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Subsystem-level groundwater footprint assessment in North China Plain – The world’s largest groundwater depression cone

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ABSTRACT

Groundwater is one of the most critical elements of global water resources. However, growing water consumption has resulted in rapid depletion of groundwater, which threaten the sustainable development of economy and environment worldwide. Groundwater footprint (GF) is the area of region capable of achieving the sustainable use of groundwater and healthy ecosystem simultaneously. However, existing studies for GF assessment fail to distinguish the difference between sub-systems at spatial and temporal scales. Moreover, the big error (> 40%) always existed due to the coarse spatial resolution. Thus, the North China Plain (NCP), the world's largest groundwater depression cone, was selected as the first demonstration to perform GF assessment at subsystem level. Disparate groundwater subsystems in NCP show notable differences in terms of unsustainable levels. The NCP’s average shallow and deep GF is 90.93 and 65.12 million km^2 with the groundwater utilization intensity is 6.56. The variation of groundwater utilization intensity under different scenarios were analyzed. Combining all agricultural management could reduce groundwater utilization intensity by around 74.58% to 96.95%, resulting that groundwater could recover to the original health level nearly. It suggested that government should implement strict and holistic management policies to better access exploit and utilize groundwater, such as exploring alternative sources and adjusting the water use structure to achieve sustainable management of groundwater.

1. Introduction

Groundwater is an important element of the Earth's freshwater resources as stored and transported in the rock stratum (Younger, 1996). It plays an important role in supporting agriculture, industry and human well-being (Qiu, 2010). However, groundwater consumption is nearly 7.5–8.0 × 10^{12} m^3/y, which accounts for 20% of the world's daily water supply (Shi et al., 2014). The dependence of human on groundwater is progressively growing as groundwater has more abundant storage and slighter pollution than surface water (Foster et al., 2004). However, over-exploitation of groundwater resources due to large demand from socioeconomic development leads to many problems in groundwater (such as wetland shrinkage, ground subsidence, seawater intrusion) (Fei et al., 2009; Shi et al., 2014). Therefore, it is important and urgent to quantify the health degree of groundwater aquifer (consists of water quality and quantity) and exploitation limits of groundwater resources to access and exploit the groundwater sustainably under rapid socioeconomic development (Berg et al., 2001).

The water footprint has been widely studied (Bulsink et al., 2010; Mekonnen and Hoekstra, 2010) while the characteristics of groundwater are not well characterized by this method (Yu et al., 2017). Some scholars proposed the groundwater footprint (GF) – the area of region capable of realizing the sustainable groundwater use and ecosystem services simultaneously (Schnoor, 2011; Patra et al., 2018). Gleeson et al. (2012) calculated the GF for major aquifers over world firstly and compared the seriousness in different groundwater systems. Many studies assess the GF at some special regions (e.g. the Crete Island in Greece, the Central Valley and the High Plains in U.S.) or estimated the balancing between water requirement and resources within agriculture and tourism (Esnault et al., 2014; Kourgialas et al., 2018; Perez et al., 2019). However, most studies’ accuracy are too coarse (at basin or national level) to explore GF characteristics precisely. Their results have a large error (> 40%) commonly and cannot reflect accurate situation. The policies implement at smaller level (such as county level) may be more feasible and suitable for solving groundwater problems efficiently (Lovarelli et al., 2018). Also, current study has not been carried out along time series, and the regular pattern of GF changes with time cannot be obtained. To fill this gap, we adjusted the GF

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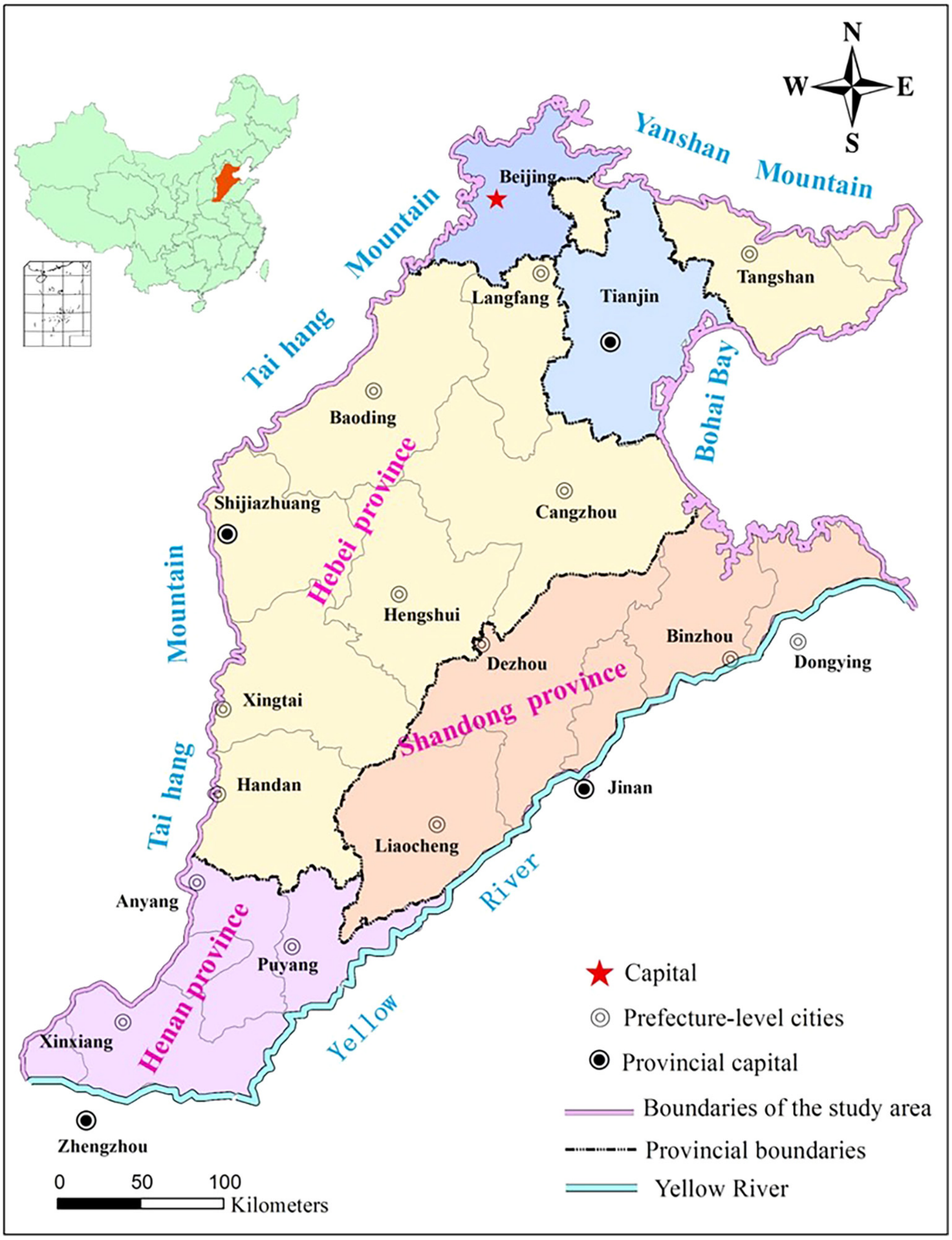


Fig. 1. The study area.

assessment method based on groundwater recycling pattern at county level, assessed the spatial and temporal dynamic characteristics of GF, and discussed the driving factors and suggestions for reducing GF.

The North China Plain (NCP), the world's largest composite groundwater landing funnel, was selected as the first demonstration to assess GF at subsystem level. The following questions were addressed in this study: (1) How to achieve GF assessment at subsystem level? (2) What are the spatial and temporal characters of GF at different scales? (3) What drives GF change and how to reduce the GF effectively? To answer the above questions, we employed GF method to assess GF in NCP at subsystem level, analyzed the spatial and temporal variation characteristics of GF from 1993 to 2014, and discussed the scenarios and policies to reduce GF.

2. Methodology

2.1. General situations of study region

The NCP locates in east of China (112°30′E − 119°30′E, 34°46′N − 40°25′N, as shown in Fig. 1) covers all the plains of Beijing, Tianjin municipalities and Hebei province and part of Henan and Shandong provinces. The total area of the study region is about 13.0×10^4 km^2 and consists of 207 counties. Beijing, located in northern of NCP, is the political and cultural center of China. NCP serves as the national agricultural base and major grain production area in China. Water resources are merely 456 m^3 y^{-1} per capita in NCP, which is below 1/7 of national average and 1/24 of world average and far less than internationally recognized standard of water resource shortage (1000 m^3 y^{-1} per capita) (Yu et al., 2015). There are approximately 80% of rainfall infiltrated into groundwater in NCP. The overall available fresh groundwater reaches 1.92×10^{10} m^3 y^{-1} while almost all areas in NCP are facing groundwater over-exploitation. The population of the NCP has increased from 97 to 150 million during 1980 to 2016 (+54.6%) (Liu and Li, 2012). The NCP is one of the world's largest areas utilizing groundwater resources for irrigation and has developed into the world's largest groundwater user due to continuous over-exploitation (Yuan et al., 2013). There are many rivers in the plain, and the Yellow River and Hai River are the main rivers in the plain. Most of the North China Plain is a warm temperate deciduous broad-leaved forest zone. The native vegetation has been replaced by crops. Only arid, semi-arid shrubs or shrubs grow on the edge of the foothills of Taihang Mountain and Yanshan Mountain, and deciduous leaves forest appears in some valleys or foothills; the south NCP is close to subtropical. The south of the Yellow River alluvial fan and the north of Dabie Mountain are relatively low-lying.

The North China Plain is mainly a loose rock pore aquifer subsystem, including Quaternary aquifer subsystem and Paleo-Neogene aquifer subsystem (carbonate rock karst aquifer, bedrock fissure aquifer and Quaternary pore aquifer). It is mainly divided into single-layer structure area and multi-layer structure region. The single-layer structure region is mainly distributed on the top of the piedmont plain. The lithological grains are coarse, and the cohesive soil is mostly distributed in the form of lenses, and the upper and lower hydraulic connections are good. The layers and the cohesive soil layers are distributed between each other, and the upper and lower hydraulic connections are poor.

2.2. Groundwater footprint

GF refers to the area required to sustainable use of groundwater and to maintain the groundwater-dependent ecosystem services of a region of interest, such as an aquifer, watershed or community (Gleeson et al., 2012). The shallow groundwater recharge consists of rainfall infiltration, river leakage, irrigation return, lateral flow and leakage yield, which satisfies the NCP's hydrogeology condition. Deep groundwater recharge includes lateral inflow and leakage yield. The calculation formula is shown in Table 1.

where *A, C, R, E* denote the groundwater aquifer area (km^2), groundwater consumption (m^3), groundwater recharge (m^3) and groundwater ecological water consumption (m^3), respectively. The groundwater cycling mode under simplified mining conditions is as presented in Fig. 2, as complying with the basic principles of regional groundwater resources evaluation and the state of groundwater aquifer (Shao et al., 2009). α, P, F denote the precipitation infiltration recharge factor, rainfall (mm) and area (km^2), respectively. There is nearly 10% precipitation which is ineffective in the process of precipitation infiltration due to the late effects of surface interception and infiltration (Huo and Jin, 2015). Therefore, 0.9 was taken as precipitation infiltration recharge factor for effective precipitation. where ω, L, ΔT denote canal seepage intensity [m^3 (s km)$^{-1}$], river length (km) and days of river-line water (d A^{-1}), respectively. Hai River, Hutuo River and Chaobai River, etc. are the rivers studied with obvious seepage recharge. Yellow River, as the southern boundary of the NCP, also has a certain recharge relation to the groundwater aquifer with adjacent area. The major rivers are listed in Table 2.

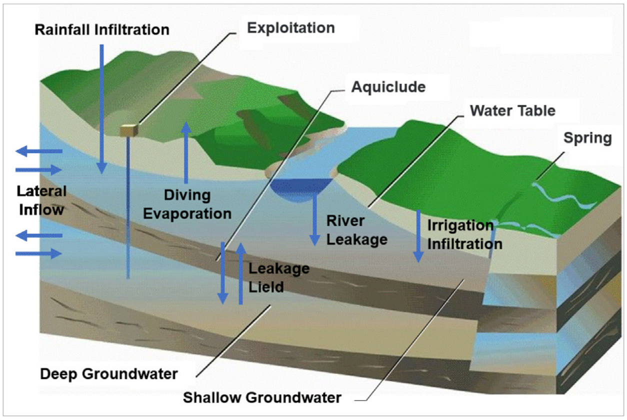


Fig. 2. Groundwater recovery balance and cycle pattern.

where R_{ir}, β_{ii}, Qi represent canal return supply (m^3 A^{-1}), irrigation regression recharge factor and groundwater irrigation water consumption (m^3 A^{-1}), respectively; R_{li}, K, I, L, H, T indicate lateral inflow (m^3), average permeability coefficient of aquifer (m d^{-1}), section hydraulic gradient (‰), section length (m) average aquifer thickness (m) and length of calculation (day), respectively; R_{ly}, H_d, H_u, M, K_z, F denote leakage yield, shallow groundwater level, deep groundwater level, weak permeable layer thickness, vertical permeability coefficient (m d^{-1}) and flow area, respectively. The supply regions are distributed in the piedmont plain while the groundwater recharges only occur in Hebei plain (Wang and Li, 2004).

The characters of irrigation infiltration coefficient in NCP are closely related to water level burial depth and lithology of the aeration zone. The piedmont plain has relatively loose aeration zone structure with water level burial depth > 10 m. The aerated zone is mainly composed of clay, silty clay and silty interbedded, and the irrigation infiltration coefficient is between 0.05 and 0.15. The coastal plain has a small buried water level, silty clay, silt, and silt in the aerated zone, and the irrigation infiltration coefficient is 0.15–0.3. The water supply degree of the piedmont and alluvial plain in NCP ranges from 0.03 to 0.28; the central alluvial plain is mainly clay and coarse sand, with a water supply degree of 0.025 to 0.16; the coastal plain has a water supply degree of 0.05 to 0.075. In general, the water supply of the aquifer in the alluvial and alluvial plains in the front of the mountain is greater

Table 1

Groundwater footprint calculation functions and data sources.

No	Name	Function	Source of data
1	Groundwater footprint	$GF = A \times \frac{C}{R-E}$	/
2	Groundwater Recharge	$R = R_{ri} + R_{rl} + R_{ir} + R_{lf} + R_{ly}$ $R_P = R_{li} + R_{ly}$	/
3	Rainfall recharge	$R_{ri} = 0.9 \times \alpha \times P \times F$	China meteorological administration Water Conservancy Yearbook
4	River leakage recharge	$R_{rl} = 8.64\omega \times L \times \Delta T$	Water Conservancy Yearbook
5	Canal return supply	$R_{ir} = \beta_{ir} \times Q_i$	Water Conservancy Yearbook
6	Lateral inflow	$R_{li} = K \times I \times L \times H \times T \times 10^4$	Hydrogeology and environmental geology survey center of China geological survey
7	Leakage yield	$R_{ly} = (H_d - H_u)/M \times K_z \times F \times 365/100$	Hydrogeology and environmental geology survey center of China geological survey
8	Groundwater consumption	$C = C_{sgw} + C_{de} + C_{ple} + C_{lo} + C_{ly}$ $C_d = C_e + C_{lo} + C_{ly}$	Water Conservancy Yearbook
9	Ecological Water requirement	$E = \frac{100 \times \mu \times A \times \Delta h}{n}$	China geological environment information site

Table 2
Main Rivers in the North China Plain.

Number	River	Length (km)	Basin area (million km^2)
1	Yellow River	786.3	2.30
2	Hai River	1050.0	31.82
3	Hutuo River	587.0	2.73
4	Chaobai River	458.0	1.95
5	Luan River	82.3	0.21
6	Tuhai River	436.4	1.39
7	Majia River	425.0	1.22

than that in the central alluvial plain and the eastern coastal plain. The distribution map of various hydrogeological parameters was shown in supplementary materials Figs. 1–3.

2.2.1. *Groundwater consumption*

The exploitation of shallow groundwater, shallow groundwater withdrawal, diving evaporation, phreatic-labeled evaporation, lateral outflow and leakage yield were considered as the consumptions of shallow groundwater. Deep groundwater consumptions involve exploitation of deep groundwater, lateral outflow and leakage yield (see details in Table 4).

2.2.2. *Groundwater ecological water requirement*

The groundwater ecological water requirement refers to the water demand, which is capable of recovering groundwater environmental health, and ecosystem services function. It also considers the urban ecological water demand (Wang et al., 2009; Ye et al., 2009). The major problems in NCP refer to the over-exploitation of groundwater and the decrease of water level. Thus, the groundwater ecological water requirement in this study should be theoretically identical to the cumulative amount of groundwater over-exploitation (Xu et al., 2007; Van Aggelen et al., 2010; Yu et al., 2017).

where E, μ, F, Δh, n denote groundwater ecological water requirement (m^3), water supply, area and the duration of groundwater recovery from current level to original level, respectively. Thus, the recovery period was assumed thirty years (Qiao et al., 2002; Stegen et al., 2016).

2.3. *Health assessment system of groundwater aquifers*

The supplement or loss of groundwater can be obtained by comparing recharge to exploitation and ecological water requirement on the basis of the equation of GF. The GF per area (GF/A, groundwater utilization intensity) is used to perform relevant analysis further to explore the intensity of groundwater loss and exclude the impact of area in different aquifer. If groundwater recharge can satisfy exploitation and ecological water requirement ($GF/A < 1$), it suggests that this aquifer can offset groundwater exploitation and it is healthy. Conversely, it means unrecoverable loss (Lu et al., 2018). The larger the groundwater utilization intensity is, more serious the loss will be. This study gathered the global main aquifer's groundwater utilization intensity and divided it into four levels by Natural Jenks Method to help policy-makers set out conservation plans aimed at managing groundwater more scientifically. It represents four different kinds of degrees of groundwater over-exploitation and health levels as listed in Table 3.

2.4. *Partition principle for groundwater systems*

The boundary and scope should be determined as GF reveals the recovery characteristics of continuous aquifer. All areas are partitioned and calculated, and abide by four principles except bedrock area. The principles are as follows: Maintaining the relative integrity of the groundwater system; the hierarchical subordination of the groundwater system rational; the environment and dynamics of the groundwater system; accuracy and feasibility.

There is no groundwater system with continuous aquifer distribution in the whole NCP, as the survey and evaluation of groundwater sustainable utilization and China Geological Environment Monitoring

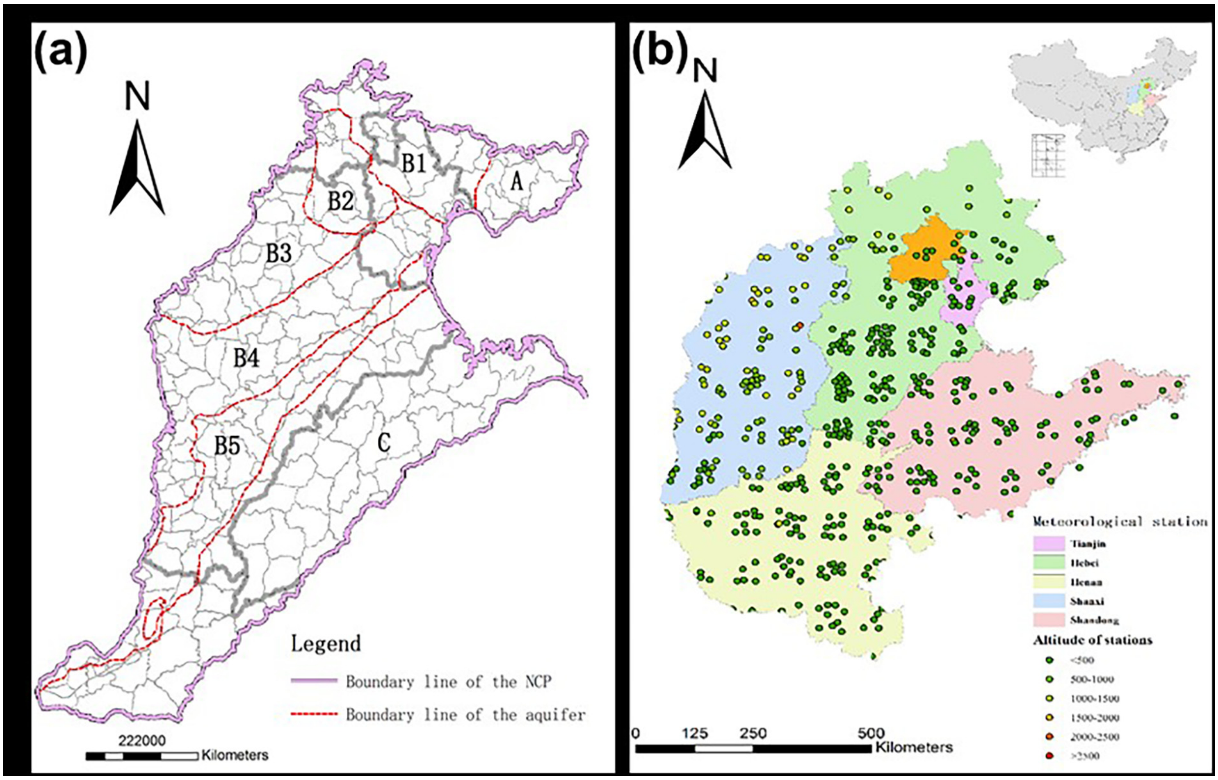


Fig. 3. Distribution of groundwater sub-systems in North China Plain.

Table 3

Groundwater over-recovery level and aquifer Health rating.

Level	GF/A	Degree of exploitation	Health degree of groundwater
I	≤1	Aquifer Repair	Healthy
II	1 ~ 2	Mild over-exploitation	Sub-unhealthy
III	2 ~ 5	Medium over- exploitation	Unhealthy
IV	> 5	Heavy over- exploitation	Very unhealthy

Groundwater Yearbook in NCP suggest (Survey 2005, 2007, 2012). Accordingly, the study region is divided into three groundwater systems, e.g. Luan River plain system, Hai river system and middle-lower plain of the ancient Yellow River system. For higher accuracy, the secondary groundwater sub-systems were further divided. We divide Hai River plain into Chaobai-Ji Canal Plain sub-system, Yongding River Plain sub-system, Daqing River Plain sub-system, Ziya River Plain sub-system and Zhangwei River Plain sub-system, as presented in Fig. 3 and Table 4, to improve the accuracy of the assessment.

2.5. *Data sources and processing*

2.5.1. *Data sources*

The precipitation and other meteorological data during 1993 to 2014 applied in this study was obtained from the 318 meteorological stations located in Beijing, Tianjin, Hebei, Shandong, Shanxi, and Henan provinces (Fig. 3, http://data.cma.cn/). The meteorological data in this paper has covered all the surface meteorological stations in use at present. The hydrogeological parameters of groundwater in NCP primarily originate from the atlas of groundwater sustainable utilization, inclusive of 2850 hydrogeological drilling tests (http://www.cgs.gov.cn/). These data are the most detailed hydrogeological data in NCP at present. The basic parameters (e.g., groundwater depth, water supply degree and rainfall infiltration coefficient) are collected and calculated by geographical coordinate registration, vectorization collection, and interpolation processing and raster statistics in ArcGIS (Geographic information system version 10.1, ESRI, Ireland). See detail in Supplementary Information Figs. 1–3. The data of groundwater exploitation was collected from the annual *Water Conservancy Yearbook*, etc. The above noted data was selected at county level, and the statistical analysis was performed in groundwater system. The vector data of stations were converted into raster data, and the sum value was then calculated by zonal statistics for each county or subsystem in ArcGIS (Zhang et al., 2017).

2.5.2. *Data processing*

The geographical relationship between calculation units was established digitally using spatial interpolation or superposition, which provided the basis for the calculation and analysis of GF. Because the acquisition of meteorological data was not collected with enough spatial detail, kriging was used to interpolate meteorological data, transform vector data into raster data, and integrate the calculated unit data for subsequent calculation and analysis (Jeffrey et al., 2001; Pokhrel et al., 2013). The accuracy of interpolation was verified by comparing the differences of adjacent cells. According to the county boundary, the data was converted to vector data by assigning attribute information to each calculating unit. Because the model attribute data and the vector data boundary and scope did not always overlap perfectly, we used reconstruction and registration for geographic data processing. The accuracy of the established computing cells was tested by comparing the cell area with the total area, and the connectivity of point, line and polygon elements were visually inspected and adjusted to ensure continuity. To test the statistical significance of energy consumption and driving factors over time, statistical tests were performed using the software SPSS Statistics v20 (Statistical Product and Service Solutions, IBM, USA). ArcGIS 10.0 Desktop was used for spatial data analysis and mapping.

3. Results and analysis

3.1. *The spatial characteristics of GF in NCP*

The average GF is 1.59 million km^2 and 10.68 times larger than actual area of NCP from 1993 to 2014 (Fig. 4 and Table 5). It suggests that the groundwater exploitation and supplement in NCP are extremely unbalanced. In addition, the NCP's groundwater has been unsustainable all the time. 1.59 million km^2 area will be taken to achieve the groundwater exploitation and replenishment balance if the current exploitation intensity is maintained. During this period, the maximum GF reached 2.20 million km^2 in 2003, while the minimum GF was 1.25 million km^2 in 1998. The shallow and deep GF in NCP are both larger than the total area of NPC and represents 0.91, 0.68 million km^2. Moreover, only in 1995, 1996 and 2005, the deep aquifer's GF is less than shallow's, whereas the deep GF is greater than shallow in all rest years during study period (see Table 6).

The higher precision analysis is urgently required because there are substantial variations between results at different scales. The ancient Yellow River middle-lower plain groundwater subsystem has the largest GF (0.75 million km^2) while the Luan River Plain groundwater subsystem has the smallest (0.068 million km^2). The GF of deep and shallow groundwater in each groundwater sub-system are also substantially different from each other. The largest value is 0.463 million km^2 occurs in the middle-lower plain of the ancient Yellow river subsystem. It is obviously larger than the actual area (the projected area) of NCP (8.44 times larger). GF of Luan River Plain groundwater subsystem is the smallest (0.012 million km^2). The largest shallow GF also occurred in the middle-lower plain of the ancient Yellow river groundwater subsystem representing 0.285 million km^2 y^{-1}, whereas the minimum for the Yongding River Plain groundwater subsystem represents 0.044 million km^2. Besides, GF of deep groundwater subsystem is larger than the shallowes except Luan River, Chaobai-Ji Canal and Daqing river Plain groundwater subsystems. Over the years, these areas have been over-exploited and have formed a large-scale groundwater depression cone (Zhou et al., 2014; Zhu et al., 2014).

Table 4

General situation of groundwater system in North China Plain.

Groundwater system			Groundwater sub-system			
Name	Code	Area /km^2	Name	Code	Area/km^2	exploitation/10^8 m^3
Luan River Plain	A	7000	–	A	7000	13.05
Hai River Plain	B	75,332	Chaobai-Ji Canal Plain	B1	12,006	20.35
			Yongding River Plain	B2	6553	13
			Daqing River plain	B3	14,774	42.51
			Ziya River plain	B4	23,805	21.87
			Zhangwei River Plain	B5	18,194	23.45
Ancient Yellow River middle-lower plain	C	56,906	–	C	56,906	51.01
Total	–	139,238	Total	–	139,238	185.24

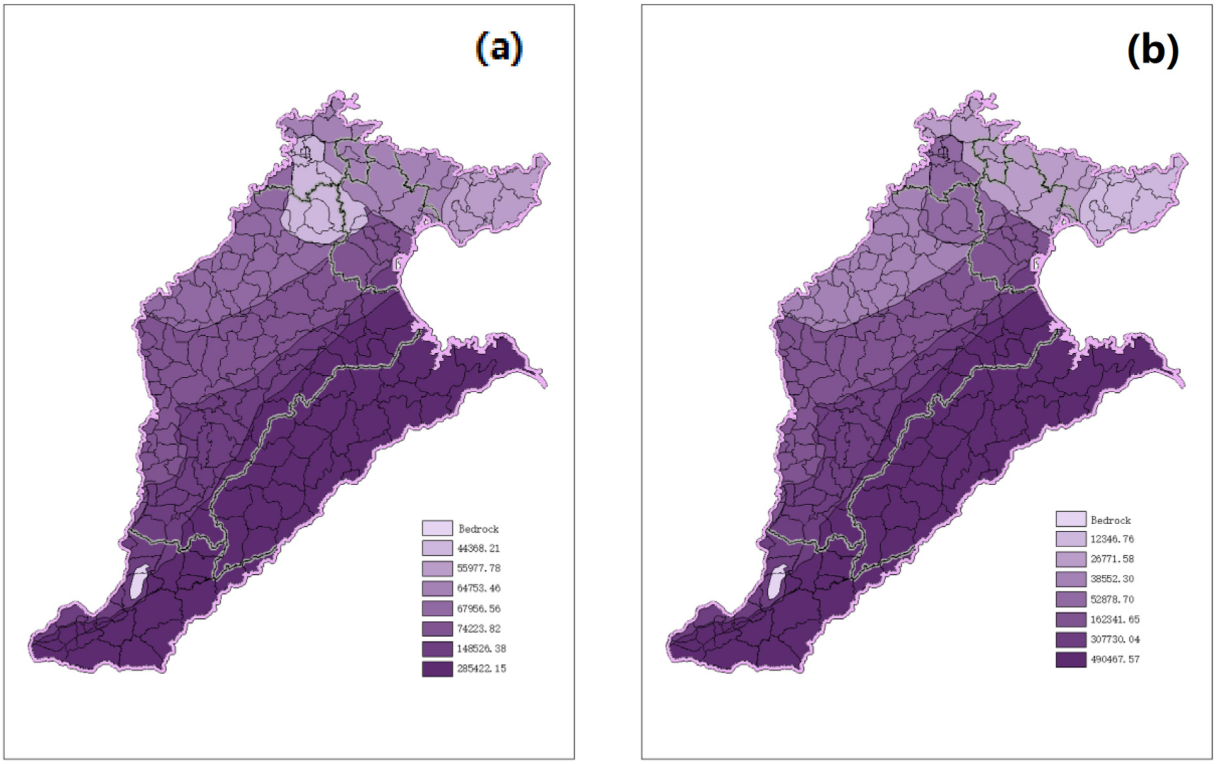


Fig. 4. Spatial distribution of the Deep and shallow Groundwater footprint.

Table 5
Average groundwater footprint from 1993 to 2014 in North China Plain.

Code	GF (km^2)	A (km^2)	GF/A
A	16324.92	6071	2.689
B1	31616.56	11,749	2.691
B2	24459.07	6781	3.607
B3	39663.72	11,233	3.531
B4	76291.63	23,976	3.182
B5	66555.76	18,727	3.554
C	268970.80	54,892	4.900

3.2. *The temporal variation of GF in NCP*

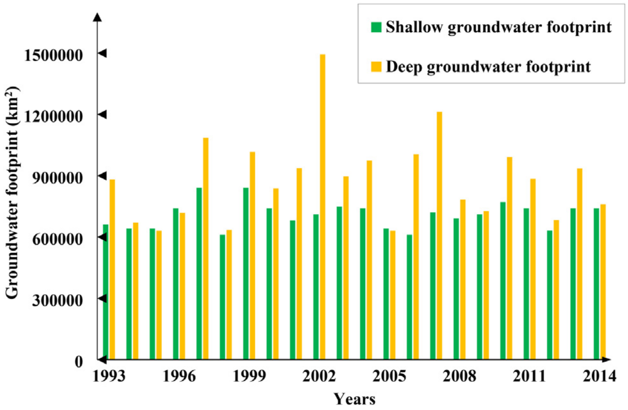


Fig. 5. The change of groundwater footprint during 1993 to 2014.

The variation of annual GF is random without any notable change law with time (Fig. 5). The deep and shallow GF of groundwater subsystems in NCP are both much larger than the actual area. The GF of shallow aquifer is varying more dramatically than that of deep aquifer and the maximum value is 1.494 million km^2 (10.97 times than NCP) appeared in 2002 while the minimum is 0.631 million km^2 (6.34 times). The deep aquifer's GF fluctuates in the range of 0.60–0.85 million km^2. Since the groundwater over-exploitation is a cumulative effect, we sum up the gaps between GF and NCP total area during 1993 to 2014. The cumulative excess GF is 31.99 million km^2, which is 234.86 time bigger than total area of NCP and even 3.33 time larger than total area of China mainland.

Table 6
Summary of scenarios for the study.

Scenario	Assumption (medium/high objective)	Reference
Industrial and domestic water	Baseline: Current water requirement is maintained	/
S1	Industrial water recycling efficiency increased by 20%/50%	(Zhang et al., 2016)
S2	Increased population leads to a 20%/50% increase in domestic water use	(Candela et al., 2011)
Agriculture management	Baseline: No change in agriculture management	/
S3	Irrigation area reduced 10%/20%	(Dippenaar et al., 2009)
S4	Planting pattern (fallow for half year / one year)	(Su et al., 2007)
S5	Irrigation upgrade to drip, sprinkler or other water-saving irrigation). Reduce water use by about 15%/25%	(Rodrigues et al., 2013)
Climate change	Baseline: Recharge remains equal to historical period	/
S6	Reduction of recharge by 3%/5%	(Candela et al., 2009; Mani et al., 2016)

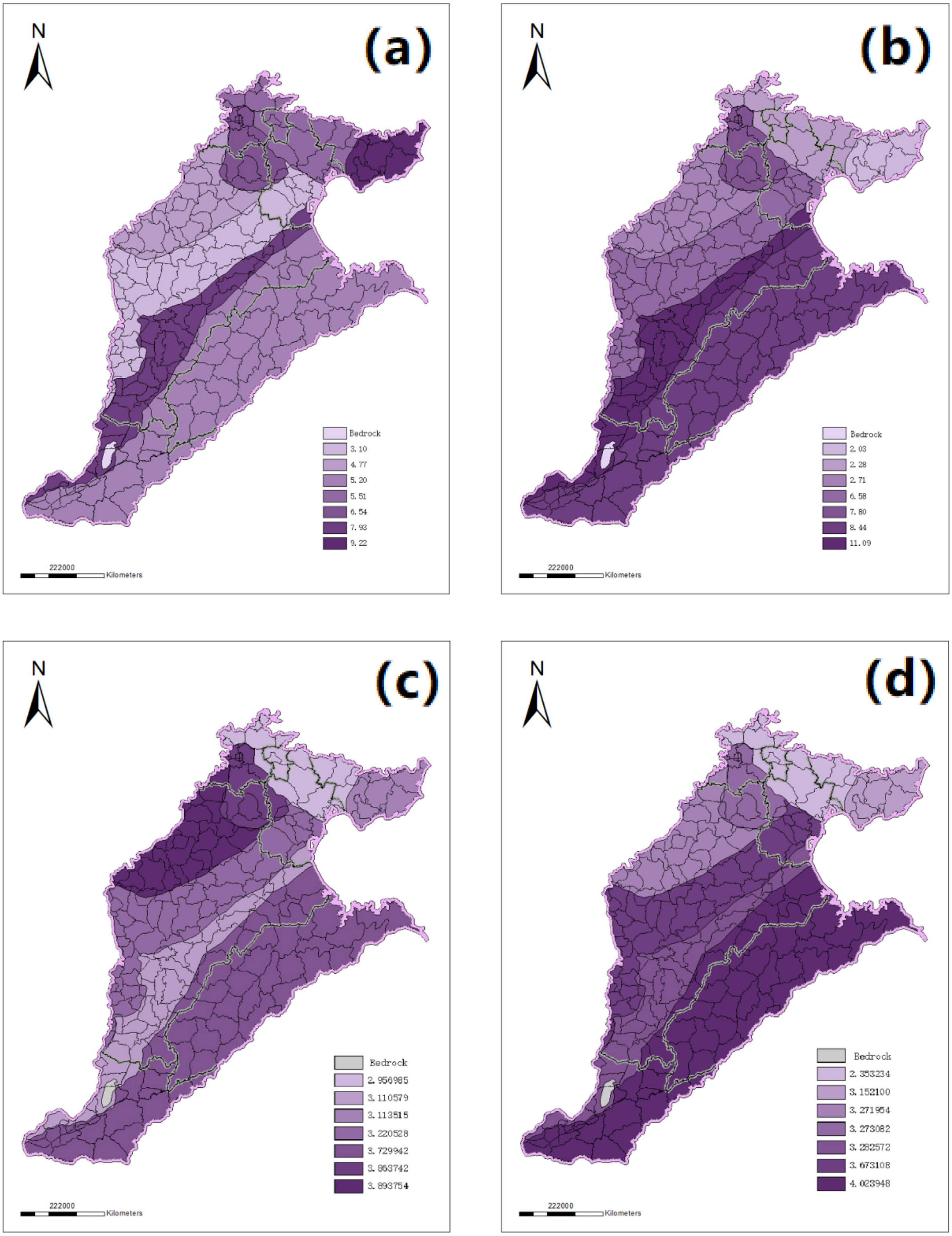


Fig. 6. Groundwater utilization intensity in North China Plain.

3.3. Spatial and temporal variability of groundwater utilization intensity

Groundwater utilization intensity was proposed to characterize the relationship between GF and aquifer area more clearly. Groundwater utilization intensity of shallow and deep aquifers are different in each sub-system in NCP (Fig. 6). Zhangwei river plain and middle-lower plain of the ancient Yellow River groundwater subsystem, located in northern Shandong, Hebei Plain and values 11.09 and 8.44 respectively. The biggish groundwater utilization intensity for deep groundwater aquifers are Luan River plain, Zhangwei River Plain groundwater subsystems, which is 9.22 and 7.93, respectively (Fig. 6a, b). The area with the greatest intensity of exploitation mainly distributes in the southern and eastern of NCP.

There are substantial spatial-temporal variations in groundwater utilization intensity across groundwater subsystems in NCP from 1993 to 2014 (Fig. 6c, d). In 1993, the maximum value of groundwater utilization intensity 3.89 appeared in Daqing river Plain groundwater subsystem, while the minimum value of groundwater utilization intensity 2.96 appeared in Chaobai-Ji Canal Plain groundwater subsystem. Yet the middle-lower plain of the ancient Yellow River groundwater subsystem showed the largest groundwater utilization intensity 4.02 in 2014, while Chaobai-Ji Canal groundwater subsystem showed the minimum groundwater utilization intensity (2.35). The average of groundwater utilization intensity for groundwater subsystems had decreased from 3.83 to 3.29 (−14.1%) during 1993 to 2014 (The groundwater utilization intensity map for each year from 1993 to 2014 were shown in the supplementary material Fig. 4). Most of groundwater subsystems showed increasing trends in all groundwater subsystems except for the bedrock area. The highest increasing trend occurred at the Ziya river plain groundwater subsystem where the groundwater utilization intensity increased from 3.22 to 3.67 (+13.98%). Besides, the decrease of groundwater utilization intensity merely appeared at Daqing river plain and Yongding River Plain groundwater subsystem.

4. Discussions

4.1. The exploitation and intension of groundwater aquifers in NCP

All groundwater subsystems in NCP are unsustainable ($GF/A > 1$) mainly attributes to the unsustainable development and utilization of groundwater. Therefore, the groundwater aquifer in NCP is extremely unhealthy and unsustainable. The GF of the Northern China evaluated by Gleeson is (1.4 ± 0.6) million km^2 and is close to our result representing 1.56 million km^2. However, the results of this study can largely reduce the error and improve the calculation accuracy. The groundwater's over-exploitation degree in NCP is higher than most of the world's major aquifers. It ranks the 4th of the world's 60 major aquifers, only lags behind the Northern India (54.2 ± 15.6), Arabic-Persian (38.5 ± 14.7) and western Mexico (26.6 ± 9.4) (Gleeson et al., 2012). The Arab and Mexican pertain to tropical deserts with drought climate and fragile groundwater environment (Bazzaz, 1994), so groundwater loss in the Arab and Mexican is much severer than NCP because of the bad groundwater recharge conditions.

There are huge differences of the groundwater utilization intensity among different groundwater subsystems. Given that shallow aquifer is more on-limits and has a more frequent and complex exchange with outside, the variation of shallow aquifer is greater than that of deep. Shallow groundwater has a tendency that the water level would decrease gradually in dry years due to the increasing over-exploitation. More precipitation in rainy years can make up the groundwater storage losses in dry years, the shallow groundwater could recover to some extent. But the deep groundwater is difficult to be recovered to original condition before over-exploitation as it cannot accept the external water recharge directly (Alley et al., 2002).

The burial depth of groundwater has been greatly changed in NCP in the past six decades and a perennial groundwater depression cone was formed (the total area exceeded 0.03 million km^2 (Zhang et al., 2010)). It suggested that most regions' groundwater burial depths are deeper than 50 m (Fig. 7a). If the current exploitation intensity maintained, the groundwater burial depth in NCP will deeper than 100 m in 2020 as presented in Fig. 7b.

4.2. Driving mechanisms and scenario analysis

Due to the particularity of groundwater recharge, we consider to select precipitation and mining amount to study the driving mechanism for GF. The shallow and deep groundwater utilization intensity are negatively correlated in precipitation anomaly ($p < 0.05$) (Fig. 8a). It means the smaller precipitation accompanies with the larger groundwater utilization intensity. The precipitation affects the infiltration recharge directly then affects the groundwater. The increase of precipitation leads to increases in the soil and surface water and decreases in demand for groundwater indirectly (Knapp et al., 2003). There is a significantly positive correlation between annual recharge and precipitation. Conversely, there is a negative the correlation between infiltration recharge coefficient and precipitation intensity. The groundwater exploitation and utilization intensity shows positive correlation ($p < 0.05$) (Fig. 8b). The reason is that NCP is a large agricultural base with a huge consumption of groundwater that takes up nearly 76.7% of total groundwater exploitation (Yang et al., 2015; Gao and Lu 2016). The development process of agriculture in NCP was similar to the United States Plains because their agricultural development was both relying on a large amount of groundwater exploitation. The increase of food production in the United States Plains is 10 times, resulting in 336 billion m3 cumulative groundwater consumption (Pei et al., 2015).

The contribution of the impacts among precipitation, exploitation and ecological water requirement on groundwater utilization intensity are quite different. The exploitation has the greatest influence (68.1%), followed by Precipitation (27.0%) and ecological water requirement (4.9%). To assess how climate changes and management affect the groundwater utilization intensity, seven scenarios with medium and high objectives were compared with baseline situation (Table 5).

Climate changes (S6, S7) could increase or reduce the groundwater utilization intensity by 11.26%-17.45% and 14.53%–26.81%, respectively (Fig. 9). The climate tends to be warm and dry as suggested from the analysis of meteorological data (Xu et al., 2017). Changes in water requirement dominate the impacts on groundwater utilization. For industry, improve industrial water recycling efficiency (S1) could reduce the groundwater utilization intensity by 13.79%-17.13%. However, as the population grows (S2), the domestic water requirement would lead to a 7.09%-9.78% increase of groundwater utilization intensity. For agriculture, the reduction of irrigated area (S3) decreases 18.40%-25.24% of the groundwater utilization intensity. In addition, changing planting pattern and promoting efficient water-saving irrigation can save agricultural groundwater consumption (Guo and Shen 2015). These two situations (S4, S5) would reduce the groundwater utilization intensity by 34.36%-45.75% and 21.92%-28.66%, respectively. In line with the differentiated impacts of the different scenarios, agricultural management contributes the most to the reductions in groundwater utilization intensity.

To understand how the combined implementation of some or all of the discussed measures could influence the groundwater utilization intensity of NCP, we constructed an environmental option space by combining all measures of agriculture management. The analysis indicates that high groundwater utilization intensity could mitigated if measures combined (Fig. 9). Combining all measures of medium or high objectives could reduce groundwater utilization intensity by around 74.58% and 96.95%, resulting in groundwater can be recovered to the original health level nearly.

4.3. Policies to reduce regional GF at county-level

Water administrative departments at different levels need to manage groundwater in accordance with a clear division of labor (Fig. 10). It is very necessary to establish the corresponding regulation and policies of groundwater protection at different level; government should improve the policy of groundwater exploitation and utilization (Foster and Garduno, 2013), clarify the authority and responsibility of groundwater intake (Schwarz and Mathijs, 2017) and management and promote the development of sustainable irrigation agriculture (Ahmad et al., 1997). The strict management and rescue measures should be adopted through reasonable ways and measures should be reshaped since the wells for extracting groundwater have exceeded in depth

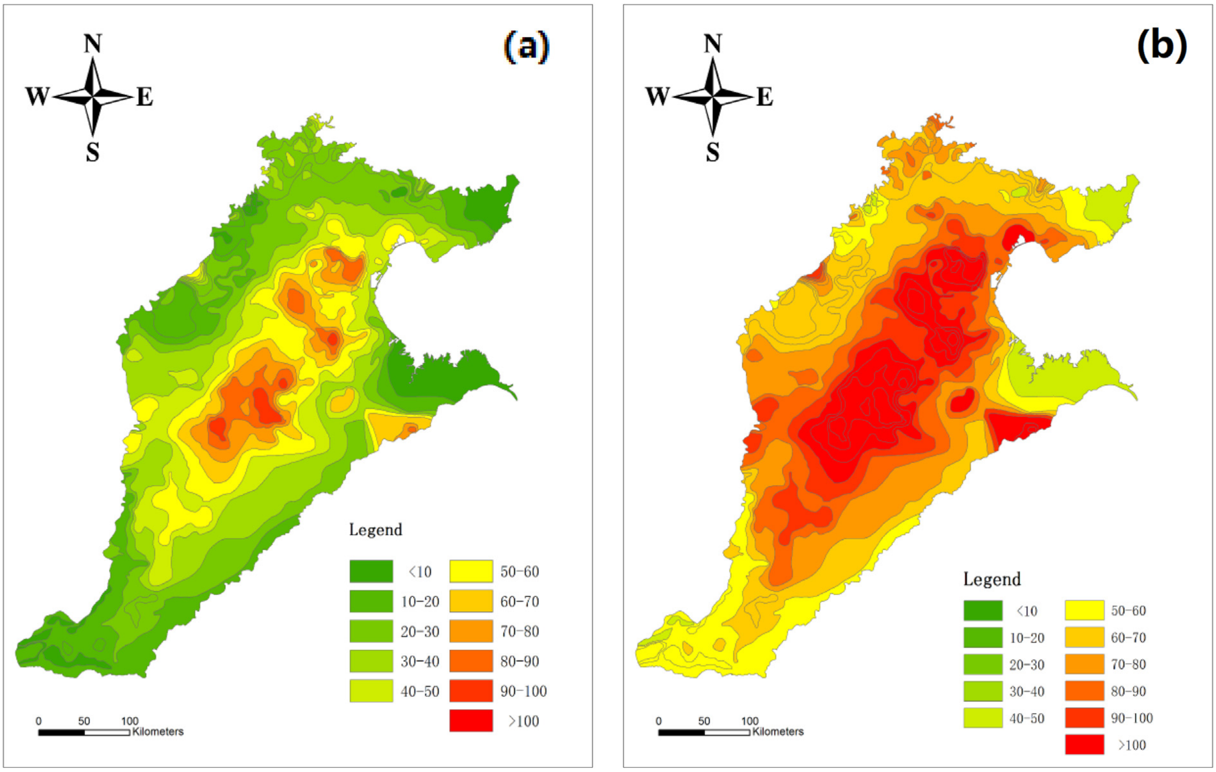


Fig. 7. Current and predict groundwater burial depth in North China Plain.

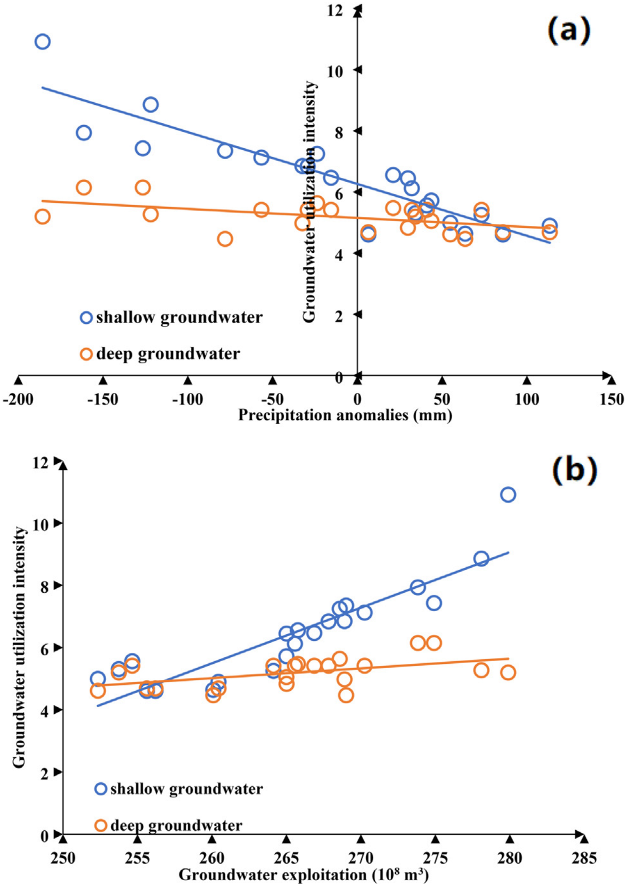


Fig. 8. Correlation between precipitation, exploitation and groundwater utilization intensity.

150 m (Wang et al., 2015). Government should set cooperation across different departments to manage and make plans in order to establish a comprehensive groundwater automatic monitoring network system and build holistic policies to achieve sustainable development of groundwater utilization (Lim et al., 2018). Specific alternatives include enhancing the monitor of water intake, use and drainage and implementing the most stringent water resources management system and water-saving actions (Feng et al., 2017).

The exploitation of groundwater can be reduced by transferring alternative water resources from the Yellow River and others surface water to NCP. Developing and utilizing the surface brackish water and reclaim water which reaches the standard after treatment in sewage treatment plant for irrigation can save the groundwater for irrigation (Barbosa et al., 2017). Increasing water sources while control pollution such as soil and groundwater pollution can protect groundwater quality. Besides, the South-to-north Water transfer project provides 14.14 billion m^3 water every year that could largely alleviate water scarcity. The ecological benefits of South-to-north water Diversion project can largely repair the groundwater aquifer of NCP (Wang et al., 2010). Government should propose corresponding management countermeasures at the county level given that the county is the basic administrative unit in groundwater planning and management. The department of water administration at the county level should perform its functions, supervise and manage relevant groundwater over-exploitation issues.

5. Conclusion

The assessment of GF has been carried out at subsystem level, and the spatial and temporal characteristics of GF in NCP were analyzed. The NCP's average shallow and deep GF are 90.93 and 65.12 million km^2, respectively. The spatial distribution of deep and shallow GF is almost the same. However, the spatial distribution of deep and shallow groundwater utilization intensity is obviously different. The groundwater utilization intensity in NCP is 6.56. All aquifers are notably

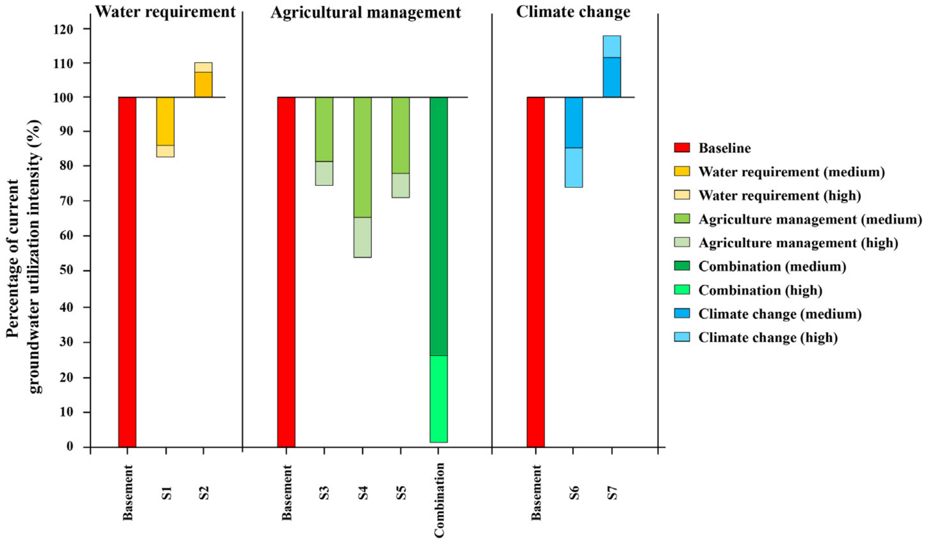
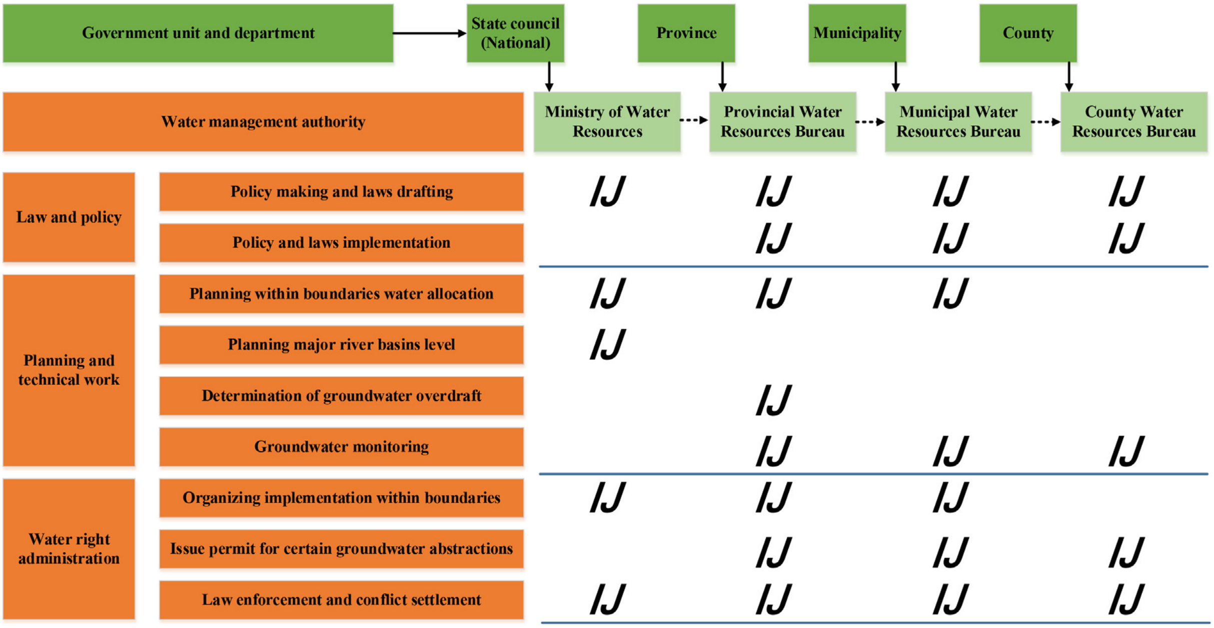


Fig. 9. Scenarios analysis for groundwater utilization intensity.



Water management authority		Ministry of Water Resources	Provincial Water Resources Bureau	Municipal Water Resources Bureau	County Water Resources Bureau
Law and policy	Policy making and laws drafting	✓	✓	✓	✓
	Policy and laws implementation		✓	✓	✓
Planning and technical work	Planning within boundaries water allocation	✓	✓	✓	
	Planning major river basins level	✓			
	Determination of groundwater overdraft		✓		
	Groundwater monitoring		✓	✓	✓
Water right administration	Organizing implementation within boundaries	✓	✓	✓	
	Issue permit for certain groundwater abstractions		✓	✓	✓
	Law enforcement and conflict settlement	✓	✓	✓	✓

Fig. 10. Roles of groundwater authorities at different political levels.

unhealthy and under unsustainable losses. Government should implement strict and holistic management policies considering these influencing factors to better access exploit and utilize groundwater. In addition, exploring other alternative water sources and adjusting the water use structure might help the sustainable management of groundwater.

CRediT authorship contribution statement

Xiuzhi Chen: Methodology, Data curation, Writing - original draft, Visualization, Investigation, Software, Validation, Writing - review & editing. **Pengxiang Wang:** Writing - review & editing. **Tahir Muhammad:** Writing - review & editing. **Zhenci Xu:** Writing - review & editing. **Yunkai Li:** Conceptualization, Data curation, Supervision, Writing - review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Y.L. and X.C. designed the project; X.C. collected and compiled data; X.C. and Y.L. analyzed data; X.C. drafted the manuscript; all authors provided constructive comments and revised the manuscript. We appreciate financial support from the National Key Research and Development Plan (2017YFD0201504) and the National Natural Science Fund of China (51621061).

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