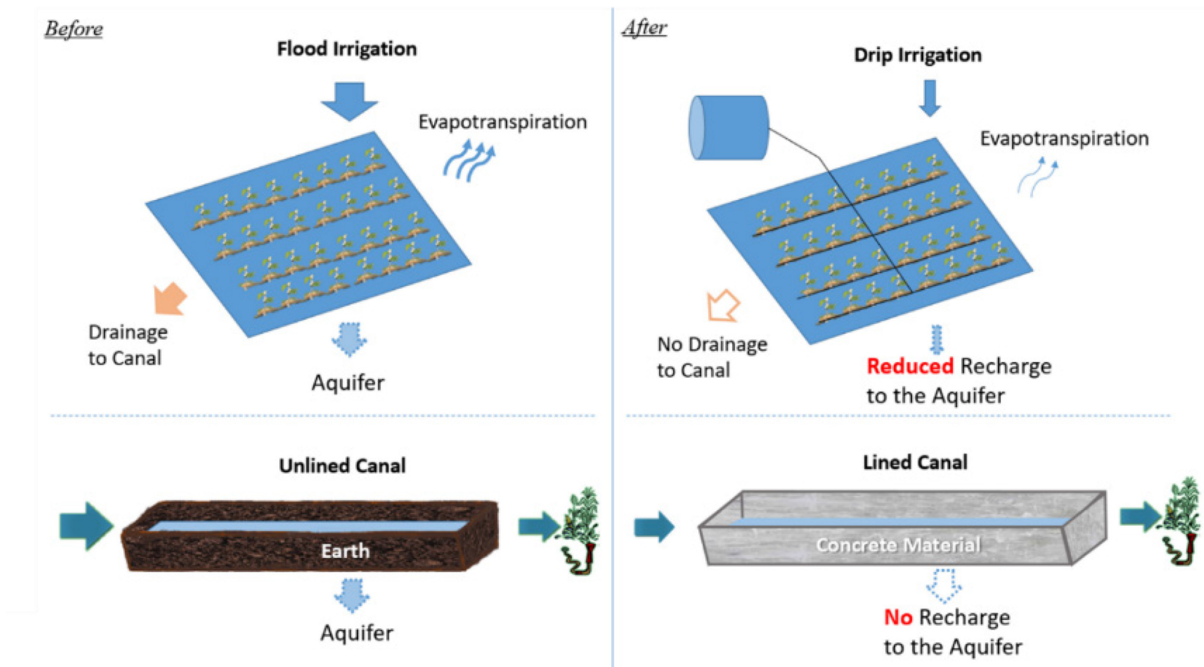


Figure S5.1 Illustration of connections between water-saving projects (i.e. the canal lining and drip irrigation) and aquifers The left two figures display the water cycle before the management system is constructed (with flood irrigation and unlined canal) while the right shows the water situation after the management system (with drip irrigation and lined canal). The arrows represent the water movement. The red words highlight the differences on the aquifers before and after the management.

Thank you very much for your answers and valuable sharing. It will help us to deepen the understanding and research on the sustainable water management. We will contact you if we have further questions. We will share the result with you if you leave your contact information. Many thanks!

# Connecting to Chapter 6

Groundwater can be depleted by human over-extraction, but we learned through Chapter 5 that it is not always the case. Groundwater depletion can be an outcome of mismanagement as well. Through water budget analysis, I found that the reduction of the groundwater recharge is the main contributor to the groundwater storage decrease between 2003 and 2016. This decline of groundwater recharge was also significantly correlated with the increase of high-efficient irrigation area, a practice promoted by the WRT system in Ningxia. It is suspected that the current WRT system may have unexpectedly decreased groundwater storage. Still, how we can improve the system to reduce and even reverse this unanticipated impact of the management system on groundwater storage remains to be explored. As traditional policy instruments showed difficulty in regulating groundwater use, there is a pressing need to develop new ways of groundwater governance. Chapter 6 corresponded to the third objective to explore an improved institutional design for sustainable groundwater management. In this chapter, I examined the condition of the WRT system through the lens of adaptive governance and synthesized the information obtained from local community (through interviews, surveys, and focus group discussions) to explore how we can manage groundwater in a sustainable manner.

# 6 Revealing the potential of community on groundwater governance in a market-based scheme: A case from Northern China

**Highlights:**

- The water rights transfer system in Ningxia is not good at governing groundwater
- Stakeholders lack rights of rule-making for adaptive groundwater governance
- Community-based management may work for groundwater with governmental assistance.
- We suggest the market and community work together with government for water governance


## Abstract

Market-based schemes, such as Tradable Environmental Allowances (TEA), can do a good job in allocating natural resources for which property rights are well-defined. But TEAs are weak in adaptively preventing the resource depletion for a few common pool resources like groundwater, whose boundaries may change with environmental dynamics but are hard to detect. Community-Based Management (CBM) can address the weaknesses of TEAs by increasing the adaptability of the management system, thus showing potential to be used together with TEA for natural resource management. However, it is not always clear how to introduce CBM into an existing TEA system. Accordingly, our research aims to empirically introduce CBM into existing TEA in a real-case scenario to improve groundwater governance and promote sustainable water management as a whole. We chose to work on a system of groundwater management in Ningxia, northern China, where the Water Rights Transfer (WRT) system, a TEA regime, is well underway. We conducted 338 surveys, 22 interviews, and 4 focus group discussions to collect information about the inevitable challenges faced by WRT managers, as well as the existing institutional situation for groundwater governance (i.e. rules and norms for groundwater recognized by the community). Then we empirically examined the existing institutional situations for groundwater governance with a CBM framework which encompasses Ostrom's common governing principles (i.e. conditions to run CBM) and Dietz's requirements for adaptive governance that these principles help to meet (i.e. expected outcomes from CBM). Our analysis suggest that the WRT system developed in Ningxia had several issues that impaired its ability to respond to environmental threat (e.g. drought) in a timely manner. At the same time, the lack of stakeholders' participation in

decision-making hampered the potential for CBM to facilitate groundwater governance. We suggested governmental assistance to engage the community so that we can hold the strengths of both TEA (for surface water) and CBM (for groundwater) for sustainable water management.

**Keywords:** groundwater management, adaptive governance, collective action, stakeholder participation, sustainable water management

## Glossary

This glossary is provided for clarity about the way we use some well-known, but often vague terms in this paper.

**Common-pool resource (CPR):** A type of good consisting of a natural or human-made resource system (e.g. aquifers, oceans, atmosphere, space, or telecommunication), whose size or characteristics makes it costly to exclude other users (i.e. non-exclusivity or less exclusivity) and one user's consumption of the resource subtracts from the ability of others to consume (i.e. subtractability) (Ostrom, 1990). Common-pool resources are susceptible to overuse and are thus prone to the 'tragedy of the commons' (Gardner et al., 1990)

**Tragedy of the commons:** A situation in a shared-resource system where individual users acting independently according to their own self-interest behave contrary to the common good of all users by depleting or spoiling that resource through their collective action (Hardin, 1968).

**Community-based management (CBM):** A bottom up approach of organization which can be facilitated by a government or non-government organization, but aims for local stakeholder participation in the planning, research development, management, and policy making. While the specifics of each way of organization might differ, community-based management, when implemented successfully, is incredibly beneficial not only for the health of the environment, but also for the well-being of the stakeholders. (Dietz et al., 2003; Agrawal & Gibson, 1999; Armitage, D., 2005).

**Adaptability**: The ability of a socio-ecological system to adapt to change and respond to disturbances while retaining critical functions, structures, and feedback mechanisms. It is an aspect of resilience that reflects learning, flexibility to disruptions, and innovation. (Olsson et al., 2004; Walkers et al., 2002; Armitage, 2005; Chapin III et al., 2010).

**Adaptive governance**. The ways in which institutional arrangements (e.g. rules and norms) evolve to satisfy the needs and desires of the community in a changing environment. This concept aims to deal with the complexity and uncertainty of the socio-ecological system in pursuit of a desired future (Hatfield-Dodds et al., 2007; Chaffin et al., 2014; Allen et al., 2011). Here, the normative criteria used to judge whether a change in institutional arrangements is 'adaptive' or 'good' are derived from values and preferences of the community, rather than being imposed by experts or authorities (Hatfield-Dodds et al., 2007; Holling, 2017).

## 6.1 Introduction

Since the beginning of the 21st century, market-based systems such as Tradable Environmental Allowances (TEA) have been increasingly promoted by the World Bank, the United Nations, and other high-level environmental management organizations as a viable solution for improving the governance of natural resources (Hahn, 1989; McCay, 2003; Rose, 2002). TEAs work by defining an overall limit to environmental withdrawal or emissions, allocating allowances to individuals or organizations, and permitting free trade of allocated allowances within those limits (Dietz, 2003). Rights-holders can either use their permits or sell them, depending on the price of the TEA and their own costs to reduce withdrawal or emissions. In particular, TEA systems are increasingly being used to manage water resources in dry regions (Colby et al., 1993; Murphy et al., 2000; Bjornlund, 2003; Brown, 2006). For example, in the western US, the water rights transfers are increasingly considered as a policy alternative to encourage the optimal use of limited water resources through private reallocation (Theesfeld, 2010). Such TEAs have shown good environmental performance and economic efficiency for the management of surface water, as demonstrated by examples in the western US (Garrick, 2015), Australia (Brooks & Harris, 2008) and Chile (Bjornlund & McKay, 2002).

However, groundwater is subject to overuse even when TEA systems for surface water use are in place. Groundwater is a less-visible resource (Birkenholtz 2015) with unclear boundaries (Alley et al., 1999), whose changes are usually massive but hard-to-predict (Yang et al., 2015; Konikow & Kendy, 2005). With these characteristics, groundwater is often not clearly defined in TEA systems. People can freely use more water through unregulated wells instead of buying the water allotments (i.e. free riders) (Theesfeld, 2010; Knapp et al., 2003; Novo et al., 2015). The inflow of such ‘undefined resources’ in TEAs is detrimental to the fairness of the system (Konikow & Kendy, 2005) and typically leads to the overexploitation and depletion of the “unprotected” or undefined resource (Singh & Singh, 2003; Burchi & Nanni, 2003). Indeed, some regions experience groundwater depletion despite (or perhaps *because of*) the implementation of market-based schemes to manage water (Shiferaw et al., 2008; Salman, 1999; also see Chapter 5).

With the reliance on total take, TEA systems face additional weaknesses in adapting environmental uncertainties (Rose, 2002). TEA systems are conditioned by a rigorous definition of the total property rights which cannot by adjusted accordingly or as quickly as environmental changes (Miller et al., 1997; Dietz et al., 2003). For example, sudden droughts might require relatively rapid reductions in water use, which can be difficult to implement in a slow-changing TEA system.

Also, TEA has simplified indicators representing the total volume of the allowances but fails to consider the different qualities of resource for various needs (Chen et al., 2009; Z.Y. Ma, pers. comm., 2018). In order to make sure it is easy to measure and thus tradable, TEA system has to rely on one simplified metric to measure the property rights, for example using water volume (Speed, 2009). However, the very simplicity of indicators may exclude the possibility of innovative use and reuse based on different needs and may bring harm to the users’ livelihoods (Said et al., 2004; Beretta et al., 2014; Qadir et al., 2007). For example, groundwater can have different solutes that may ask for higher cost in treatment to reduce the hardness for the uses of boiler water or cooling water (Malaeb & Ayoub, 2011; Hudak, 2001).

At the same time, TEA may have limited influence in regulating the individual behavior. The main mechanism for a TEA system to regulate individual behavior is through the market which has limits and will not influence wider groups of people than the users in the market (Gustafsoon, 1998; Hasselman & Stoker, 2017). For example, when the labor required to bring the good to the market or facilitate exchange (i.e. transaction cost) is high, low-income buyers will leave the market and be free from the economic regulation (Garrick et al., 2013). It is especially true for groundwater, as it requires more transaction costs paid for electricity to pump water and water treatment to satisfy various needs (Kumar, 2005; Miller & Potts, 1995; Crook, 1991).

**Table 6.1 Mirrored strength of CBM to the weaknesses of the TEA scheme for groundwater resource management** (Adapted from Rose, 1999 and referred to literatures listed as below)

| TEA Steps for resource management | **TEA weaknesses** | **CBM strengths** | **Groundwater features that further impairs TEA's ability** |
|---|---|---|---|
| **Setting the total take** | Human-induced or nature-induced change of total available resource (either increase or decrease) would induce inequality and chaos in the market (Konikow & Kendy, 2005; Dietz et al., 2003). | Collective bearing of stress can make sure benefits and risks of the changes in resource availability are shared by the community (Soviana & Kuhl, 2010) | It's hard to detect and regulate illegal wells, which easily lead to free-riders (Theesfeld, 2010) |
| **Managing individual allotments** | Indicators are usually defined in volumes which fails to consider the quality of the resource for use (Chen et al., 2009; Z. Y. Ma, 2018) | Multi-stakeholders can cooperate and develop innovative ways to use the different qualities of resource based on various needs. (Sturdy et al., 2008; Han et al., 2015) | Groundwater has different features (e.g. temperature, solute) from surface water that will affect outcome of water use (e.g. cooling water) (Malaeb & Ayoub, 2011) |
| **Rule-keeping** | The rule compliance induced by TEA totally rely on the market which may be not effective if the transaction cost is high for the community (Garrick et al., 2013) | Collective norms (e.g. values, conduct) can encourage voluntary compliance to the rules. (Heckathorn, 1990) | The transaction costs for trading groundwater is higher (e.g. electricity for pump) than surface water (Kumar, 2005) |

Previous research indicates that community-based management (CBM) could be a potentially viable way to address the weakness of TEAs in managing groundwater (Table 6.1, Rose, 2002; Foster & Garduño, 2013; Tharmendra & Sivakumar, 2016; Azizi et al., 2017). Where the market in TEAs is disturbed by new entrance of groundwater that may induce user conflicts, CBM can strengthen the adaptation of the system by making sure the benefits and risks of the changes in resource storage can be shared by the community (Soviana & Kuhl, 2010; Narayan, 1995;

Barnett et al., 2003). CBM can function in this way because it encourages a collective bearing of the environmental stress instead of leaving the stress to single end-users (Rose, 1999).

Where TEAs are weak in satisfying various needs of water uses with a single criterion to define water rights, CBM could encourage innovative water use according to different qualities of water resource. This advantage is due to the involvement of the community in decision-making in the CBM scheme, through which multi-stakeholders can cooperate and develop innovative ways to optimize the use of water (Ison et al., 2007; Sturdy et al., 2008). For example, while fresh groundwater is good for drinking, it may not be a good source of crops considering its relatively low temperature compared to river water (Lyons, 2012; Han et al., 2015). While brackish water may be good for growing forage grass, it may not be a good source for industry as boiler water or cooling water (Qadir, 2007).

Where TEAs rely on the market to induce rule compliance, CBM can establish social norms in the community (e.g. individual's basic knowledge and informal understanding of what others do and think that they should do) which encourage voluntary compliance to regulation rules. Participants of CBM are both the users and enforcers, thus can be motivated to protect the norm that potentially would benefit themselves. They would feel duty-bound to chastise infringers who disobey the community's rule of water use (Grey, 2001; Fernandez-Gimenez et al., 2008).

Considering that TEA is generally good for surface water regulation but not groundwater while CBM has shown strengths for managing groundwater, it is promising to use these two schemes together to improve sustainable water management. Since market-based management strategies (such as TEA) are already applied in many places around the world and are efficient for surface water management (World Water Assessment Programme, 2009; Bakker, 2014), it is valuable to explore the possibility for these two schemes to work together to realize a conjunctive and sustainable use of surface and groundwater.

A remaining question is how CBM can be applied alongside existing TEA schemes in a way that retains the strengths of both schemes. While many empirical studies have identified a series of institutional designs for CBM to adaptively govern common-pool resources (Ostrom et al., 1999; Holling, 2001; Ostrom, 2008; Lopez-Gunn, 2003), including groundwater (Ross & Martinez-Santos; 2010; Seward & Xu, 2019), There are limited empirical studies about how CBM could work with an existing TEA. Thus, the main goal of this research is to empirically introduce

CBM into existing TEA in a real case scenario to improve groundwater governance and promote sustainable water management as a whole. We chose the Water Rights Transfer system (WRT) in Ningxia, China as an example TEA. Our objectives are 1) to identify the manifestation of TEA weaknesses for managing groundwater in this particular WRT system 2) to explore possibilities and ways to introduce CBM into TEA to improve the groundwater governance of Ningxia

## 6.2 Place and system context

### 6.2.1 Ningxia and its groundwater resource

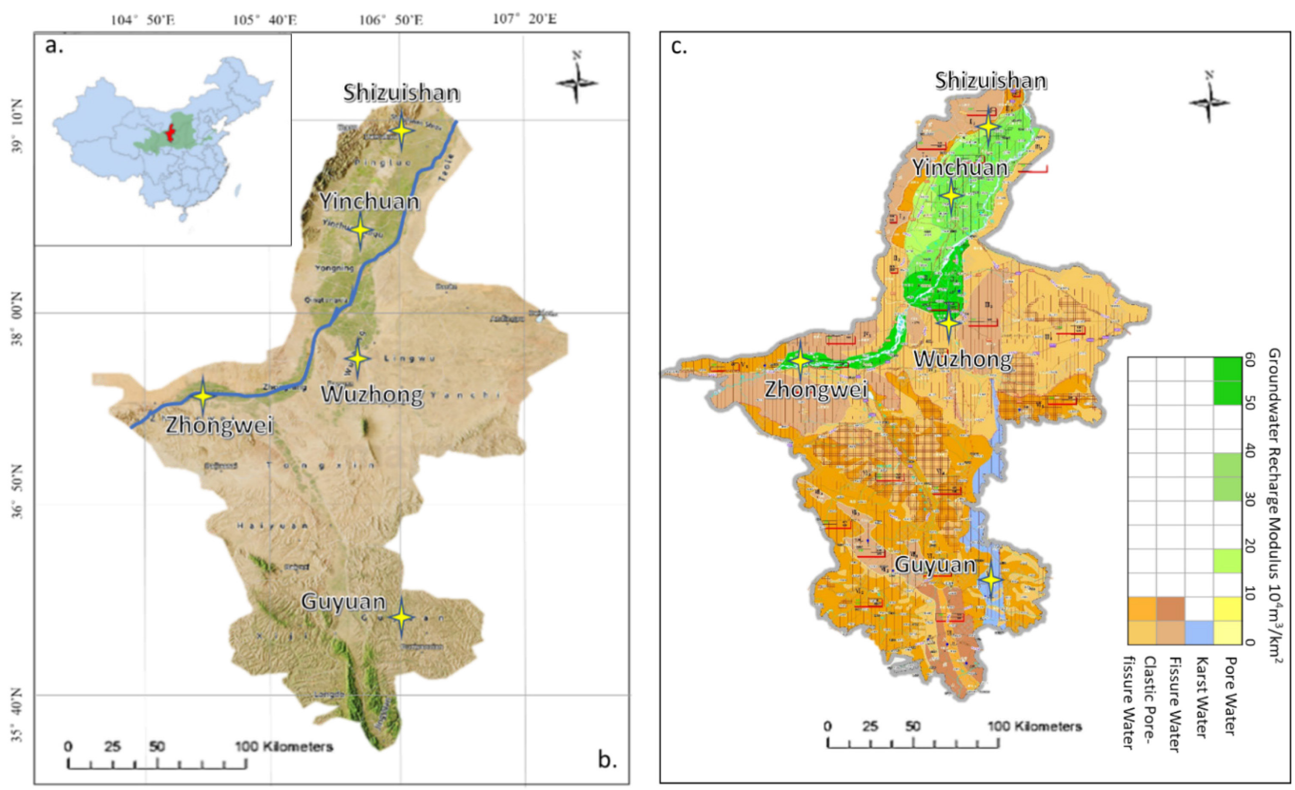


**Figure 6.1 Ningxia topological and groundwater map.** a) The thumbnail of China, Yellow River Basin and Ningxia. The blue polygon represents that total area of China, the green polygon represents the Yellow River Basin, the red polygon in the middle is Ningxia area. b) Topological map of Ningxia. The blue line is Yellow River flowing from southwest to northeast. Ningxia contains 5 major cities: Shizuishan, Yinchuan, Wuzhong, Zhongwei, and Guyuan. The two main irrigation regions are near Zhongwei and Yinchuan shown as green polygons. c) The aquifer map of Ningxia. Ningxia (Revised from OSGEO China, 2019). The main aquifers are in green, located in the north, recharged by the irrigation water and the Yellow river. The shape and location of the aquifers are similar to the two irrigation regions on the surface as shown in Panel b.

Located in the middle of the Yellow River Basin in the north of China (Figure 6.1a), Ningxia is a typical continental area with a temperate semi-arid to arid climate, and very limited water resources (Zhang et al., 2017). The average volume of water available to each person is 176 $m^3$ per year, which is just one-twelfth of the national average for China (NWCD, 2016; Yang & Zehnder, 2001). Nearly 90 percent of the water supply in Ningxia comes from the Yellow River (Figure 6.1b). With over 2000 years of irrigated agriculture, Ningxia has a strongly bonded rural community: In 2007, there were 3.865 million people living in rural areas of Ningxia (63.4%) and 892 farmers' associations at various scales, from provincial to village levels. (Li et al., 2008). The water use in the region is dominated by agriculture, and the rural community mainly consists of small-scale farmers (UN Environment Management Group, 2011; Shah, 2010).

The groundwater basin in Ningxia is mainly located in the north, beneath the two major irrigation regions: Yinchuan Irrigation Region and Weining Irrigation Regions (Figure 6.1b & c). Apart from a limited amount of precipitation (289 mm/year), the groundwater basin receives surface water recharge mainly from the Yellow River (>75% of total recharge, Winter, 1999) through canal seepage and river-water irrigation (Ningxia Water Resources Bureau, 2017; also see Chapter 5). Recent studies have shown that the engineering projects designed to reduce surface water use (e.g. canal lining and drip irrigation) are likely reducing the groundwater recharge, potentially contributing to groundwater depletion in Ningxia (Jansen et al., 2006, also see Chapter 5). Between 2011 and 2014, the groundwater depth in Yinchuan, the capital of Ningxia, had decreased by 0.84 m/yr on average (Wang & Chen, 2016). Evidences show that the area wetlands are shrinking, and the land is subject to subsidence (Shao, 2008; Yinchuan wetland web, 2019; Xu et al., 2008; Galloway, 2011). Because the groundwater basins and the implementation of schemes to reduce surface water use are mainly located in the north Ningxia, we focused our data collection on north Ningxia in the two irrigation regions mainly covering Yinchuan city and Zhongwei city (Identified in green in Figure 6.1b).

### 6.2.2 Water Rights Transfer system

The current water management system in Ningxia, called the Water Rights Transfer system (WRT), is a typical TEA system. The goal of this WRT is to maintain the balance between increasing water needs and constrained supply, while encouraging a structural transformation from agriculture to industry in the region (Liu et al., 2013). In this system as it plays out in Ningxia, industry pays for engineering projects to increase agricultural water use efficiency and then, based on the amount paid, is allocated an increased water quota for industrial use (Yang et al., 2011).

This management system has been remarkably successful in increasing water use efficiency. It has successfully increased the irrigation efficiency rate to over 50% (Zhang et al., 2017), and the canal lining rate to over 65% (NWRB, 2017). With massive implementations of agricultural engineering projects, the Yellow River water consumption has remained under 4 billion $m^3$/yr, meeting the requirements of river water use control set by the Yellow River Conservancy Commission (YRCC) for Ningxia. In 2017, the Chinese government approved Ningxia as a pilot project, hoping to introduce the WRT system in other arid parts of the country soon (JICA, 2006).

## 6.3 Materials and methods

To introduce CBM into the WRT system for groundwater governance, we first collected both quantitative and qualitative information through governmental reports, surveys, interviews, and focus group discussions, and then, based on this information, identified evidences of TEA weaknesses in the WRT system and analyzed existing institutional conditions (i.e. norms and rules recognized by the community) for CBM to function using a CBM framework adapted from Ostrom, (1990) and Dietz et al. (2003).

### 6.3.1 Data collection

The information collected through a series of social investigations includes: 1) expert perceptions and community's evidences about challenges of the WRT system for water management, with a special attention on groundwater resource; 2) existing rules and norms recognized by community for groundwater governance; 3) the community's values and knowledge on groundwater which potentially would help to create social norms; 4) the community's expectations and suggestions for water management.

*Literature and reports*

We obtained governmental e-bulletins for water resources and hydrological engineering practices through the website of the Ningxia Water Bureau (available at http://slt.nx.gov.cn/ ). The literature referenced for the study include but is not limited by the Development and Research Center of the Chinese Ministry of Water Resources (2018), Wang et al. (2010), Speed (2009), Moore (2014), Sun et al. (2017); Japan International Cooperation Agency (2006). We also obtained other detailed reports through personal communications, which include policy planning of water rights transfer system and investigation on groundwater situation in Ningixia (Ningxia Geological Survey Department, pers. comm., 2016; NWRB, pers. comm., 2017).

*Interviews*

Semi-structured interviews can uncover the perceptions and opinions of respondents on complex or sensitive issues (Barriball & While, 1994). We conducted semi-structured interviews with stakeholders whose work closely relate to the WRT system or to groundwater (Text S6.1), including surface water managers, groundwater managers, water policy makers, employees of local non-governmental organizations, representatives of industrial water users, municipal water users, and agricultural water users. The questions for interviewees centered around water management, including their viewpoints on the current situation of surface water and groundwater, roles they themselves played in the WRT system and difficulties they came across, as well as their perceived achievements and challenges of WRT for water management. The information is mainly used to identify the evidences of TEA weaknesses in the WRT system.

We conducted 22 semi-structured interviews between June 2017 and October 2018 (Text S6.1). We used structured snowball sampling to find interviewees (Noy, 2008), by first listing related stakeholders (Table S6.1), and then started from existing contacts to explore opportunities to connect with other stakeholders on the list. Oral consents were obtained at the start of each interviews. Within each category of stakeholders, opinion saturation has been reached when no distinct new points were identified. The conversations were audio-recorded and transcribed into text.

*Surveys*

Interviews can only get expert knowledge on the advantages and disadvantages of the existing management practices, but not necessarily real influence of the management on the community. At the same time, we need to collect information about existing institutional conditions for CBM to work, which includes norms and rules generally recognized by the community. Therefore, we conducted surveys to understand the management practices perceived by the community, and their daily behaviors for groundwater protection (including what they have done in the past and what they think people shall do). The survey also collected information about their values on groundwater resource and knowledge on their own footprint on groundwater. This information can help to understand how the community can be encouraged to get involved in groundwater management or establish social norms for sustainable use of groundwater.

We distributed 338 surveys in Yinchuan city (26% of the total participants) (including regions Xingqing, Jinfeng, and Xixia) and Yinchuan prefecture-level cities (67%) (including Helan and Yongning), and Zhongwei city (7%) (including Zhongwei, Shapotou, and Zhongning). We haphazardly selected people (e.g. along the street, in the buildings, in the farmland, etc.) in each of these three regions to hand out the surveys and helped participants complete the surveys through face-to-face communications (Text S6.2). Female accounts for 49% of the total population while male accounts for 51%. The major occupations of respondents include workers (32%), students (26%) and farmers (11%). Half (49%) of the respondents were between age 20 and age 40, followed by age 40-60 (22%), and age 13-20 (17%).

*Focus groups*

Focus group discussion provides a way to initiate closed and focused conversation to reveal people's perceptions on specific topic (Edmunds, 2000; Rabiee, 2004). Surveys can get a general understanding of the community's perceptions on water management but may have missed some deeper and unknown connections and perceptions that survey questions may not necessarily can cover. To further explore how we can incorporate CBM into TEA, we conducted four focus group discussions between July 2016 and October 2018 (Text S6.3) to get more detailed understanding on community's preference and expectations for institutional design, and possible rules and norms that they may set if they were the decision-makers.

The focus group discussion was broken up into two sections. In the first section of the discussion, we invited participants to discuss general understanding of the WRT system and their expectations for the future. In the second section, we invited them to map their stances and roles in groundwater management on pre-developed stakeholder worksheets (Text S6.4). Then they could freely share their opinions. Here we used four proposals as a trigger for stakeholders to express their opinions on groundwater management in depth. The four proposals touched four aspects of groundwater management: control on groundwater discharge (1), and groundwater recharge (2), and amelioration for ecological stress (3) and financial stress (4) (Text S6.6). These four proposals were based on preliminary studies in June 2016 and a synthetization of suggestions from water managers and local residents. The focus of the stakeholder worksheet is not the content of the four proposals but how community would take a role when facing situations relating to groundwater management.

To recruit the participants of focus groups, we connected with the key informants (e.g. village head, head of NGO, departmental director of the water bureau) in Ningxia who helped us to find prospective stakeholders and then we selected randomly from the satisfying participants (Table S6.1). Each focus group discussion consisted of six to eight participants and lasted one to two hours. We audio recorded the focus group discussions with oral/written consents and then transcribed the audio recording to the text. Main themes and important quotes of the transcribed interviews and discussions were then independently identified by two researchers based on the transcripts, and then converged to a consistent version.

### 6.3.2 Data analysis

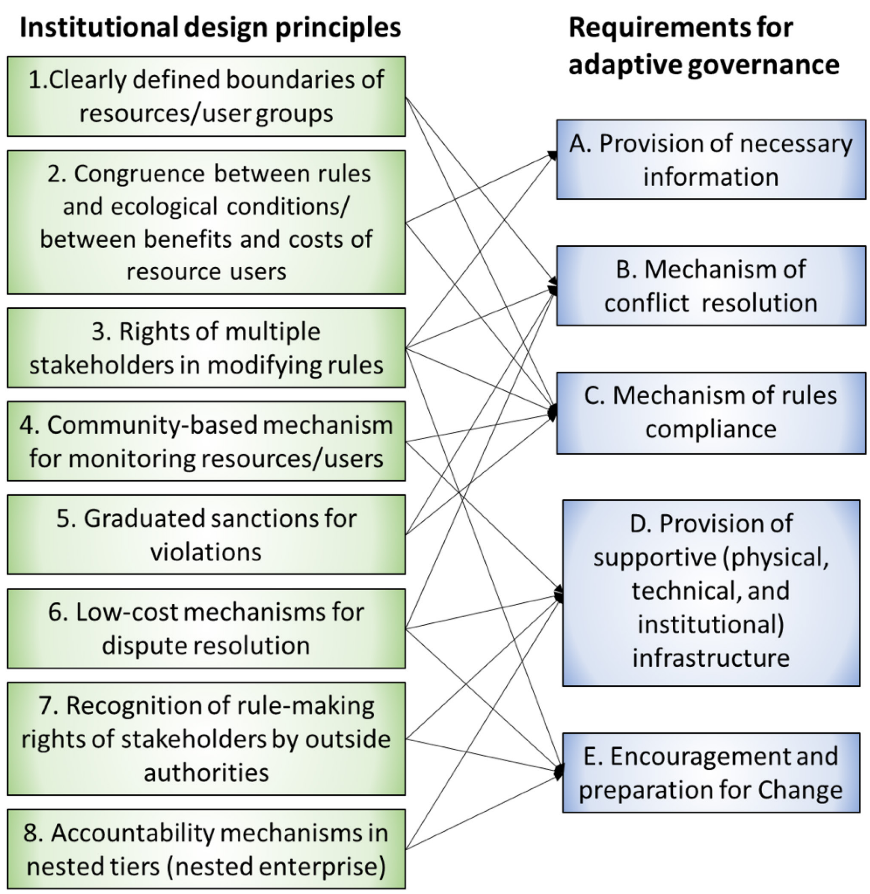


**Figure 6.2 Framework of adaptive governance used for CBM analysis in Ningxia.** The framework was adapted from Dietz et al., 2003. The description of the eight institutional design principles were based on Ostrom (1990) and revised according to Cox et al. (2010), Walljasper (2011), and Chow (2012).

Based on the first-hand information from interviews of water experts and the first section of focus group discussions, and second-hand information from literature and reports, we identified the evidence of TEA weaknesses in the WRT system for groundwater governance. We collected the main themes in the interviews and focus group discussions, grouped them based on TEA weaknesses listed in Table 6.1, excluded the examples that were contradicted by government report and literature, then selected the examples with highest relevance and occurrence frequency as evidence.

Based on the quantitative information collected in surveys and qualitative information collected in the second section of focus group discussions, we examined the institutional conditions for CBM to function through the lens of a CBM framework (Figure 6.2). The examination is through a similar procedure as the analysis for TEA weaknesses. In addition to the main themes collected from interviews and focus group discussions, we also analyzed the survey results along with government data (available at http://slt.nx.gov.cn/) to identify where people's understanding was, and was not, consistent with data on groundwater storage and management. Evidence was grouped according to the eight institutional design principles and was chosen based on the relevance, occurrence frequency as well as the consistency with the other sources of information. Then the implementability of each principle was identified based on the evidence using three indicators: "Y" means it can be found in Ningxia with sufficient evidence, "Y-" means it can be found in Ningxia with minimal evidence, "N" means it cannot be found in Ningxia with our evidence. Then we mapped the result to the five requirements of adaptive governance based on Figure 6.2 and analyzed its indications.

The framework used for examination is a new interpretation of a few past frameworks for CBM (Armitage, 2005), self-governance (Ostrom et al., 1990) and adaptive governance (Dietz et al., 2003). Self-governance studies identified eight institutional design principles which were often present when communities successfully governing the commons through collective actions (Ostrom; 1990; Cox et al., 2010). Dietz (2003) and related studies further connected them to five requirements of adaptive governance that these principles help to meet (Holling, 2001; Hatfield-Dodds et al., 2007). Considering that the advantages of CBM are realized by collective actions, and manifested through adaptive governance (Ostrom, 2008; Lopez-Gunn, 2003; Ross & Martinez-Santos; 2010; Seward & Xu, 2019), we incorporated these two criteria together. Our revised framework suggests the conditions for CBM to function using common governing principles (Ostrom et al., 1990) and expected outcomes of CBM using adaptive governance requirements (Dietz et al., 2003). As a normative criterion, this framework serves as a lens to examine current institutional design in Ningxia for successful groundwater governance. (Ostrom, 2005; Cosens & Gunderson, 2018; Seward & Xu, 2019).

## 6.4 Results: evidence of TEA weaknesses in the WRT system

### Challenges for setting the total take

In Ningxia, our survey in communities revealed the existence of free-riders in the WRT system. Ningxia governmental report showed that water use rights in irrigation and industry have been clearly defined (4564 million $m^3$ for agriculture and 127 million $m^3$ for industry). With this total allowable water use in each sector, industrial users could invest in the water-saving infrastructures and obtain extra virtual water rights to satisfy their increasing needs. At the same time, farmers were required to use the water-saving infrastructures, like drip irrigation, to save water. But quite a few community members in our surveys confessed that the wells were unregulated and free, so they didn't have the willingness to save water.

Our interviews also provided evidence that the WRT system fails to alleviate the extreme stresses imposed on end-users in environmental extremes. Informants in some villages of Ningxia complained that they can hardly survive in a recent drought as they are in the downstream receiving no canal water from upstream. As indicated by water experts in a village, this disaster for end-users may result from a same-as-usual volume of water use in the upstream which leaves the water stress imposed totally on the downstream villages.

### Challenges for managing individual allotments

For the allocation of water rights, our survey proved that the single metric of water volume in the WRT system doesn't satisfy various water needs. We found that a lot of farmers were suffering from the WRT system as the crop growth does not only rely on the total volume of the irrigation water, but also the irrigation time, temperature, and other features of the water supply. For example, farmers who used drip irrigation complained that this new system needs continuous water supply which the rotation-basis supply of river water (i.e. water supply only lasts several hours for each household in each season) cannot satisfy. At the same time, in some areas when groundwater can be used for drip irrigation, farmers also complained that "*the groundwater* *temperature is too low which is not good for the crops*". The evidence indicates that a single metric of rights definition is insufficient to represent the different ways of water supply that may affect the outcome of water use.

### Challenges for rule-keeping

Our interviews of water experts, focus group discussions, as well as community surveys collectively provided evidence on the weakness of rule-keeping in WRT system. Focus group discussions revealed that because community members were exempt from rulemaking, they had minimal motivation to follow the rules set by government. For examples, farmers usually passively followed the rules of changing traditional flood irrigation to drip irrigation as required in the WRT system. But they would also easily break the rules or even fight against them if their own profit were seriously affected. In some villages we visited, farmers indicated that quite a few forerunners had seen the reduction of crop production. This reduction, according to interviewed water experts, were partially due to a lack of technology to adopt drip irrigation in a proper way. However, the transactions cost for knowledge and information is high for small-scale farmers. As crop production is their main livelihoods, these small-scale farmers can hardly bear the risk brought by new technology. As a result, there were serious objection on new implementations of drip irrigation, some cases of which even induce acute conflicts.

## 6.5 Results: existing institutional conditions for introducing CBM into WRT

### 6.5.1 Examining common governance principles

Table 6.2 Implementability of institutional design principles for managing groundwater in Ningxia. Y represents "Yes" meaning this principle is currently or potentially implementable. Y- represents "Yes, but not fully implemented". N means the principle is not yet met in Ningxia.

| Institutional design principles | Implement-ability | Evidence in Ningxia for groundwater management (source of result) |
|---|---|---|
| **Principle 1.**<br>Clearly defined boundaries of resources/user groups | **Y-** | Water user groups were defined, but not specifically for groundwater use (interviews), but user usually underestimate their water use (surveys and Figure 6.3). |
| **Principle 2.**<br>Congruence between rules and ecological conditions/ between benefits and costs of resource users | **Y-** | Regulations on groundwater were consistent with groundwater condition (interviews), but the rules may hamper the benefits of the resource users (surveys and focus groups). |

| | | |
|---|---|---|
| **Principle 3.** Rights of multiple stakeholders in modifying rules | **N** | Water users (especially agricultural water users) and groundwater managers lacked the rights for decision-making on water use plans (focus group). |
| **Principle 4.** Community-based mechanism for monitoring resources/users | **Y-** | Mechanism existed but was less available to the community in Ningxia (interviews and Figure 6.4). |
| **Principle 5.** Graduated sanctions for violations | **Y-** | Step water price were implemented, but there were limited sanctions for illegal well water use, which was partially due to a lack of accurate monitoring (surveys). |
| **Principle 6.** Low-cost mechanisms for dispute resolution | **Y-** | Urban residents committee and the rural village committee took the role in resolving the conflicts between residents. But the disagreements among officers were mostly suppressed by the institutional hierarchy (interviews and focus groups). |
| **Principle 7.** Recognition of rule-making rights of stakeholders by outside authorities | **N** | The channels for stakeholders, especially agricultural water users to convey their concerns were limited (focus groups and interviews). |
| **Principle 8.** Accountability mechanisms in nested tiers (nested enterprise) | **Y-** | Water use has been governed from group level, village level, county level, city level, to watershed level, and federal level. Still, the responsibility of governing groundwater among institutions were vaguely defined. (interviews) |

By examining the existing institutional conditions with Ostrom's eight principles to investigate the WRT system in Ningxia (as determined from surveys, interviews, and focus groups), we found that two of the principles related to the rights of multiple stakeholders remained to be met (Principle 3 & Principle 7 in Table 6.2). For example, groundwater managers mainly took charge of monitoring resources, but not informing policy. As one informant indicated, "w*e only generate monitoring report for policy-makers to read and analyze. We don't know much about the policy-making, it is the business of policy-makers*". The agricultural users, mostly farmers, also indicated that "*We have discussed our challenges with our village head, but the upper-level government didn't listen*". They explained that "*local government provided some initial infrastructure for us, but maintaining these infrastructures is costly*". Governmental informants indicated that as drip irrigation was promoted in the WRT system, local government provided the first-year infrastructures to farmers and taught them how to change from flood irrigation to drip irrigation. Still, village heads indicated that farmers lacked the continuous technological and financial support to maintain these infrastructures. For instance, the tubes of the drip irrigation had to be changed every year without the right protection in winter. Farmers also lacked sufficient knowledge and technology to make sure the water emitters along the tube were free of clogging, to apply both fertilizer and water through drip irrigation, or to adjust the water supply according to crop needs. As a result, some farmers in the survey found a reduction of crop production after changing the irrigation methods.

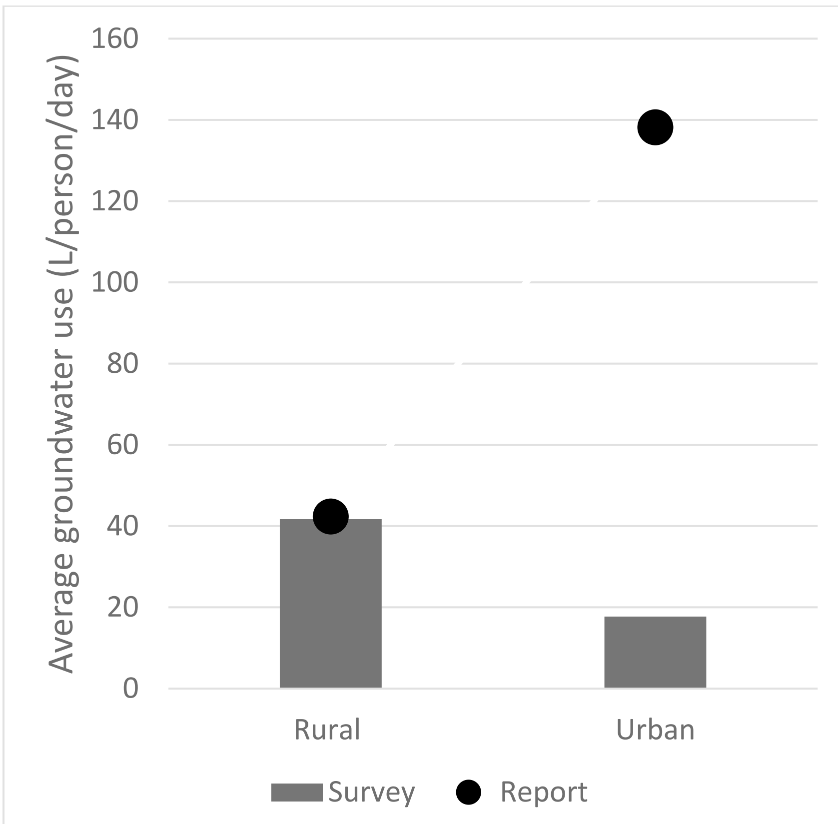


Figure 6.3 Comparison of the survey result and governmental report on average groundwater use in urban and rural areas.

We found that evidences in Ningxia adhere to the rest six principles but have the potential to be improved. For example, principle 1 indicated that there should be well-defined water user groups for CBM to work (Table 6.2). We found the general existence of water use associations in villages in Ningxia, however, the user groups formed in Ningxia were mainly for the irrigation water use, having no regulation on groundwater use, as indicated by the heads of the water use associations. Also, the comparison between survey data and governmental reports indicated that the installation of a tap water system in urban areas had masked the boundary and availability of the groundwater resource which led the users to underestimate their own impacts on the groundwater resource (Figure 6.3).

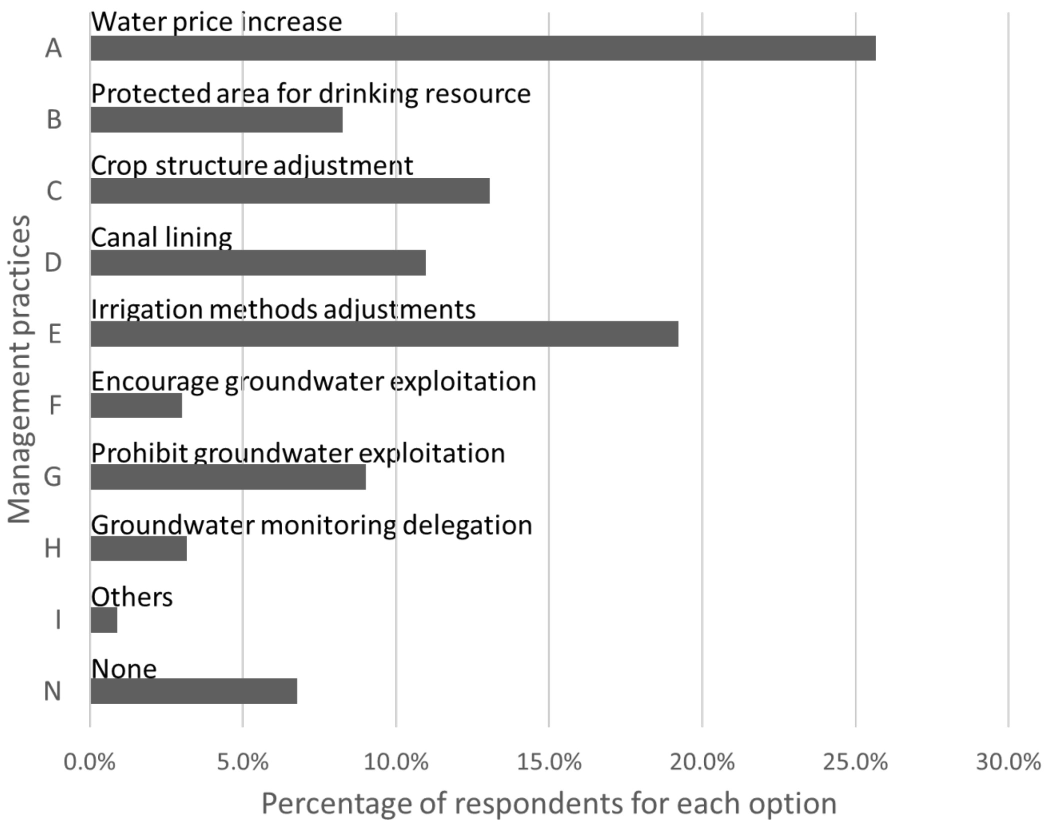


Figure 6.4 Management practices that the community have experienced or heard of. The y axis lists the ten options in the survey, and the x axis represents the percentage of respondents for each option. Among them, C, D, and E are the three main measurements related to WRT.

Existing management practices in Ningxia, according to interviewed groundwater managers, include both restrictions on groundwater use in overexploiting regions (e.g. the surroundings of urban residential areas), and the encouragements of groundwater use in the farmlands where surface water was limited (Figure 6.4). These regulations are theoretically consistent with the ecological condition of local aquifers storage (Principle 2). However, some of these rules may affect the benefits of the resource users, which makes it hard for the users to follow. As indicated by the farmers who participated in our surveys, the temperature of groundwater was relatively lower than surface water which may bring harm to the production of vegetables. Even though these farmers were encouraged to use groundwater on farmland, they would still withdrawal river water for irrigation to maintain their profits.

The survey result further indicates that community-based management for monitoring groundwater resources existed (Principle 4) but had a great potential to be promoted. Only 3% of the participants in the survey had experienced groundwater monitoring delegation (Figure 6.4) which was very minimal compared to other practices related to groundwater (e.g. water price increase 25%, irrigation methods adjustments 19%, crop structure adjustments 11%, and prohibition on groundwater overexploitation 9%). At the same time, groundwater managers indicated that they came across the staff shortage for the monitoring work. Current monitoring staffs were mostly in age 50+ and it was hard to find young employees because of the heavy workload with relatively low salary.

### 6.5.2 Examining requirements of adaptive governance

Table 6.3 Situation of adaptive governance for groundwater management in Ningxia. Y represents "Yes" meaning it is currently or potentially implementable. Y- represents "Yes but not fully implemented". N represents the principle is not met in Ningxia.

| Requirements for adaptive governance | Implement-ability | Corresponding institutional design principles that help to meet each governance requirement |
|---|---|---|
| **Requirement A.** Provision of necessary information | **Y-** | **Principle 2.** Congruence between rules and ecological conditions/ between benefits and costs of resource users |
| | **N** | **Principle 3.** Rights of multiple stakeholders in modifying rules |
| **Requirement B.** Mechanism of conflict resolution | **Y-** | **Principle 1.** Clearly defined boundaries of resources/user groups |
| | **N** | **Principle 3.** Rights of multiple stakeholders in modifying rules |
| | **Y-** | **Principle 5.** Graduated sanctions for violations |
| | **Y-** | **Principe 6.** Low-cost mechanisms for dispute resolution |
| **Requirement C.** Mechanism of rules compliance | **Y-** | **Principle 1.** Clearly defined boundaries of resources/user groups |
| | **Y-** | **Principle 2.** Congruence between rules and ecological conditions/ between benefits and costs of resource users |
| | **N** | **Principle 3.** Rights of multiple stakeholders in modifying rules |
| | **Y-** | **Principle 4.** |

| | | |
|---|---|---|
| | | Community-based mechanism for monitoring resources/users |
| | **Y-** | **Principle 5.** Graduated sanctions for violations |
| **Requirement D.** Provision of supportive (physical, technical, and institutional) infrastructure | **Y-** | **Principle 4.** Community-based mechanism for monitoring resources/users |
| | **Y-** | **Principle 6.** Low-cost mechanisms for dispute resolution |
| | **N** | **Principle 7.** Recognition of rule-making rights of stakeholders by outside authorities |
| | **Y-** | **Principle 8.** Accountability mechanisms in nested tiers |
| **Requirement E.** Encouragement and preparation for Change | **N** | **Principle 3.** Rights of multiple stakeholders in modifying rules |
| | **Y-** | **Principle 6.** Low-cost mechanisms for dispute resolution |
| | **N** | **Principle 7.** Recognition of rule-making rights of stakeholders by outside authorities |
| | **Y-** | **Principle 8.** Accountability mechanisms in nested tiers |

By matching the eight principles to the five components of the adaptive governance, we gained more insights on the ways to reveal the potentials of CBM (Table 6.4). We found that at least one principle was missing in each of the requirements for adaptive governance in Ningxia which cross-validate the existing TEA weaknesses in the WRT system: Ningxia was mostly weak in embracing the changes (Requirement E) with two missing principles related to the rights of stakeholders. According to the focus group discussions, stakeholders don't have proper channels to provide timely feedback for groundwater governance. Without the recognition of the decision-making rights of stakeholders from outside authorities, the unsolved disputes were mostly suppressed by the institutional hierarchy instead of contributing to innovations.

## 6.6 Discussion: trigger the community's power for groundwater management

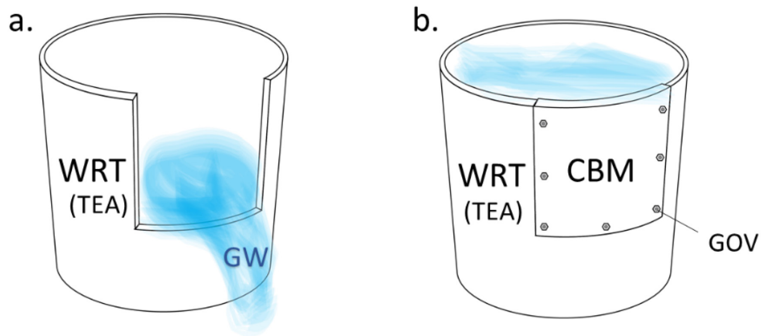


**Figure 6.5 A conceptual diagram on our proposed institutional design for water management.** WRT refers to water rights transfers system, which is a local version of tradable environmental allowances (TEA) regime. CBM refers to the community-based management scheme, and the nails refer to the governmental assistance (GOV). In panel a, groundwater (GW) is lost without the support of the community. Panel b indicates a mixed institutional design that can protect both surface and groundwater. This mixed institutional deign organically incorporates the water market, community-based management, and governmental assistance.

In this paper, we analyzed the weaknesses of the WRT system in Ningxia and investigated the possibility of applying CBM to address these weaknesses. We found that the WRT system relied on well-defined water rights which were measured by a single metric (i.e. volume) and had limited influence on water users' behavior. These properties resulted in weaknesses in adapting to changes in water storage (either through illegal groundwater extraction or environmental disturbances), innovation for optimal water use, and regulating user behaviors who are outside of the market. While CBM was said to have strengths mirrored to TEA's weaknesses, we found additional efforts required to reveal its potential to aid in managing groundwater in Ningxia (Figure 6.5). By examining Ningxia's case to the revised framework for CBM, we found that the missing rights of stakeholders in decision-making was potentially an important barrier to the success of CBM. Therefore, we suggested a combination of WRT and CBM assisted by government to achieve sustainable water management (Figure 6.5b). Based on the focus group discussions with stakeholders, we proposed strategies that could be applied to groundwater management in the current WRT system in Ningxia and many other groundwater-dependent societies elsewhere. These are:

## Trigger the community's motivation: Increase awareness

The local government and water institutions should improve the awareness of people about their reliance on groundwater and their impact on groundwater. In the tap water system, the source of water is hidden, thus discouraging the community's willingness to protect groundwater. People tended to believe water in Ningxia was easy to get as long as you open the tap and did not have a holistic picture of their collective impact on water scarcity. Increasing awareness of water resources and of individual water footprints could be a first step to motivate people to take actions on their own behalf.

## Trigger the community's adaptability: Goal-based strategy clarification

The community requires explicit instructions and explanations about the resource use strategies and risk response strategies. People can follow the rules more easily and adaptively when they understand the main goal and underlining logic of the policies (Simmons, 1998; Barrett & Stavins, 2003). In groundwater's case in Ningxia, it has to be clearer where and why groundwater use was restricted or encouraged. Individuals tend to be reciprocal or even altruistic when they find their actions are contributing to a bigger cause (Ostrom et al., 1999; Batson et al., 2002). The understanding on the goal and logic of groundwater use strategies would not only facilitate the rule compliance but also encourage the community to resolve the problem adaptively and innovatively (Reed et al., 2006; Clark & Clarke; 2011). Considering that sustainable governance at the global scale is undergoing a major transformation from rule-based to goal-based (Kanie et al., 2019), there is no better time for local government to substantiate the sustainable development goals for the local community and clarify goal-based strategies, especially for those marginalized groups who are subject to the most devastating impacts when facing unanticipated environmental changes.

## Trigger the community's initiativeness: Collaborative monitoring

Agencies responsible for monitoring should encourage groundwater monitoring delegation and information-sharing. Collaborative monitoring has been proven to induce social learning, community-building, and conflict resolution between multiple stakeholders in the community (Fernandez-Gimenez et al., 2008). Different from governments, which usually have electoral cycles within a decade (Geys, 2007; Bastida et al., 2013), a community (e.g. a village) has a relatively stable composition of members which leads to stronger bonding and internal trust (Foster & Chilton, 2003; Wang et al., 2010). They are able to document and learn from long-term actions and structural experiments (Holling, 2001; Gunderson, 2001; Cosens & Gunderson, 2018) and develop adaptive strategies that benefit all and future generations. Moreover, the involvement of community in monitoring would increase the sense of urgency and sense of accountability for the resource management, thus giving rise to mutual regulation and self-organization (Bliss et al., 2001; Conrad & Daoust, 2008; Tzovaras et al., 2019).

## 6.7 Limitations

In this study, we used a series of social investigations to explore the ways to engage a community in groundwater management. Actually, the process of data collection in this study is a way to engage community. By having opportunities to express their opinions on water management, people feel more interested in the topic and feel more empowered in taking actions. Also, by discussing with different community members, participants may have a more complete understandings of the groundwater and management issues which might affect their future behaviors.

Admittedly, none of the methods used could sufficiently demonstrate the real situations of the management system on their own. For example, the data collected in the surveys on the groundwater awareness may not sufficiently represent the actual awareness of the community on groundwater. Despite the personal conversations, there still exists different interpretations on the statements. Our test only shows that different people may have various levels of awareness on different aspects of groundwater, indicating the importance as well as challenges of engaging multi-stakeholders.

Likewise, the method of focus group discussions helps to deepen the knowledge on institutional conditions for groundwater governance but is expected to improve. Discussions in focus groups are subject to biases because participants' replies may be affected by others who are present. Still, their replies are an outcome of collective decisions that show the general opinions community holds for groundwater management. In this sense, the method is reasonable and has helped to answer our questions on CBM's potential role in groundwater management. Further studies are expected to conduct participatory research on innovative ways to involve the stakeholders in decision-making processes and actions of groundwater protection.

## 6.8 Conclusion

Groundwater management requires a community-based approach to influence the behavior of individual groundwater users (Foster & Garduño, 2013). Despite the management efficiency of the WRT system for surface water regulation in Ningxia, CBM would provide an opportunity to maintain sustainable use of groundwater which is currently facing unattended stress in this example TEA system. We found that the missing component for groundwater governing in Ningxia, which ultimately hampered adaptive governance, is the decision-making rights of stakeholders. There requires governmental assistance to engage the community into decision making process so as to make sure we can enjoy the strengths of both CBM and TEA for sustainable water management.

## Acknowledgements

The authors would like to acknowledge the Chinese Scholarship Council (CSC), Natural Sciences and Engineering Research Council (NSERC) of Canada (RGPIN-2014-4100) and Centre for Social and Cultural Data Science (CSCDS) which funded this research. A big thank for the inspiration of colleagues in the Resilience Alliance, who provide necessary platform and financial support for the discussion of the ideas. Special acknowledgements are due to Ms. Jiahua Chen who provided essential support for the survey process, Dr. Klara Johanna Winkler and PhD Sam Darling who provided important suggestion on refining the manuscript and the validity of the results. This project cannot be done without the community in Ningxia, including NGOers (Mr. Hu Yanqin, Mr. Wang Yuxiao, Mr. Chenxu, Mr. Gancao etc.) and water managers who provide essential contact for the interviews; students and teachers in Ningxia university (Fan Qi, Wang Junhui, Liu Peng, Wang Hong, Wang Jiaxing, Ma Jinlong, Zhangjun, Cao Lanzhou, Jin Anni, Wang Hengheng, Mian Haikun, Wukailong, Ma Xiaomei and professor Wang Huihui & professor Zhu Zhiling, etc.) who voluntarily helped with the surveys, interviews and focus group discussions and provided necessary information and suggestions for research on local community. The authors are also grateful for Dr. Lehner Bernhard and Dr. Gordon Hickey, and all the lab members of Dr. Elena Bennett and Dr. Asim Biswas who provide essential suggestions for this project.

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## Appendix 6.1

Table S6.1 Stakeholder list

| STAKEHOLDERS | REPRESENTATIONS | NUMBER OF INTERVIEWEES |
|---|---|---|
| **GROUNDWATER MANAGERS** | Land and Resources Department of Ningxia (e.g. Research institute of Ningxia land and resources survey, Ningxia land resources geographic information center) | 2+ (use interview guide and stakeholder worksheet) |
| **SURFACE WATER MANAGERS** | Water Resources Department of Ningxia (e.g. agriculture water division, water conservancy division, water resource division, hydrology and water resource engineering office, and water planning office,) | 10+ (use interview guide and focus group discussion guide) |
| **POLICY MAKERS** | Water planning office of Ningxia | 2 (use interview guide and stakeholder worksheet) |
| **INDUSTRIAL WATER USERS** | Vineyards park along the Helan Mountain (e.g. Lilan Chateau); Water company (e.g. Changcheng water company, Taiyangshan water company) | 6 (use interview guide and stakeholder worksheet) |
| **MUNICIPAL WATER USERS** | Yinchuan Afforestation Office | 2 (use interview guide and stakeholder worksheet) |
| **FARMERS (AGRICULTURAL WATER USERS)** | Farmers in Yinchuan (e.g. Huangyangtan farmland) and Zhongwei (e.g. Changshatou farmland) | 20+ (use survey and focus group discussion guide) |

| | | |
|---|---|---|
| **URBAN AND RURAL RESIDENTS (RESIDENTIAL WATER USERS)** | Residents in Yinchuan and Zhongwei cities and surrounding villages | 20+ (use survey and focus group discussion guide) |
| **LOCAL NON-GOVERNMENTAL ORGANIZATIONS** | Yinchuan Green Environment and Sustainable Development | 4+ (use survey and focus group discussion guide) |

### Text S6.1 Semi-structured interview guide

We are students from McGill University and Ningxia University doing research on water. We wish to know more about the water situation in Ningixia to find out the key problems we can contribute to with our knowledge. Therefore, we wish you could spare one hour discuss with us about the water situation and water management in Ningxia. The interview will be within one hour. To ensure the accuracy of the information, we need to record during the interviewing process to concentrate our focus on following your talk. These record materials will be kept safely and secretly and will be destroyed once the research has been finished. The description of the result will be anonymous. If you want to stop recording, you are free to say so any time during the interview.

1. Your work unit? The work content? How long have you worked here? Your self-assessment for your work?

2. Please talk about your view on the water situation in Ningxia from the professional and personal perspective respectively. (water quality, water quantity, surface water, groundwater).

3. Your knowledge about water-saving infrastructures and measures, any relations to your own work?

4. Will you come across any difficulties relating to water management? Please give 2~3 examples if you have any.

5. Since 2003, Ningxia starts to implement water rights transfers system (WRT). Could you discuss about the effect of the WRT system generally, the impacts on yourself and your aspiration?

6. Will you connect with other stakeholders, could you share their reflection on the WRT system?

7. Have you ever come across some difficulties in the process of implementation, or could predict any in the future?

8. Groundwater, or well water, is the main drinking water resources. What do you know about current situation of groundwater in Ningxia? (E.g. The volume? Could it satisfy the needs? The connection of groundwater and surface water? The change of groundwater with policy making and climate change? Where are the regions that require more attention? Where in the management work could manifest the consideration on the sustainable use of groundwater?)

9. Do you have other new ideas on water management? Or have you heard others mentioning any? What is it?

Thank you very much for your support! We will have a transcription of the interview based on the audio record. Please leave your contact information if you wish to have a look. We will mute your personal information in the research report and will respect your other concerns if there are any. Wish you a very enjoyable life!

### Text S6.2 Survey design

Dear Sir/Madam,

We are students from McGill University and Ningxia University doing research on groundwater. Groundwater is the water resource underground, like the water from spring, well, etc. Groundwater is the main resource for irrigation and drinking in many area. It will sustain the health of ecosystem and will support the land. Groundwater can be affected by the way we irrigate, we mine the ore and the way we consume the water. We wish to know more about the water situation (especially groundwater) here in Ningxia to find out the key problems we can contribute to with our knowledge. Therefore, we wish you could spare 10-20 mins to fill out this questionnaire about the water situation in Ningxia and its relations to your daily life. Your invaluable input will help us better understand current water situation in Ningxia and develop a better water plan for all the residents. Please notice that submitting your study responses indicates that you consent to participate in this study.

Occupation________ City/County________ Gender______ Age__________

Water fee you know/guess________ yuan/$m^3$

1. Please fill out your daily water resource (you can write: tap water, well water, river water, rain water, etc.)

   Drinking Water:_________

   Water for living: _________

   Water for production: __________

   Other__________

2. Please judge the arguments below based on your own knowledge:

   □ Tap water never ends

   □ My use of well water won't affect my neighbors

   □ Wells won't be polluted by the surface

   □ If we don't have the wells, we can use the river instead

   □ If we run out of the groundwater, the land will sink

3. Do you know how much water you approximately consume every day (if you have a family, please indicate the number of family members)? And please also indicate the percentage groundwater accounts for. (1 barrel of water is about 15-20L).

   **Number of family members_______**

   □ <50L  Could you specify________

   □ 50-200L Could you specify________

   □>200L  Could you specify________

   **The percentage of the groundwater in my daily water use is :**

□ 0%  □ 20%  □40%  □60%  □80%  □100%

Do you know the resource of tap water? If you count tap water into groundwater, how much groundwater is used in your daily life?

□ 0%  □ 20%  □40%  □60%  □80%  □100%

4. Overall, do you think if groundwater is important to your life?

□ Very important  □important  □not too important  □not at all

**Please indicate the aspects of groundwater use you think are important (multi-choice):**

□ Drinking □ Irrigation □ Livestock □ Fishing □ Industry □Municipal

Other, please specify_______

5. Do you think the water is in stress now in Ningxia?

□ Yes  □ Part of, please specify __________  □ No

6. Have you seen the phenomenon below (Multi-choice)?

□ Well level decline

□ Dry soil which leads to the reduction of crop production

□ Land subsidence

□ River dry-up, please specify the river_______

□ Wetland shrinks

□ Other signs you think related to groundwater__________

□ Didn't see any signs

7. Have you tried to save water in your daily life? In which way?

□ Yes, very often, please specify the water-saving strategy________

□ Yes, once in a while, please specify the water-saving strategy ________

□ No, but want to know how to save.

□ No, and I think there is no necessity.

8. Do you see the advertisement or education column about saving-water in your place?

□ Yes, very often, please specify the place________

□ Yes, once in a while, please specify the place ________

□ No, but think it is necessary

□ No, and I think it is not necessary

9. Who do you think take the main charge for the groundwater protection (Multi-choice)?

□Government □ Industry □ NGO □ Urban residents □ farmers □Everybody

□Others, please specify________

Please briefly explain the reason_____________________

10. Have you ever experienced/heard of the government policy for water-saving (Multi-choice)?

□ Water price increase, please specify_____

□ Protected area for water resource, please specify_______

□ Plant structure adjustments, please specify_______

□ Canal lining, please specify__________

□ Irrigation methods adjustments, please specify___________

□ Encourage groundwater exploitation, please specify__________

□ Prohibit groundwater exploitation, please specify_________

□ Groundwater monitoring delegation, please specify_________

□ Others, please specify______________

11. Has the abovementioned policy brought benefit/impacts to you and your family?

□ Yes, please specify______

□ I guess it will, please specify_____________

□ Not at all

12. Your suggestions for this research?

Thank you very much for your support!

### Text S6.3 Focus group discussion guide

- ✓ Welcome and introduction 5'

Welcome to this discussion! Thanks for taking the time to join us discussing how we can use water more wisely! My name is ~~ and the assistant moderator is named ~~. We are students from McGill University and Ningxia University doing research on water. We wish to know more about your feelings on the current water situation and water management system. We expect to obtain your invaluable suggestions on a better water management system. You were invited because you represent one type of stakeholders relating to water use. You all live in Ningxia and use water every day. So you have the right as well as the ability to discuss the usage of water in Ningxia. There are no wrong answers but rather differing points of view. Please feel free to share your point of view even if it differs from what others have said. Keep in mind that we're just as interested in negative comments as positive comments, and at times the negative comments are the most helpful.

- ✓ Settings and confidentiality 5'

You've probably noticed the audio recorder. We're tape recording the session because we don't want to miss any of your comments. People often say very helpful things in these discussions and we can't write fast enough to get them all down. We will be on a first name basis today, and we won't use any names in our reports. You may be assured of complete confidentiality. The record materials will be kept safely and secretly and will be destroyed once the research has been finished. The analysis results without identifiable information will be published to help informed the public of the water situation in Ningxia and provide suggestions on water management.

Please sign the Confidentiality Agreement and consent form when you are enjoying the refreshments on the table. The bathroom is ~~ and the exit is ~~. If you are free to leave any time during the discussion. Our discussion will begin after 5 min. This discussion will last about 1.5 hours.

✓ Ground rules 5'

Now let's start. First, we need to establish a group norm. What manners or rules do you think that we need to follow during the discussion to keep everyone is heard and discussion is smooth and informative?

Example list:

- Everyone should participate.
- Stay with the group and please don't have side conversations
- Turn off cell phones if possible

✓ Discussion

**Session 1: Water Right Conversion System 40'**

<u>Introduction of the current water management system in Ningxia and water-saving constructions. (8')</u>

- Water situation according to statistics
- History of the water right conversion system
- Explanation of water-saving constructions

<u>Reflection on your role in this system (5')</u>

-Do you like this system? Why or why not?

-What this system will relate to you? (From the aspect of work, life and future generation, etc.)

Scenario Analysis (10')

-What the possible stakeholders will relate to this system? Describe their roles?

-What this system will lead to the future of society in 50 years according to your opinion? (In the aspect of society, economy and environment, etc.) (See Figure S6.1 for four different scenarios: progressive, passive, conservative and active)

-What we can do now for a desirable future?

Free Discussions 15'

Allow the participants to exchange ideas and reach consensus on the stakeholder list and future mapping in each scenario. (The purpose is not to finally reach the consensus, but to exchange their ideas and understand from each other)

**Break + restatement of the ground rule + logistics (signing documents) 10'**

**Session 2: Groundwater in the system 45'**

Introduction of groundwater 5'

- What is groundwater
- How it relates to daily life
- The constructions relating to groundwater in the system

Introduction of the groundwater proposals  8' (See Text S6)

- What the proposal is
- Why it is proposed
- How people may relate to that

Stakeholder Analysis on the proposal 15'

- Identify the stakeholders

- Identify your role
- Express your opinion (Continuum and Relationship Cloud)

Free Discussions 15’

Allow the participants to exchange ideas and reach consensus on the stakeholder list and revision on the proposal. (The purpose is not to finally reach the consensus, but to exchange their ideas and understand from each other)

**Probes for discussion:**

- *Living condition*
    - *Livelihoods*
    - *Family, Housing, Transportation*
    - *Climate*
- *Water situation*
    - *Personal feelings*
    - *Ads and education*
- *Water resource*
    - *Yellow river, tap water, groundwater*
- *Water usage*
    - *Drinking, Crop, Livestock*
    - *Water saving ideas and activities, water fee*
- *Groundwater*
    - *Relations*
    - *Necessities*
- *Water management*
    - *Understanding*

    - *Impact (Positive + Negative)*
    - *Suggestions*
    - *Relations with different stakeholders*
- *Stakeholders*
    - *Relationship matrix*
    - *Revisions under current management system.*

✓ Ending 5’

Thank you so much for coming and sharing your thoughts and opinions with us. We have a short evaluation form that we would like you to fill out if you have time. If you have additional information that you did not get to say in the focus group, please feel free to write it on this evaluation form.

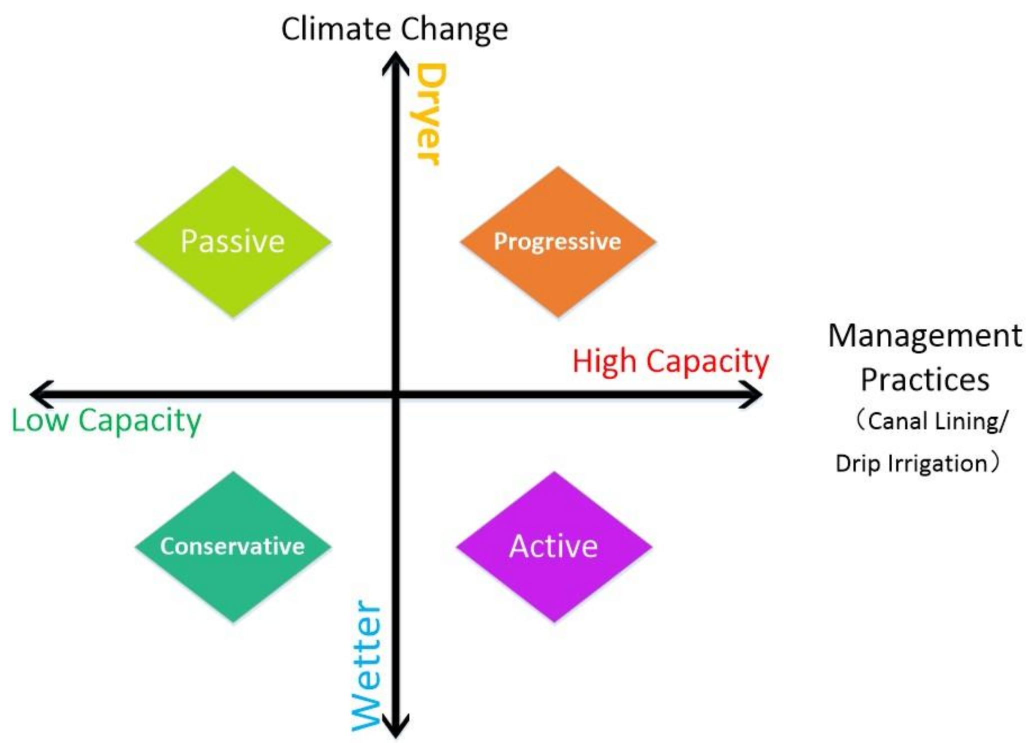



Figure S6.1 Illustration of the Scenarios Planning

Text S6.4 Worksheet for stakeholder analysis

**Stakeholder Identification**

**Please list the stakeholders you think relating to this case.**

Primary:

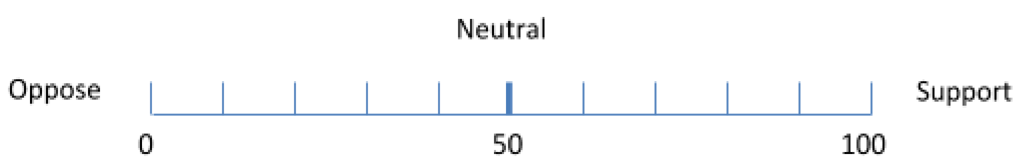
Secondary:

**You are acting (you can choose from the list as below or just write your own role with explanation)**

Farmers A/B, Policy-maker from Ningxia water bureau , Administrator from Ningxia Water Bureau, Manager of vineyard, Administrator in Geological Monitoring Agency, Residents, Afforestation Administrator, Paper Industry manager, Environmental news reporter *(See detailed description at Text S6.5)*

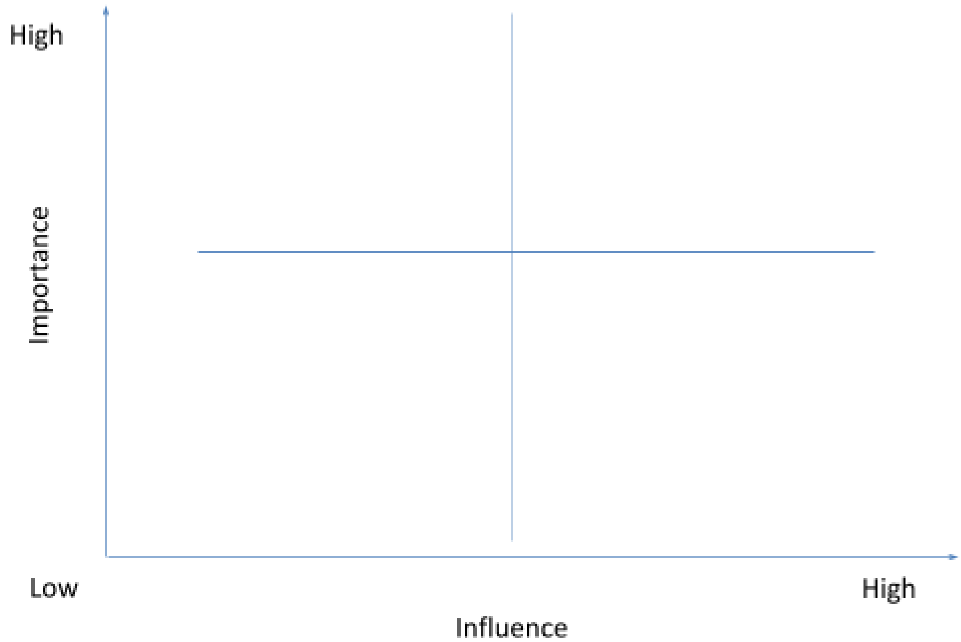
**Continuum**

**To which level you agree with the project?**




You can specify the reasons at the back of this page.

**Where will you position your role for this case?**




**Relationship Cloud**

Draw your relations with other related stakeholders as below (using +,-, bold/thin lines, and arrows)

Text S6.5 Example stories of selected stakeholders based on preliminary investigations

**NGOer**: The NGO's mission is to ensure the sustainable development of the rural area in Ningxia. You are the point of contact for farmers to ask for help. You go to the field frequently, and have good relation with government as well. Previously you have implemented energy-saving project in the rural area which was a big success. After then, farmers have a strong belief in you. Governors also treasure you, for your project can be counted as one of their accomplishments in the report to central government.

**Afforestation Administrator:** You have restricted access to groundwater for the forest and municipal irrigation. You have observed the significant decrease of groundwater level (from 3 meters deep previously to 10 meters and deeper) and you are worried that one day we may run out of it. However, you have no power for allocating water or regulating water, and the budget from the government is shrinking for afforestation. You don't know how to emphasize the importance of the greening and feel paralyzed.

**Farmer A:** You are a diligent farmer who has quite a few farmland. You grow corns, wheat, wolfberry and minor cereals. It is your main income. The main irrigation water is from the Yellow River nearby. You don't think Ningxia is lack of water, however, the government is regulating the water use. You previously used flood irrigation, but recently has been required to adopt drip irrigation. You have heard that this irrigation may lead to corn reduction. You have a well in your home for drinking, but recently, the water doesn't taste good in recent years, so you have to install the tap water.

**Farmer B:** You are a farmer who has both a few farmland and a flock of sheep. You grow melons and potatoes. You have used greenhouse cultivation for melon and has benefited from it. You have also recently adopted the drip irrigation system for your farmland. You believe the new technology will help you to earn more, even though you haven't yet perceived the difference. Your home has been installed with tap water, but sometimes the water has to be stopped. And you have to go get the water from a well quite far away.

**Policy-maker from Ningxia water bureau:**

You are the key member who draft previous water right conversion plan. You understand that it is hard to measure groundwater, and Ningxia has problem in monitoring it comprehensively, therefore you didn't consider too much about groundwater for previous plan. Considering that there are a lot replicate volume calculated in surface water belonging to groundwater, you think that ignorance of groundwater won't lead to severe problems. Nevertheless, you believe it is essential to complete the monitoring network from county level down to household level.

**Administrator from Ningxia Water Bureau:** You are a dedicated official who go to field frequently and believe you yourself has a final say for management in village. You helped to implement the previous water right conversion system, especially drip irrigation, and believe that the current system will bring all benefits to farmers. You believe the academic authorities who said that drip irrigation will not only save water, but also increase crop production.

**Vineyard owner:**

You own a big vineyard along the Helan foothill. You also receive stipend from Ningxia government, for the wine industry is supported by them and the wine you produced has already gained a reputation in China. However, while central government spares no effort in cracking down corruption, they also affect the wine industry in Ningxia. The main market of your wine is the high-level officials; however, the central government now has regulated the wine consumption for officials. Your profit in recent years has dropped significantly. You are quite worried and are looking for market abroad.

**Manager of vineyard:** You take charge of drip irrigation for grapes and know the detail of how to implement it. The facilities in this vineyard are all imported from Israel. You find that even though drip irrigation could save a lot water, it consumes a lot of electricity. Vineyard has the advantage in implementing this technology, for your expenses on electricity can be counted as agriculture electricity instead of industrial electricity (which will be much higher). The drip irrigation needs more accurate data about soil moisture, temperature, sun radiation, etc. You have installed a monitoring network on this vineyard and are very proud of it.

**Administrator in Geological Monitoring Agency:** You take charge of monitoring groundwater data. Your agency has the groundwater level data since 1980s and keeps recording till now. However, you are worried about the future of the groundwater monitoring. Many monitoring wells have been destroyed due to the construction of residential building and other constructions. You are suffering from the careless protection but has no executive power in stopping them. Even till now, you have to rely on some old staff who have to go around city every day to check the monitoring data. It is a very tough job and no new candidates are willing to do so.

**Residents:** You are a resident in the city. You use tap water, and don't pay any attention on the water price. You know people need to save water. But you think all you consumed is reasonable and necessary. You don't think Ningxia lacks water, because you know Yellow River is nearby, and there is an old saying "Yellow River is always nourishing Ningxia".

**Paper Industry manager:** You take charge of the forest plantation for paper pulp. You think your company has adopted a great system that can reuse the cooling water to irrigate these forests. With current management system, you buy water from the water conversion system and store in your own reservoir. You find it is really good for you, for now you can use more water by paying for the water right. Now you feel a lot relieved and have shut down some wells that you originally used.

**Environmental news reporter:** You are concerned with all kinds of environmental problems. You heard that coal industry is secretly extracting groundwater without any payment. Some companies even reinject the used, polluted water back to the aquifers. Whenever the inspector comes, they just stopped it and no one can tell the difference. However, some residents recently find that the dessert nearby has an outlet of very dirty water. You feel it necessary to let the public know these horrible truths.

### Text S6.6. Introduction of the proposals for groundwater management

**Background of the groundwater management in Ningxia**

Ningxia Hui Autonomous Region (Ningxia), a small area in the middle of the Yellow River Basin, is one of the most water stressed regions in China. The annual rainfall in Ningxia is low (around 230mm/year from 2000-2012) and unevenly distributed, leading to a semi-arid climate. The water available to each person, 176m$^3$ per year, is just 1/12 of the national average for China (NWCD, 2016; Yang & Zehnder, 2001). Ninety percent of this water supply comes from the Yellow River. However, "not all the water passing through Ningxia belongs to Ningxia" (Sun, Li, Cai, Wang, 2016). To equitably distribute water use among all nine provinces along the Yellow River, the Yellow River Bureau assigns a certain amount of water available to use within each province. For Ningxia, the water quota is 4 billion cubic meters per year (Moore, 2014), and the region is already straining against this limit, given demands for water to meet industrial, agricultural, residential and ecological needs. By 2012, Ningxia has already approached to its annual allotment (Bebb, 2011); further growth in agriculture, industry, and population threaten to increase water demand (Li et al., 2008).

To tackle this water stress, the Ningxia government has created a water management system named Water Rights Transfers system (WRT) in which industry pays for engineering projects to increase agricultural water use efficiency and then, based on the amount paid, is allocated a water quota for industrial use (Yang et al., 2011). In this way, government can transfer potential water use from agriculture to industry so as to increase the economic value of per unit water use, which is just 0.5 dollar/ $m^3$ in agriculture but $26 dollar /$m^3$ in industry (Liu et al., 2013).

Nonetheless, according to studies, groundwater has been neglected in this water management system, which may reduce its potential long-term sustainability. For example, the current engineering projects that increase the use efficiency for the surface water (e.g. using concrete material to replace previous porous soil for canal lining, replacing flood irrigation with drip irrigation, etc.) has blocked the interaction between surface water and groundwater, reducing groundwater recharge (Jansen et al., 2006). This reduction may lead to more severe and irreversible water problems in the long term. For example, land will sink due to the lack of support from aquifers (Chai et al., 2004) and wetlands will shrink because of the decreased recharge from aquifers (Patten et al., 2008). Also, the current strategy of reducing agricultural water use may bring harm to local livelihoods in this rural area, which can threaten food production and social equality in the long run (Li et al., 2008).

With this concern, a new water management system that takes groundwater into consideration is proposed. This stakeholder analysis is designed to understand opinions and needs from multi-stakeholders, with the hope of bringing stakeholders into the decision-making process to improve its effectiveness, equity, transparency and sustainability. The project proposes to take groundwater resource into consideration based on current water management system, striving to ensure the equality and sustainability for water use in Ningxia.

**The proposed measures and the underlining reasons**

1. **Groundwater regulation:** Regulate the electricity for industry to have an indirect regulation for groundwater use.

Groundwater monitoring has always been an issue in north China. The illegal pumping still exists especially in the night when people seldom realize. Companies could easily pass over the investigation of monitoring agency by just stopping the water pump for a few days. Some researchers proposed that since the groundwater use requires the electricity for pumping, we can measure the groundwater use indirectly by controlling the electricity.

2. **Business restriction for environmental remediation:** Close some of the vineyards along the Helan foothill for land rehabilitation.

The northwest of Ningxia is the gateway of the Tenggeli desert. The forest along the Helan foothill is an important wind break for Ningxia, protecting it from the wind erosion and desertification. But recent years, government encourages the developments of vineyards along the Helan hill which will reduce the soil quality and devastate the desertification in the long run. Water managers also indicate the aquifer along the Helan Mountain foot is currently the only clean and ample aquifer of Ningxia. Therefore, some informants suggest restricting the expansion of the vineyards so as to allow the land rehabilitation

3. **Groundwater recharge maintenance:** Build sponge city (water harvest system) to compensate the loss of buffering effect from groundwater resource

Researches have shown that changing irrigation methods (from flood.or border irrigation to sprinkling or drip irrigation) and canal lining would reduce the groundwater recharge which lead to water level dropdown. For the area that water level dropdown are affecting the regulating service of groundwater (i.e. mediating the impacts of flood and drought), some informants suggest installing water harvest system. So rain water or excessive surface streamflow would infiltrate into the water harvest system and provide water when the weather is dry.

4. **Investments restructuration:** Limit the installations of the drip irrigation system and canal system, instead, use the leftover fund to strengthen groundwater monitoring network

While national funds have been allocated to install water-saving constructions for the WRT, there are limited funds for establishing groundwater monitoring network. Monitoring agency indicated a lack of staffs and advanced facilities for groundwater monitoring. Considering that the water-saving constructions are not always suitable for crops, it is not necessary to promote the constructions everywhere. Therefore, we suggest moving some of the funds to the groundwater monitoring network to enable a conjunctive use of surface and groundwater.

# 7 General discussion and conclusions

## 7.1 Discussion, limitations and future research

The fundamental question that my thesis strives to answer is how we can manage groundwater to ensure a sustainable use. Knowledge gaps that this research aimed to fill to answer this question include: spatio-temporally explicit information on groundwater storage change (Obj. 1), transdisciplinary analysis of main stresses on groundwater storage in the socio-ecological system (Obj. 2), and identification as well as understanding of prospective management schemes for groundwater governance in the long run (Obj. 3).

My results show that groundwater storage in the YRB generally decreased between 2003 and 2016 but the change (i.e. reach and provincial scale) were heterogeneous (Chapter 2 & 3). Impacted by both biophysical and anthropogenic factors, the eastern part of the YRB (i.e. lower reach) had more severe decreases of groundwater storage than the western part (i.e. middle and upper reach). The decreases were more severe in the latter half of the study period (2010-2016). I found that the hotspots of groundwater (problematic areas with significant decrease compared with other parts of the YRB) were shifting over time. Before 2010, Qinghai and Gansu provinces in the upper reach had the most loss of groundwater storage compared with other provinces in the YRB, but the declining trend was relatively smooth. After 2010, the groundwater storage was declining more significantly in the lower reach (Neimenggu, Shaanxi, Shanxi, Henan and Shandong provinces) with an accelerating trend and high fluctuations. The coupling of declining groundwater storage and large fluctuations further suggest that decreased groundwater could reduce the buffering effect of aquifers on the surface water change, which may have led to a more vulnerable socio-ecological system (MacDonald et al., 2015; Anderies et al., 2006). With the spatio-temporally integrated indicators (i.e. Mean Relative Differences, and Standard Deviation of the Relative Difference), I not only identified the areas with severe decreases of groundwater storage that require immediate control, but also mapped out the areas with apparent fluctuations of groundwater storage that require a strengthened scheme for resilience-building and risk response. Together, Chapters 2 & 3 explicitly present the existing dynamics of groundwater in the YRB at multiple scales and provide evidence-based strategies to cope with the heterogeneous situations of groundwater storage across the basin.

Research in Chapter 4 provides an improved understanding of the socio-ecological factors that influence groundwater storage change in space and time. My results show that human actions influenced groundwater more than natural forces temporally, and that the two together had synergistic impacts spatially. The different determinants on spatial and temporal changes of groundwater storage identified in this chapter indicate that we need different strategies in governing groundwater at different scales with multi-targets. At the YRB scale, the main target is to balance the inconsistent needs and access of groundwater. My spatial analysis suggests that it is important to adjust the allocation of domestic and industrial water supply across the basin based on the existing groundwater situations and groundwater changes to ensure the proper distribution of groundwater resource. At the provincial scale, the main target can be to control the decrease of groundwater over time. My temporal analysis suggests that water managers should be cautious on the increase of population density, the plant growth, and the irrigation water consumption which were an outcome of economic development and urbanization in the YRB. Still, the management of groundwater doesn't mean to blindly minimize groundwater consumption. Cautions should be paid on the balance of groundwater discharge and recharge to achieve sustainable use of groundwater resource and secure opportunities for growth for both current and future generations (Zhou, 2009; Gorelick & Zheng, 2015). Chapter 4 confirms the conclusion in Chapters 2&3 that managers should be concerned about groundwater depletion especially in the lower reaches of the YRB. But we also learned that groundwater depletion in particular places was more related to how people on the land behave (e.g. plant growth, population gathering, allocation of water consumption by sectors) than the climate change or general water use. It is therefore critical to understand how we can manage our own footprint on groundwater (Green et al., 2011; Rodell et al., 2018).

Correspondingly, Chapters 5&6 take the challenge of answering this question on groundwater management at the local scale in Ningxia, the center province of the YRB. I started with exploring the practices that might have unanticipated impacts on groundwater. Using water budget analysis, I excluded the possibility of groundwater consumption as the contributor to local groundwater decrease between 2003 and 2016, leaving the decrease of groundwater recharge from agricultural irrigation a very likely reason for the groundwater storage decreases in these years (Chapter 5). Results warned that groundwater depletion may not just be incurred by groundwater consumption, but also improper management practices. My interviews further uncovered the underlining reason: the single target of local government on saving surface water imposed by outside authorities has reduced the ability for the managers to protect the interconnected groundwater. This research highlights that the difficulties in resource management can be a single-targeted management scheme which may have missed essential system components like groundwater. The inappropriate system boundary would bring harm to the sustainability of the socio-ecological system (Closas & Villholth, 2019; Doukas & Nikas, 2019). To further investigate the governance required to facilitate sustainable management of groundwater, I conducted a mix of social investigations to analyze the existing water management scheme in Ningxia (Chapter 6). I suggested that current market-based scheme for water management in Ningxia may have system weaknesses in managing groundwater, which can be strengthened through community-based management. Based on a framework of adaptive governance, I proposed corresponding suggestions to engage the community so that groundwater governance would not only rely on the attention of government, but more on collective actions of the community. These two chapters provide new insights on possible key reasons of groundwater changes at the local scale and propose evidence-based solutions that can facilitate a sustainable use of groundwater and an adaptive governance of the socio-ecological system.

Admittedly, the results analyzed in this study require further validations and explorations. For example, the spatio-temporal dynamics of groundwater change analyzed in Chapter 2 were based on GRACE data which has a spatial resolution of 1 Arc degree (100 km) and only provides information of storage changes instead of absolute volumes. Local groundwater management still needs to refer to baseline values of local groundwater reserve through ground-based monitoring data. In Chapter 3, I identified the management zones based on cluster analysis, in the hope of providing clearer and interpretable information for decision-makers. But it is important to notice that the increase of groundwater would not necessarily mean a healthy aquifer system. The management strategies identified in Chapter 3 are only based on the groundwater storage dynamics and remains to be testified by examining factors. Chapter 4 is therefore a necessary research that complements the results of Chapter 3. Still, there requires further studies in addition to Chapter 4 to find effective solutions to groundwater depletion problems. Specifically, there require more field experiments and social studies to test the proposed strategies and explore the interactions between groundwater and the socio-ecological system (Liu et al., 2014; Suter et al., 2012). In Chapter 5, I used both natural (water budget analysis) and social (interviews) methods to explore the underlining reasons of groundwater decrease in local aquifers in Ningxia. I found that management practices on other resources (here refers to surface water) can unanticipatedly affect groundwater resources. This result serves as a reminder for humans to reflect on our own footprints on groundwater no matter if it is out of a good will or not. Meanwhile, we shall be careful in interpreting the connection between human activities and groundwater as causal relationships. In another word, while we shall restrict our own impacts on groundwater, it is also necessary to take proactive preparations to resist the increasing disturbances on aquifers by environmental uncertainties such as climate change (Gorelick & Zheng, 2015; Gough, 1997). Chapter 6 proposed the community-based management as a complementary institutional design to address the weaknesses of existing governance in Ningxia and suggested an increased involvement of stakeholders in the decision-making processes. But same as the need for more field work to test key factors of groundwater storage change, there also requires more participatory research to recertify the proposed management strategies for groundwater governance and make it transferrable under different social contexts of local communities (Barthel et al., 2017; Carmona, 2011).

## 7.2 Conclusions

Overall, this research has improved our understanding on knowledge gaps in groundwater management. Chapters 2&3 meets the objective 1 by providing a comprehensive analysis of the spatio-temporal dynamics of groundwater, and its implications for management in the YRB. Chapter 4 meets the objective 2 by quantifying the relationship of key socio-ecological factors with groundwater storage and combing out the main impacts of the socio-ecological factors on groundwater storage change. Chapter 5 further complements Chapter 4 for objective 2 by exploring other potential reasons for groundwater change at the local scale using a combination of natural and social science methods. Chapters 5&6 together meet the objective 3 by conducting social investigations and reflections on existing management practices and proposing strategies to engage the community in governing groundwater. My research provides an example of transdisciplinary research that could potentially bridge the scientific knowledge and policy-making for sustainable groundwater management. While this study used the YRB as a study system, it is anticipated that the results and suggestions in this research may hold for other arid agricultural regions. Altogether, this thesis contributes to scientific knowledge that is necessary to maintain the health of groundwater-dependent ecosystems and foster a water-secure society in the long term.

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