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Distributed Estimation and Analysis of Precipitation Recharge Coefficient in Strongly-exploited Beijing Plain Area, China

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Abstract: The precipitation recharge coefficient (PRC), representing the amount of groundwater recharge from precipitation, is an important parameter for groundwater resources evaluation and numerical simulation. It was usually obtained from empirical knowledge and site experiments in the 1980s. However, the environmental settings have been greatly modified from that time due to land use change and groundwater over-pumping, especially in the Beijing plain area (BPA). This paper aims to estimate and analyze PRC of BPA with the distributed hydrological model and GIS for the year 2011 with similar annual precipitation as long-term mean. It is found that the recharge from vertical (precipitation + irrigation) and precipitation is 291.0 mm/yr and 233.7 mm/yr, respectively, which accounts for 38.6% and 36.6% of corresponding input water. The regional mean PRC is 0.366, which is a little different from the traditional map. However, it has a spatial variation ranging from –7.0% to 17.5% for various sub-regions. Since the vadose zone is now much thicker than the evaporation extinction depth, the land cover is regarded as the major dynamic factor that causes the variation of PRC in this area due to the difference of evapotranspiration rates. It is suggested that the negative impact of reforestation on groundwater quantity within BPA should be well investigated, because the PRC beneath forestland is the smallest among all land cover types.

Keywords: groundwater recharge; distributed hydrological model; land cover; geographic information systems

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1 Introduction

The relationship between precipitation and groundwater recharge is of great importance for effectively groundwater management (Gau and Liu, 2000). It can also help understanding the impact of climate change on groundwater (Allocca *et al*., 2014). As regulated by many factors, precipitation recharge coefficient (PRC) may vary in space. In the stochastic study of Gau and Liu (2000), the results indicated that even the location of well would influence the value. The results from widely used isotope approach also showed large spatial differences in North China Plain (NCP) (Yuan *et al*., 2011; Lin *et al*., 2013). Thus, regional studies using distributed hydrological modeling (Gong *et al*., 2012) and remote sensing can well represent its spatial variation.

The amount of precipitation that infiltrates the subsurface is the major source of groundwater recharge in the strongly-exploited NCP (Lu *et al*., 2011; Pan *et al*., 2011), where groundwater provides more than 60% of total water supply. The PRC usually known as α, is widely used in operational evaluation of water resources

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and groundwater numerical simulation. In most regions of China, such as Beijing plain area (BPA), the PRC was mainly resulted from lysimeter experiments and empirical knowledge in the 1980s, which accounting for depth to water table and soil texture (BIHEG, 1986; Huang, 1980). However, the environmental settings have being greatly modified from that time due to climatic and anthropic factors, e.g, land cover change and groundwater exploitation.

Since the groundwater has been strongly exploited for several decades, the impact of thick vadose zone on groundwater recharge has been increasingly noticed (Zhang *et al*., 2007). Meng *et al.* (2013) concluded that the declining water table would increase PRC in the NCP. Previous isotope studies revealed that the recharge rate varies spatially within the NCP (Wang *et al*., 2008; Yuan *et al*., 2011; Lin *et al*., 2013). Huang and Pang (2011) also found that the groundwater recharge rate decreased by 50% while the land cover changed from bare soil to wheat in the Loess Plateau, where the annual precipitation is similar to that of NCP. However, there is little investigation implemented to BPA, where groundwater is the major water source for the capital city of China.

Distributed hydrological modeling is a good choice to investigating the impacts of different factors regulating the recharge processes (Scanlon *et al*., 2002). The estimated recharge is an integrated representation of spatial varying land cover, soil, and climate (Batelaan and Smedt, 2007; Pan *et al*., 2011; Tan *et al*., 2013). Besides, the Geographic Information Systems (GIS) can be jointly used to reveal the impacts of various factors.

This paper aims to understand the PRC of BPA through distributed hydrological model WetSpass (Water and Energy Transfer between Soil, Plants and Atmosphere under quasi-Steady State) and GIS, with a focus on the impacts of land cover and water table, which are being changed dramatically. The distributed hydrological model WetSpass is first used to simulate groundwater recharge, evapotranspiration and surface runoff. Then, these hydrological components are compared with well observation, Moderate Resolution Imaging Spectroradiometer (MODIS)-derived evapotranspiration and measured streamflow, respectively. Finally, the GIS zonal analysis is implemented to obtain spatial statistics of these components under various land surface conditions, including land cover, precipitation, depth to water table, and soil texture.

2 Materials and Methods

2.1 Description of study area

Beijing is a water scarce metropolis with a population of more than 20×10^7 million. The annual available water is less than 100 m^3 per person per year, which is just one twentieth of China average. The annual precipitation of year 2011 for the whole Beijing was 552 mm, which was similar to the long term mean (585 mm). According to the station observation (Fig. 1), the 2011 annual precipitation was 640 mm for BPA, which is characterized by sub-humid climate with more draught than flooding. It is located in the north of NCP and represents the piedmont plain of the Haihe River Basin (HRB), with an average elevation of 42 m above sea level and slope of 1.6%. It is dominated by the alluvial fans of the Yongding River and the Chaobai River, which are now dried-up for most times of the year.

The water scarcity in this area is mainly caused by the increasing water demand from large population as well as decreasing surface water due to reservoir building in the upstream. The water supply is largely guaranteed by groundwater, which has been overexploited for several decades (Wang *et al*., 2010). According to the Beijing Water Statistical Yearbook (BWSY) (Beijing Water Authority, 2011), for the year 2011, the annual groundwater abstraction was 2.15×10^9 m^3 which accounted for 60% of the total water supply. A large component (7.9×10^8 m^3) of the exploited groundwater was consumed by agriculture, which was dominated by winter wheat and summer maize rotation. As very little precipitation happens in winter, the wheat usually consumes around 70% of the total irrigation water. At the end of 2011, the average depth to water table in BPA was 24.9 m, increased by 17.7 m compared with that of 1980.

2.2 Distributed hydrological modeling and analysis

The groundwater recharge is estimated with the distributed hydrological model WetSpass, which has been successfully applied in many regions (Batelaan and De Smedt, 2007; Pan *et al*., 2011). It calculates the recharge as a residual of the water balance:

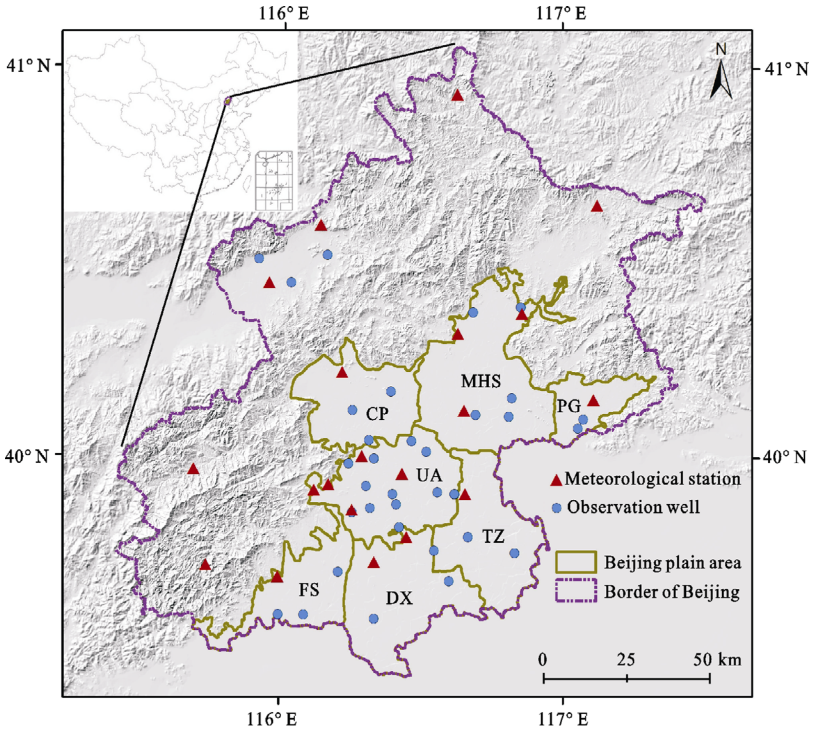

Fig. 1 Location map of Beijing plain area (BPA), which is divided into seven sub-regions according to both administrational and hydrogeological boundary: Daxing (DX), Fangshan (FS), Tongzhou (TZ), Pinggu (PG), Miyun-Huairou-Shunyi (MHS), Changping (CP), and urban area (UA)

$$R = P - I - ET - S \tag{1}$$

where R, P, I, ET, and S represent groundwater recharge, precipitation, interception, evapotranspiration, and surface runoff, respectively. The units are all in mm/yr. Each cell in WetSpass is regarded as a mixture of different land cover type such as bare soil, vegetation, water, and impervious surface. The water balance is calculated for each land cover according to its area percentage. In this paper, a scene of Landsat image on 22nd May 2011 is used to derive the coverage information of vegetation, impervious surface and bare soil. Since the irrigation is also a significant input to the water balance, the statistical amount of agricultural irrigation from BWSY (Beijing Water Authority, 2011) for each sub-region is discretized to the cells with the land cover type of irrigated cropland. When the irrigation is considered in the water budget, the original R in Equation (1) will include recharge from both precipitation and irrigation, while the P represents the summation of precipitation and irrigation. For easy reading, the symbol $R_{\mathrm{P+I}}$ will be used in the next context to represent recharge from both precipitation and irrigation.

The above estimated groundwater recharge will be validated with the water table fluctuation (WTF) method, which has been used by the local groundwater survey bureau for groundwater resources evaluation. The validated WetSpass is then used to estimate the amount of groundwater recharge from only precipitation (R_{P}). The PRC of each grid cell is then calculated with its definition, i.e. the ratio of recharge to precipitation, as described in Equation (2):

$$PRC = R_{\mathrm{P}} / P \tag{2}$$

The spatial statistics of PRC with various factors is implemented through GIS zonal analysis, which outputs the maximum, minimum, and mean value of each polygon zone.

2.3 Data sources

The data needed for modeling and analysis include raster of elevation, land cover, soil texture, as well as observations of climatic and hydrological variables. The elevation data was obtained from Shuttle Radar Topography Mission (SRTM). The land cover map was provided by the Data Sharing Infrastructure of Earth System Science of China (DSIESS) for the year 2005 with a resolution of 100 m. The soil texture map was acquired from Harmonized World Soil Database (HWSD) at 1000 m resolution. The water table data came from the Groundwater Level Yearbook published by Institute of China Geological Environment Monitoring (Institute of China Geological Environment Monitoring, 2011). The climatic variables including precipitation, wind speed, and mean air temperature came from the meteorological stations managed by Beijing Meteorology Bureau. The statistical data on the amount of irrigated water was obtained from BWSY published by Beijing Water Authority (2011). All raster were resampled to have the uniform cell size of 100 m.

3 Results and Discussion

3.1 Estimation and validation of groundwater recharge

As stated above, the vertical recharge $R_{\mathrm{P+I}}$ is firstly simulated with input of precipitation and irrigation. It is shown that the regional average $R_{\mathrm{P+I}}$ was 291.2 mm (1.754×10^9 m^3) for the year 2011 (Fig. 2). It is comparable to the result (280 mm) derived from groundwater budget for the period 2001–2008 (Zhai *et al*., 2012). It also represents a good agreement with the result (1.959×10^9 m^3) of WTF method from local groundwater survey bureau. The underestimation, i.e., -2.05×10^8 m^3, mainly comes from the recharge from surface water. According to the China Water Resources Bulletin (CWRB) 2010 (Ministry of Water Resources of China, 2010), this component accounts for around 5% of the total recharge in the NCP, i.e., 9.8×10^7 m^3 for the BPA. Thus, the net difference (-1.07×10^8 m^3) is mainly caused by the irrigation of urban green space which is greatly maintained by reclaimed water, as well as the seepage from pipes.

Besides, the ET and surface runoff are also compared with other studies as they are the major uncertainties while using water balance method for recharge estimation (Scanlon *et al*., 2002). The simulated annual ET and runoff in this study is 441 mm and 34 mm, respectively. The MODIS-derived ET is 410 mm (Xu, 2013), while the runoff calculated from gauge measurements is 44 mm according to BWSY (Beijing Water Authority, 2011). It is indicated that ET is the major source of uncertainties due to its larger amount in the water cycle. However, the difference between simulated and MODIS-derived ET in this study is acceptable, because MODIS may underestimate ET in urban areas due to its coarse resolution.

The regional average $R_{\mathrm{P+I}}$ of the sub-regions also represent good agreements with the reported values from WTF method (Fig. 3). Larger difference mainly occurs in the urban area, due to the reasons stated above, i.e. green space irrigation and pipe seepage. The precipitation data are then used as the WetSpass input for estimation of R_{P} after the validation. The result shows that the average R_{P} of BPA is 233.7 mm (1.41×10^9 m^3) for the year of 2011. It is a little larger than the value

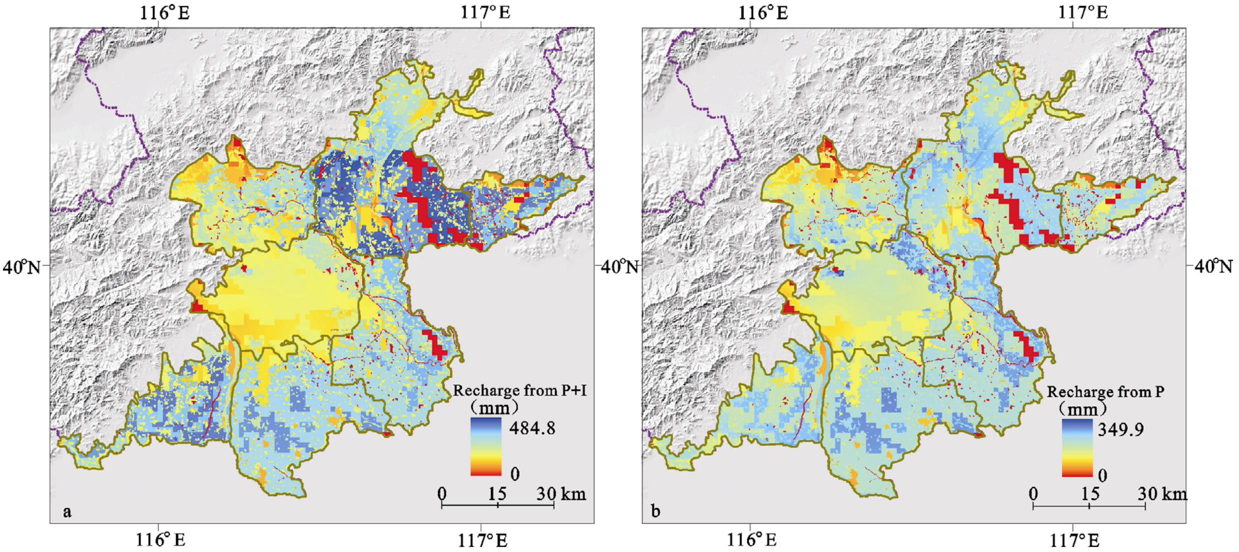

Fig. 2 Estimated groundwater recharge of precipitation + irrigation (P+I, a) and precipitation (P, b), from distributed hydrological modeling for the year of 2011 within Beijing plain area

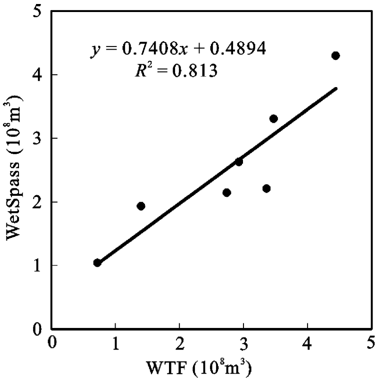

Fig. 3 Comparison of the groundwater recharge (R_{P+I}) from WetSpass modeling and water table fluctuation (WTF) method

(1.326×10^9 m^3) resulted from multiplying annual precipitation by PRC for a multi-year mean from 1981 to 2000 (Zhang *et al.*, 2008).

The relative larger recharge rate indicates that the BPA aquifer has a larger renewability compared to most places of NCP (Kendy *et al.*, 2003; Yuan *et al.*, 2011), because of the sub-humid climate with substantial precipitation and piedmont sediment with coarse vadose zone. However, the regional groundwater system still represents a negative balance as the annual abstraction exceeds the amount of recharge.

3.2 Estimation and analysis of precipitation recharge coefficient

The distributed PRC derived from Equation (2) is shown in Fig. 4. It represents a slight increase by 4.0% from 0.352 of the 1980s to 0.366 at present. Although the average value has not changed dramatically, it indeed varies in space from –7.0% to 17.5% for the sub-region of PG and TZ, respectively (Table 1).

In order to investigate the spatial variation of PRC, the GIS zonal analysis is implemented according to the classification of land cover type, annual precipitation, depth to water table, and soil texture (Fig. 5).

It is found that PRC varies from 0.314 at forestland to 0.483 at bare soil (Fig. 5). PRC in bare soil is larger than those in others land use type. This might be due to the fact that evapotranspiration is the major water loss item in sub-humid areas such as BPA. According to CWRB (Ministry of Water Resources of China, 2010), evapotranspiration accounts for around 70% of the annual precipitation in HRB. As shown in Fig. 6, the spatial distribution of recharge rate on various land covers is dominated by ET with larger magnitude than surface runoff. The forest land represents the largest ET rate while the recharge rate is the smallest among all the land covers. It should be noted that recharge beneath cropland is also greatly impacted by irrigation, which increases both ET and recharge rate. As a result, the land cover change will regulate recharge rate and thus groundwater quantity in BPA. Actually, towards a liveable city and good air quality, reforestation has been increasingly implemented within BPA, but few investigations focused on its negative impact on groundwater quantity. Besides, this study reveals that the settlement

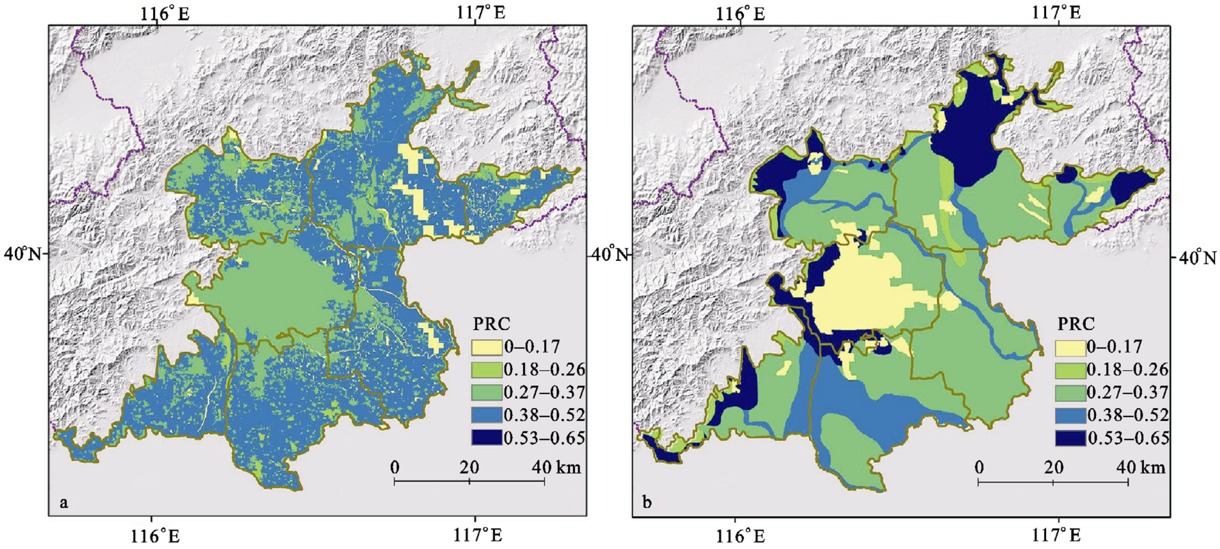

Fig. 4 Precipitation recharge coefficient (PRC) of BPA derived fromWetSpass modeling (a), and traditional PRC map (b) (BIHEG, 2006)

Table 1 Statistics of precipitation recharge coefficient (PRC) for sub-regions of BPA

Sub-region	WetSpass result	Traditional map	Relative difference (%)
DX	0.381	0.348	9.4
FS	0.396	0.390	1.5
TZ	0.373	0.318	17.5
PG	0.358	0.385	–7.0
MHS	0.370	0.395	–6.3
CP	0.355	0.365	–2.9
UA	0.329	0.283	16.2
Average	0.366	0.352	4.0

Notes: DX, Daxing; FS, Fangshan; TZ, Tongzhou; PG, Pinggu; MHS, Miyun-Huairou-Shunyi; CP, Changping; and UA, urban area

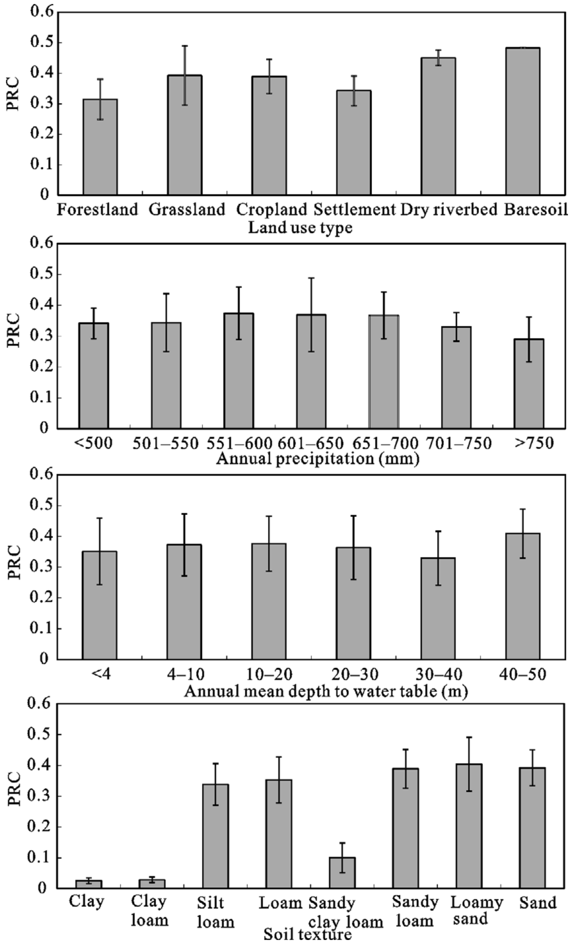

Fig. 5 Average precipitation recharge coefficient (PRC) of each classification of various environmental factors, i.e, land use type (a), annual precipitation (b), annual mean depth to water table (c), and soil texture (d), resulted from GIS zonal analysis of the distributed PRC. The vertical bar represents the standard deviation

(including urban and rural area) receives more recharge from precipitation than forestland (Fig. 5). It may differ from the result of traditional modeling, which usually treats the urban area as totally imperious surface. Actually, the settlement, including urban area, is also partially covered by various plants. This situation can be reflected in this study through distributed modeling of water budget accounting for the coverage of vegetation, impervious surface, and bare soil of each grid cell.

It is also found that PRC represents a normal distribution with the annual precipitation increases. It implicates that more precipitation will not certainly lead to more recharge in BPA. The annual precipitation that will generate maximum recharge rate ranges from 550 mm to 700 mm. This can be explained that excessive amount of precipitation will be lost in the form of surface runoff, while less precipitation will be consumed by evapotranspiration without residual water for recharge.

While referring to depth to water table, some previous studies concluded that the infiltration rate will tend to become steady as the water table falls below the extinction depth in NCP (Zhang *et al*., 2007), i.e. 4–7 m. While some other studies think the increased thickness of vadose zone will lead to more recharge from precipitation (Meng *et al*., 2013). For the BPA, the PRC shows insignificant fluctuation as the depth changes, but represents slightly increasing trend as the depth increases to 20 m. The result indicates that the depth to

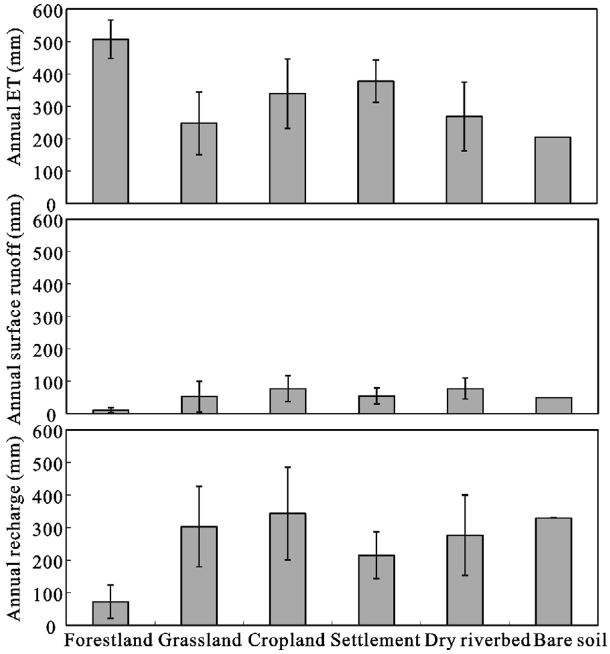

Fig. 6 Water balance components averaged over various land covers. Vertical bar represents standard deviation

water table may weakly influence the recharge rate in BPA, as nowadays the regional average depth is around 25 m. While compared to land cover change, it is believed that the depth to water table plays a less influential role on PRC in the strongly-exploited aquifers with thick vadose zone.

Although the PRC varies greatly as soil texture changes, the land cover change is regarded as the major factor that should be considered for sustainable groundwater management in BPA, as soil texture will usually not change in time. Thus, it is believed that the difference of sub-region PRC between model-estimated and knowledge-based as shown in Fig. 4 mainly lies in the land cover, which is usually ignored in the traditional PRC map.

3.3 Comparison with other studies

The previous studies in NCP demonstrate that different methods, times, and locations of researches may lead to different PRC values (Table 2). The general understanding is that the PRC decreases from the northwest piedmont towards southeast coastal plain. As BPA is located in the north of HRB piedmont with a coarse sedimentary vadose zone, the PRC in this area is larger than that in the downstream plain area. However, the result of this study is smaller than that from empirical knowledge (Meng *et al*., 2013), which mainly focused on the thickness of vadose zone. It implicates that the vegetation coverage should be well considered in PRC studies since the vadose zone is now much thicker than the extinction depth in most regions of the BPA.

3.4 Limitations of this study

Since groundwater recharge is usually investigated with multiple methods (Xu and von Tonder, 2001; Scanlon *et al*., 2002), the major limitation of this study comes from the uncertainties associated with both estimation and validation of recharge rate. The WTF method used for validation is greatly affected by the value of specific field, as well as the selection of observing wells under pumping disturbances. As a result, the investigation of other water balance components, i.e., ET and surface runoff is of great importance and adopted by this study. Besides, the input of seasonal precipitation and irrigation for WetSpass modeling is acceptable for annual estimation (Batelaan and De Smedt, 2007; Gebreyohannes *et al*., 2013), but the derived annual PRC may not be suitable for single rainfall events. The change of annual precipitation amount may also lead to different PRC. Thus, the year 2011 of similar precipitation amount as the long-term mean is selected. The relationship between precipitation and PRC was investigated

Table 2 Comparison with groundwater recharge coefficient studies within North China Plain (NCP)

Reference	Location	Method	Coefficient	Input*
Wang *et al*. (2008)	NCP	^{3}H, Br^{-}	0–0.425	P + I
von Rohden *et al*. (2010)	Shijiazhuang	^{18}O, ^{2}H	0.300	P + I
Yuan *et al*. (2011)	Beiyishui River	Cl^{-}	0.007	P
Lin *et al*. (2013)	NCP	F^{-}	0.022–0.098	P + I
		Cl^{-}	0.085–0.164	P + I
		SO_4^{2-}	0.074–0.314	P + I
Lu *et al*. (2011)	NCP	HYDRUS-1D	0.150–0.240	P + I
Tan *et al*. (2014)	NCP	Br^{-}	0.000–0.370	P + I
		INFIL model	0.140	P + I
Kendy *et al*. (2003)	Luanchen	Soil water balance	0.080–0.250	P + I
Tan *et al*. (2013)	Daxing, Beijing	Br^{-}	0.242–0.396	P + I
			0.053–0.114	P
Meng *et al*. (2013)	Pidoment NCP	Knowledge	0.498	P
Sun (2000)	Chaobai River, Beijing	Water Table Fluctuation	0.565	P
			0.303	I
This study	BPA	WetSpass model	0.366	P
			0.388	P + I

Notes: P and I represent precipitation and irrigation, respectively. When P is used, the amount of recharge used for coefficient calculation refers to R_P, likewise, when P + I is used, the amount of recharge refers to R_{P+I}

through GIS zonal analysis in this study. The results mainly represent the long-term situation and may differ in wet or dry years.

The other limitations come from the land cover and soil texture data used for model input. The land cover data used in this study from DSIESS are believed to have a relative high accuracy, but only available for the year 2005. It may lead to overestimate groundwater recharge due to underestimation of surface runoff. The impervious area is possible to increase 5% from 2005 to 2011 (Cui *et al*., 2015), thus the error can be estimated as 2.2 mm given that the average surface runoff is 44 mm according to BWSY (Beijing Water Authority, 2011). For the soil texture, the 1000-m-resolution HWSD data are used as it provides good reference values on soil properties compared with other higher resolution soil data. However, it may weaken the impact analysis of soil texture.

4 Conclusions

This study focuses on the spatial distribution of PRC within the strongly-exploited BPA through distributed hydrological modeling and GIS. The estimated amount of groundwater recharge from precipitation plus irrigation and only precipitation is 291.0 mm and 233.7 mm, respectively, which accounts for 38.6% and 36.6% of the corresponding input water. However, the large renewability due to sub-humid climate and piedmont coarse sediment is still hard to support sustainable groundwater development because of large amount of abstraction.

The regional average PRC derived from distributed modeling is 0.366, representing small differences with the traditional map resulted from empirical knowledge, which mainly focuses on the depth to water table. But it varies from –7.0% to 17.5% for the sub-regions within BPA mainly because of vegetation coverage, which is usually ignored in the traditional studies. It is suggested that the negative impact of reforestation on groundwater quantity within BPA should be well investigated, because the PRC beneath forestland is the smallest among all land cover types

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