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Responses of the sustainable yield of groundwater to annual rainfall and pumping patterns in the Baotou Plain

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ABSTRACT

Serious water deficits are threatening the sustainable socio-economic development and the protection of the ecology and the environment in North China, especially in Baotou City. There is a common misconception that groundwater extraction can be sustainable if the pumping rate does not exceed the total natural recharge in a groundwater basin. The truth is that the natural recharge is mainly affected by the rainfall and that groundwater withdrawal determines the sustainable yield of the aquifer flow system. A new sustainable yield method introduced in this paper is a useful baseline for groundwater management under all rainfall conditions and given pumping scenarios. The dynamic alternative to the groundwater sustainable yield for a given pumping pattern and rate would consider the responses of the recharge and discharge to the groundwater level fluctuation, then predict the groundwater head at the end of this period to determine the control storage, and then determine the sustainable yield for the shallow and deep aquifer. The simulation results show that the dynamic sustainable yield for a shallow aquifer ranges from 70 to 143 million m^3, and the yield for a deep aquifer varies from 54 to 77 million m^3; the average yield is 95.61 million m^3 for the shallow aquifer and 38.03 million cubic meter for the deep aquifer. The results of this study indicate that the multi-year sustainable yield only accounts for about one-half of the average annual recharge. These actions show that sufficient rainfall supports excessive pumping patterns, causing a slow and disproportionate groundwater storage recovery and water level rise. In addition, the decrease in the recharge and the increase in the discharge were found to have a notable effect on the dynamic annual sustainable yield, especially in a drought year.

Keywords: Sustainable yield; Change in groundwater level; Groundwater recharge and discharge; Rainfall intensity

1. Introduction

Groundwater represents an available and low-cost water source for public supply and domestic use worldwide. Compared with surface fresh water and other available water resources, groundwater captured from porous media in aquifers generally has better quality, requires less cost for treatment and is better suited for drinking water.

In North China, nearly three-fourths of all cities rely on groundwater resources for public supply and domestic economic development, and the primary groundwater consumption is for agricultural irrigation, which amounts to 80% of the total groundwater use [1]. Especially in North China, groundwater accounts for more than half of the total water supply and 70% of the urban water supply [2,3]. Baotou Plain is part of the Yellow River Basin and is located in a semi-arid area at the northern edge of the Inner Mongolia Plateau; the area is used as an example of the over-extraction area of groundwater in North China. Baotou City represents not only the largest concentration of industry and energy but also the most important natural ecological barrier in the Inner Mongolia Autonomous Region of China.

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To cope with the adverse problems caused by groundwater over-extraction, the government has implemented a widely integrated surface water and groundwater allocation and management system for supporting the urban and rural sustainable development. However, it is difficult to put the management scheme into practice due to a lack of research on the hydrological mechanism and appropriate technical solutions for quantitative water management from pumping to consumption.

The concept of a safe yield for groundwater was introduced first by Lee [4], who claimed that a maximum amount of groundwater withdrawal exists in a zone aquifer without causing a cone of depression and reducing the natural recharge and discharge in the groundwater. Meinzer [5] and Theis [6] emphasized the calculation of a safe yield based on the regional water balance. Todd [7] noted that the safe yield is the amount of groundwater that can be used without causing undesirable influences. Domenico explained that the quantity and quality of the groundwater should be considered to avoid undesirable or negative results [8]. Kalf and Woolley suggested that the safe yield should include the needs of the local population and the economic effects resulting from excessive groundwater depletion [9].

The quantification of a safe yield for groundwater management poses challenges and difficulties in practical applications [10], and the traditional methods that the sustainable yield is equal to the safe and available pumping rate multiplied by the allowance pumping coefficient may not reveal the serious problems induced by over-extraction. Although the rate of groundwater depletion is less than the rate of natural recharge, the trend of groundwater level decline may also arise continuously due to the concentrated layout of pumping wells and the unscientific development of groundwater field management. In basins or regions that are sensitive to changes in groundwater levels, such as degraded wetlands and riparian ecosystems [11], the safe yield is not equal to the sustainable yield for the dynamic requirements of the complex interactions between natural systems and humans [12,13]. The excessive utilization of groundwater resources may lead to a downward trend in the groundwater level and decreased discharge and subsequently cause an apparent decline in the recharge ability through the unsaturated zone, resulting in lower groundwater quality. The shortcomings of the concept of safe yield may not be sufficient to maintain the sustainable development of the synthetic system including society, economy, and ecology, and may call for a scientific concept and method that will abandon the groundwater quantization management [11–13].

Meanwhile, the concept of the sustainable yield of groundwater resources introduced by Alley [14] has been defined more comprehensively than the safe yield, and the implications of the sustainable yield have been accepted for maintaining the groundwater flow and to determine a balance in the regional or watershed-scale water budget without causing undesirable environmental and socio-economic effects [15]. To transition from a safe yield to a sustainable yield, the estimates for controlling the groundwater level and extraction not only depend on the changes in the recharge and discharge processes affected by the natural environment and human activities but also on the acceptable trade-offs between groundwater consumption and associated changes. Achieving a water budget for a time series is a core theme in the evolving concept of sustainability [11,12,14–16].

The traditional method to determine the sustainable yield mainly depends on the average recharge and some safe coefficients for different geological units so that the potential or actual available yield based on the flow system is underestimated in many piedmont plains in arid or semiarid areas. How to reflect the natural storage and adjustment capacity of an aquifer in the groundwater flow system and its response to pumping to determine the proper sustainable yield need to be modified.

The dynamic sustainable yield introduced in this work aims to avoid the negative influences due to excessive pumping and the continuous decline in the groundwater level. The dynamic sustainable yield reflects the dynamic changes in the recharge and discharge of the groundwater in aquifers. The current calculation methods to estimate the sustainable yield did not agree with the groundwater level; therefore, the dynamic sustainable yield was introduced [17,18].

In practice, one set of values does not work under all rainfall conditions. When the pumping intensity is smaller than the sustainable yield in the groundwater system, the total recharge based on the rainfall is enough to support the water demand for a healthy and steady socio-economic development without generating any adverse problems. However, when the pumping intensity is greater than the sustainable yield in the aquifer, the groundwater level will be continuously depleted or have fluctuations due to excessive groundwater demand, and this will eventually alter the relatively steady balance in aquifers under natural conditions.

One possibility to address these issues is to develop scientifically based pumping patterns and rates that tie the magnitude and distribution of the rainfall to the magnitude of the natural recharge and to consider the decline in discharge due to groundwater extraction.

Therefore, during periods of recharge depression (i.e., rainfall during droughts), the decline in groundwater storage levels may lead to pumping that exceeds the sustainable yield, resulting in a negative influence on vulnerable aquifer systems. During periods of abundant recharge (i.e., rainfall during wet periods) and increases in groundwater storage, the groundwater extraction may be lower than the sustainable yield. The goals of this work are to assess and quantify the dynamic changes in groundwater recharge and discharge under excessive pumping patterns and rates and to estimate the sustainable yield of groundwater flow based on natural rainfall conditions and specific groundwater development scenarios during the period of 2007 to 2014.

2. Methodology

2.1. The regional water budget equation

According to the mass conservation law for groundwater, the regional annual variance of the groundwater storage and the groundwater table and the input and output flows from the aquifer are combined in the regional water budget equation to determine the sustainable yield.

In a natural condition prior to groundwater extraction, the water budget equation of a basin's groundwater flow system can be written as follows:

$$\begin{cases} \Delta St = Rt - Dt - Et \text{ for shallow } t = 1,2,3,...,N \\ \Delta S't = R't - D't \text{ for deep } t = 1,2,3,...,N \end{cases} \tag{1}$$

in which ΔS_t, D_t, E_t, and R_t denote the groundwater storage, discharge from the aquifer, evapo transpiration, and recharge to a shallow aquifer in year *t*, respectively. The variables $\Delta S'_t$, D'_t, and R'_t are similar to the ones above except they denote a deep aquifer versus a shallow aquifer.

It is clear that the natural discharge originates from the natural recharge and is affected by the rainfall. Since the pumping intensity is lower during the initial steady period, the pumping rate is maintained by the capture of groundwater storage alone.

Instead of natural fluxes, the groundwater extraction affected by human activities has the most important influence on the recharge and discharge when there is an apparent increase in the pumping rate or a lack of capturing enough groundwater storage increment parts (see, $Q \geq \Delta St$). After capturing all of the groundwater storage increment parts, excessive pumping only supports the increase in the recharge and the decline in the discharge in the next relatively steady period both for the shallow and the deep aquifer. Eq. (1) can be written as follows:

$$\begin{cases} \Delta St = (Rt + \Delta Rt) - (Dt + \Delta Dt) - (Et + \Delta Et) - (Qt + \Delta Qt) \\ \text{for shallow } t = 1,2,3,...,N \\ \Delta S't = (R't + \Delta R't) - (D't + \Delta D't) - (E't + \Delta E't) - (Q't + \Delta Q't) \\ \text{for deep } t = 1,2,3,...,N \end{cases} \tag{2}$$

where ΔRt and $\Delta R't$ are the increased recharge induced by rainfall or pumping for a shallow and deep aquifer, respectively; ΔDt and $\Delta D't$ are the decreased discharge (positive value) caused by pumping for a shallow and deep aquifer, respectively; and $\Delta E't$ is the decreased evapotranspiration (positive value) led by pumping.

2.2 Change in aquifer storage induced by groundwater table fluctuation

Because the groundwater flow system is complex and multiple factors control the process among aquifer characteristics, climate and human activities, it is evident that the groundwater recharge, discharge and extraction are known only approximately or not at all. The statistical data of pumping by wells may contain subjective error due to the lack of a completed groundwater monitoring network, and groundwater levels are commonly measured as indicators for estimating groundwater depleted in various wells or water consumed cells. In this work, the aquifer storage can be taken as a function of change in groundwater levels within a water budget zone and year, as follows:

$$\begin{cases} \Delta S_t = \sum_{K=1}^{K} \mu_c, \dfrac{\Delta h_{tk}}{\Delta t} \; k = 1,2,...,K \; t = 1,2,3,...,N \\ \Delta S'_t = \sum_{K=1}^{K} \mu_e, \dfrac{\Delta H_{tk}}{\Delta t} \; k = 1,2,...,t = 1,2,3,...,N \end{cases} \tag{3}$$

in which μ_c and Δh_{tk} denote the gravitational specific yield of aquifer layer *k* (dimensionless) and the fluctuation of groundwater level for the shallow aquifer in layer *k*, respectively. μ_e and ΔH_{tk} denote the elastic specific yield of aquifer layer *k* (dimensionless) and the fluctuation of groundwater level for the deep aquifer, respectively.

The estimation of aquifer storage requires the gravitational specific yield or elastic specific yield determined by a pumping test and the knowledge of the three-dimensional geological structure around the basic groundwater system. The changes of groundwater level response to the storage variation induced by rainfall and extraction in an aquifer can be described in Eq. (4).

$$\begin{cases} \Delta S_{control} = \sum_{k=1}^{K} \mu_c \cdot \Delta h_{k-Down\,limited} / \Delta t \quad k = 1,2,...,k \quad t = 1,2,3,...,N \\ \Delta S'_{control} = \sum_{k=1}^{K} \mu_e \cdot \Delta H_{k-Down\,limited} / \Delta t \quad k = 1,2,...,K \quad t = 1,2,3,...,N \end{cases} \tag{4}$$

in which $\Delta h_{k\text{-}Down\ limited}$ and $\Delta H_{k\text{-}Down\ limited}$ are the down-limited water level standard for the shallow and deep aquifers, respectively. The limited water level is mainly determined by the historical geological survey report, pumping test, ecological sampling, groundwater protection requirement and the empirical value from the field trial.

2.3. Numerical simulation models

The groundwater flow numerical simulation model is widely used for quantifying the basin or regional water budget balance and forecasting the change of groundwater level affected by different groundwater management and planning in the future. The control mathematical model of the groundwater system in an unconfined aquifer can be conceptualized as a three-dimensional, isotropic heterogeneous flow system if the geological structure and hydrological cycle conditions are appropriate for some given assumption. Then, the governing mathematical equation for the groundwater system can be expressed as a function of groundwater level change as follows:

$$\begin{cases} \dfrac{\partial}{\partial x}\left(Kh\dfrac{\partial h}{\partial x}\right) + \dfrac{\partial}{\partial y}\left(Kh\dfrac{\partial h}{\partial y}\right) + r - d - e - q = \mu_c \dfrac{\partial h}{\partial t} \quad \text{for shallow} \\ \dfrac{\partial}{\partial x}\left(KH\dfrac{\partial H}{\partial x}\right) + \dfrac{\partial}{\partial y}\left(KH\dfrac{\partial H}{\partial y}\right) + r' - d' - q' = \mu_e \dfrac{\partial H}{\partial t} \quad \text{for deep} \end{cases} \tag{5}$$

where *h* and *H* are the hydraulic head in the shallow and deep aquifer (L), respectively; *t* is the time of groundwater flow from inflow to outflow (T); *K* is the hydraulic conductivity in the x, y coordinate that obeys the assumption of geological isotropic homogeneity (LT^{-1}); *r*, *d*, *e*, *q*, *r′*, *d′*, and *q′* are source/sink terms that includes the groundwater recharge, discharge, evapotranspiration, and pumping for the shallow aquifer and the groundwater recharge, discharge, and pumping for the deep aquifer in geological units ($L^3T^{-1}L^2$); and *S* and *S′* are the gravitational specific yield and elastic specific yield (dimensionless), respectively.

For this work, the initial groundwater head, rainfall and given pumping case are taken as input to each geological unit for the calculation of the basin or regional water budget balance, and second, the recharge and discharge can be estimated for determining the t-period sustainable yield through a numerical simulation model with a given groundwater extraction scenario. Then, the groundwater head at the end of this period is predicted to determine the control storage in Eq. (4). At last, the sustainable yield for the shallow and deep aquifer is estimated with Eq. (5) (Fig. 1).

3. Study area

3.1. General description

Baotou city is located in the mid western region of the Inner Mongolia Autonomous Region, extending from 109°25′ E and 40°25′ N to 110°25′E and 42°50′N, and covers an area of 27,768 km^2 (Fig. 2). The population of Baotou City is nearly 2.83 million, and the GDP is 37 billion (in 2015).

Baotou Plain is located in the southern portion of Baotou City and it accounts for 6.8% of the total land area, but its GDP is 80% of the total GDP and the water consumption is 50% of the total for Baotou City. The average annual temperature in the study area ranges from 2ºC to 6ºC. The average precipitation is 239 mm with large differences in the temporal and spatial distribution. The northern part of the area, receives only 175 mm, while the southeast, receives 450 mm. Most of the rainfall occurs during the humid summer, with very little rainfall during spring and autumn and even less precipitation during the dry, cold winter. The potential evapotranspiration is 2000 mm/y or higher in this area.

The aquifer structure of the Baotou Plain can be divided into a shallow and deep groundwater flow system based on the geo-hydrological conditions and survey report. The aquifer layers consist of Quaternary or Neogene alluvial deposit fans, diluvial deposit fans, and lacustrine deposit fans that are used for intensive groundwater exploitation. The shallow

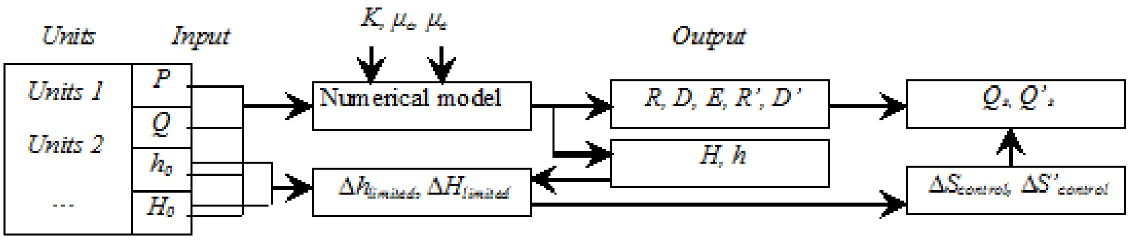

Fig. 1. The framework for estimating the sustainable yield.

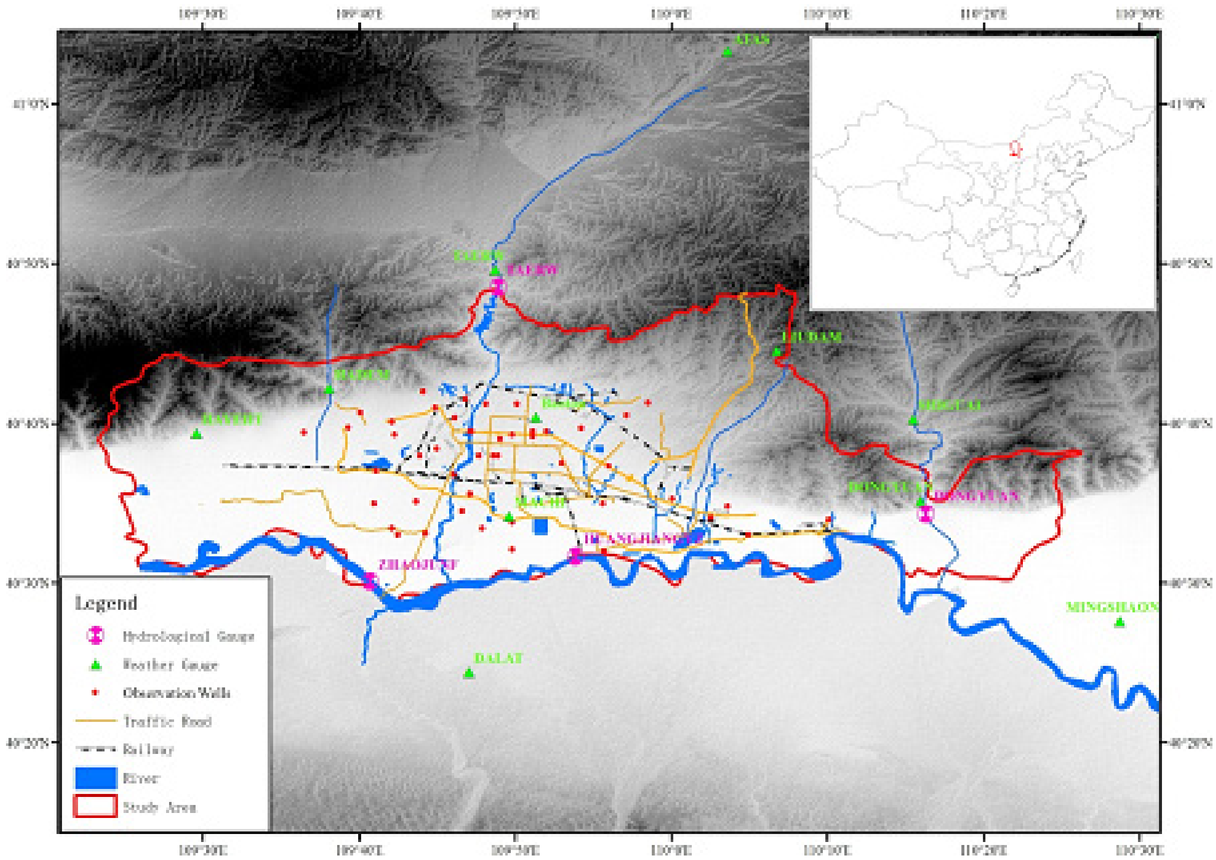

Fig. 2. The general description of the study area.

aquifer is composed of sand and gravel with variable thicknesses ranging from 10 m at the southern edge of the fans and the Yellow River alluvial plains to 30 m in the middle and northern piedmont sloping plains; the shallow table extends to a depth of approximately 10–20 m below the surface. The hydraulic conductivity ranges from 10 m/d to 50 m/d, and the water productivity is higher in the piedmont than in the Yellow River alluvial plain. The deep aquifer is mainly composed of clay and sandy silt with a thickness of up to 20 m and a thin sand and gravel layer extending to the bedrock at 200–250 m depth. The permeability is higher for the deep aquifer than for the shallow aquifer, and the water quality is higher for the deep aquifer; therefore, the water in this aquifer has been the primary public drinking and domestic water supply for a long period. With the increase in intensive development and groundwater depletion, the deep aquifer is hydraulically connected with the shallow aquifer, and these two aquifers are considered an integrated basin groundwater flow system in this study.

The groundwater flow direction is from the piedmont's fault in the northern area to the Yellow River at the southern edge of the study area. The groundwater flow system is mainly affected by the change in groundwater storage, which is closely related to the recharge and discharge processes; precipitation and pumping are the two controlling factors under natural climate change and with disturbances due to human activities.

3.2. Observation gauge

There are 11 weather gauges and 4 hydrological stations around the study area that have been there since 1956 and are shown in Fig. 1, and the observation data, including precipitation, evapotranspiration, temperature, relative humidity, runoff depth, runoff volume and water quality, are collected by the Baotou Water Service Bureau and the website of China Meteorological Administration (http://data.cma.cn). Time-series automatically logged groundwater monitoring data are recorded from 203 observation wells within the study area by the Baotou Water Resources Management Center, and the data are available for the simulation period 2007–2014. The statistical and survey data of groundwater resources for pumping and consumption are derived from the Baotou Water Service Bureau and the statistical data of national economy and society are sourced from the Baotou Statistical Bureau.

3.4. Hydro geological divided units

Hydro geological units were used for the calculation of the groundwater budget and the numerical simulation of the groundwater flow system. The units can be partitioned based on the administrative zone, the region of groundwater function, and the water resource management cell.

Based on the hydro geological conditions in the Baotou Plain, the shallow and deep aquifers are separated by a complete and continuous silt layer. There are 12 shallow units and 5 deep units in the study area (Table 1, Fig. 3), and the map shows the piedmont alluvial fan aquifer and the Yellow River diluvial and alluvial plains based on the geomorphology. The lithology of the piedmont alluvial fan aquifer consists mainly of sandy gravel with cobble for the shallow aquifer and medium-coarse sand for the deep aquifer.

3.5. Parameters

Based on a hydro geological survey report published by the Ministry of Land and Resources and pumping tests, most hydro geological parameters, including permeability, gravel specific yield, and elastic specific yield, can be determined. The aquifer permeability ranges from 15 to 42 m/d for the shallow aquifer and from 30 to 45 m/d for the deep

Table 1
Hydrogeological divided unit in Baotou Plain

Terrain district	Geological units	Aquifer layer	Area/km^2	Lithology	Thickness/m
Piedmont sloping plain	MEILIG unit	Shallow	182	Sandy gravel with cobble, coarse sand and silt sand	10~20
	HADEM unit	Shallow	279	Sandy gravel with cobble, coarse sand and silt sand	10~20
		Deep	100	Medium-coarse sand	15~60
	KUNDUL unit	Shallow	299	Sandy gravel with cobble, coarse sand and silt sand	5~20
		Deep	222	Medium-coarse sand	20~70
	DONGDABB unit	Shallow	306	Sandy gravel with cobble, coarse sand and silt sand	2~80
		Deep	88	Medium-coarse sand	20~60
	LIUBAOY unit	Shallow	73	Sandy gravel with cobble, coarse sand and silt sand	5~20
		Deep	35	Medium-coarse sand	10~40
	BABAI unit	Shallow	52	Sand and gravel	15~20
	ASHAN unit	Shallow	41	Sand and gravel	15~20
	WUDANG unit	Shallow	162	Sand and gravel	30~40
Yellow river alluvial plain	SANHEH unit	Shallow	234	Fine and silt grain sand	10~25
		Deep	190	Medium and fine grain sand	20~40
	WANSHUIQ unit	Shallow	131	Sandy gravel with cobble, Medium and fine grain sand	20~50
	NAHAI unit	Shallow	85	Fine and silt grain sand	10~25
	DONGY unit	Shallow	57	Fine and silt grain sand	10~25

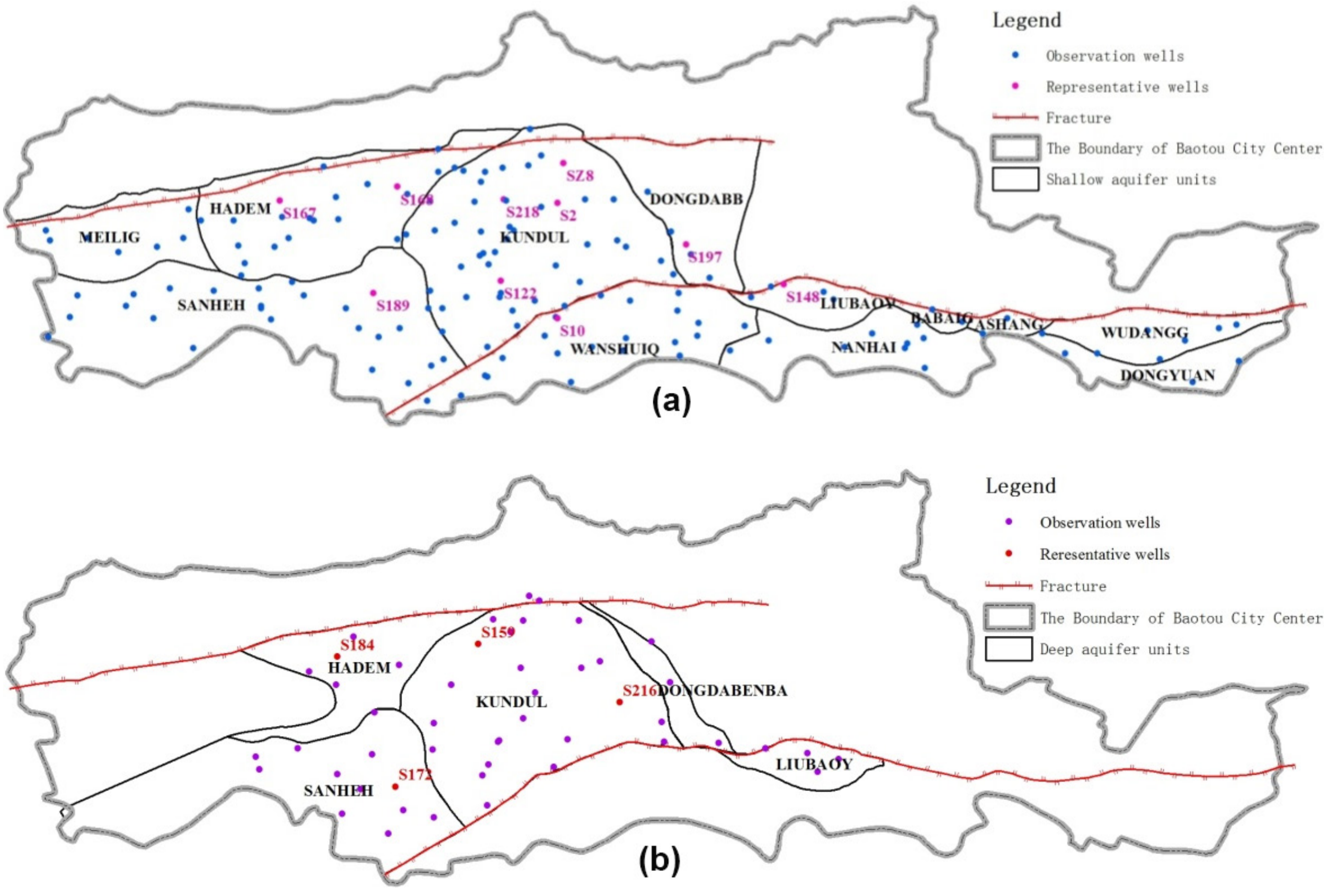

Fig. 3. Hydro geological divided units in Baotou Plain for the shallow (a) and the deep (b) aquifers.

aquifer. A higher hydraulic conductivity was expected for the Yellow River diluvial plain than for the edges of the piedmont fracture alluvial fan.

4. Results and discussion

4.1. The basin rainfall

Fig. 4 portrays an overall steady fluctuation in the rainfall trend beginning in January of 2007 and lasting through December of 2014. This was followed by an apparent increasing trend from June to September of each year. Within these short climatic changes, there were interspersed periods of wetness and dryness. The representative period herein chosen (2007–2014) began during a relative dry phase and exhibited several wet and medium rainfall periods and an average annual rainfall (264 mm) very close to that of the entire period of record (248 mm). Other representative periods were identified; however, the chosen period meets all the required criteria well.

4.2. The relationship among precipitation, pumping and groundwater level

Fig. 5 presents two typical examples of the observation data where the rainfall, the total pumping, and the groundwater level are proportioned to hydro graph. The left set of graphs in Fig. 5 indicates that compared with the precipitation of Baotou Gauge, the total pumping has a much greater variable magnitude than the groundwater level (No. S2) according to the well hydro graph. The long-term groundwater trend exhibited a decline of 2 m over the period of increased pumping intensity. The right set of graphs in Fig. 5 shows that the precipitation at the Machi Gauge has a significant fluctuation in magnitude for the groundwater level (No.

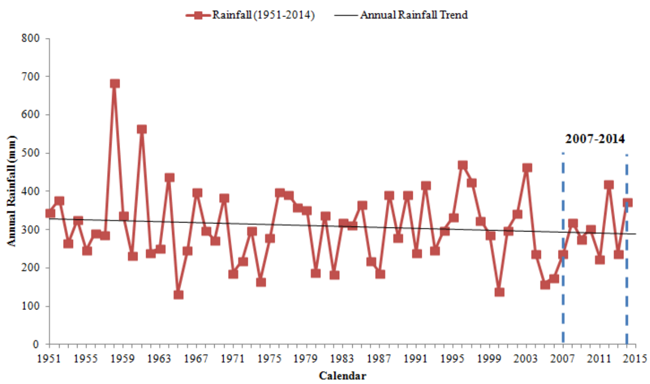

Fig. 4. The annual rainfall of the study area from 2007 to 2014 compared with the whole historical record.

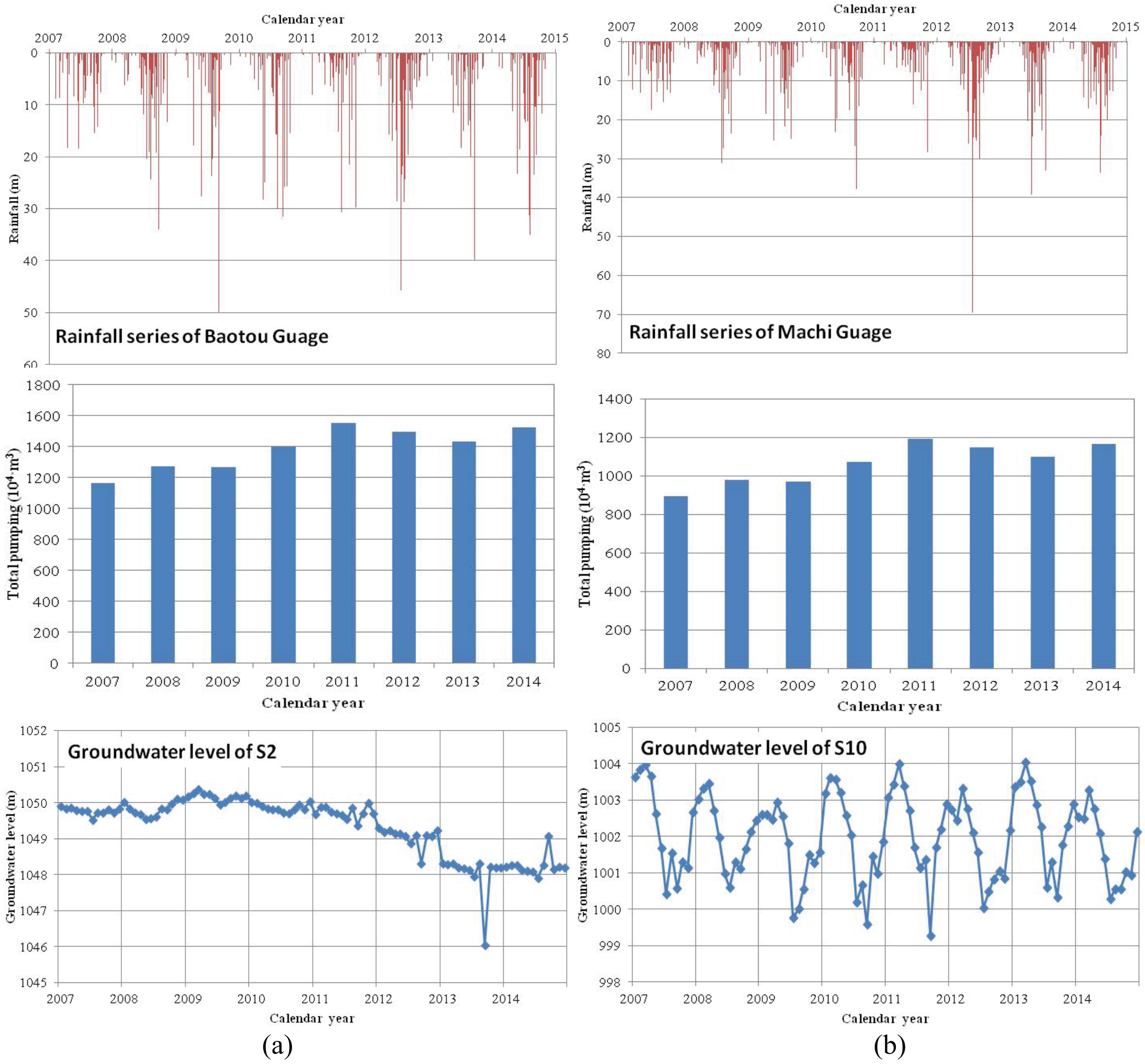

Fig. 5. Observed and statistical data of the Kundul unit (a) and the Wanshuiq unit (b) for rainfall (the upper figure), total pumping (the middle figure), and groundwater level (the lower figure).

S10) according to the well hydro graph, and the statistical value for total pumping is the second most significant factor. A change in the long-term rainfall altered the underlying groundwater level, which changed downwards to 1000 m or upwards to 1004 m according to the well hydro graph.

4.3. Multi-year average of basin groundwater budget

A numerical simulation model of the groundwater flow was used to quantify the water budget and to estimate the sustainable yield of the groundwater resources in the Baotou Plain under various groundwater development scenarios. The model can be solved together with the initial and boundary conditions. The calibration and validation results from 2007 to 2014 showed good performance at the regional scale according to the 1:1 line fine fitting diagram (Fig. 6), and the correlation coefficient (R^2) was 0.952 for calibration and 0.938 for validation based on the statistical analysis.

Table 2 lists the calculated average annual water budget and the average annual groundwater level change during the representative period (2007–2014). The recharge, discharge, and evapotranspiration were calculated using Eqs. (12) and (13), and the groundwater extraction data originated from the Baotou Water Service Bureau. Table 3 also lists the average change in groundwater storage obtained by multiplying the regional groundwater level fluctuation by the specific yield for the shallow aquifer and by the storage ability for the deep aquifer using Eq. (12). The recharge in the Baotou Plain aquifer is calculated based on the change in groundwater flow in the different geological units for the recharge area and from the runoff generated within the piedmont permeable fracture zone. The results presented in Table 3 indicate that the recharge values related to the rainfall and the groundwater extraction are the two most important variables in the water budget. The relationship among recharge, discharge, evapotranspiration, and total pumping of the shallow and deep aquifers

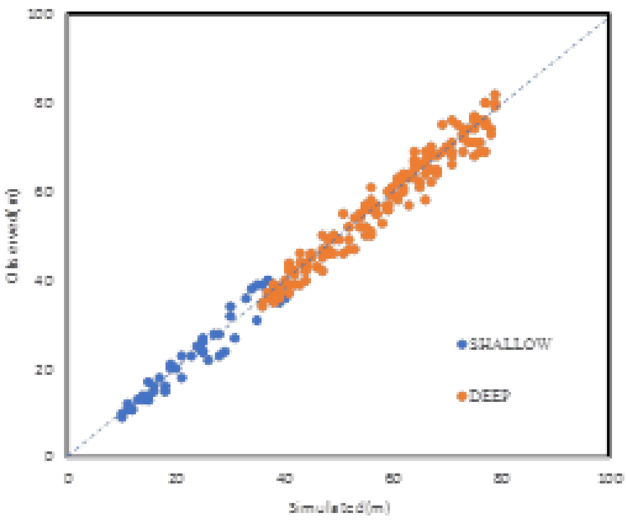

Fig. 6. Comparison of the simulated and observed shallow groundwater table depth.

Table 2
Multi-year average of groundwater budget from 2007 to 2014 in the study area

Water budget item	Shallow aquifer	Deep aquifer	Total
R/10^4 m^3	14 282	5 639	19 921
D/10^4 m^3	1 446	186	1 632
E/10^4 m^3	3 655		3 655
Q/10^4 m^3	9 335	6 715	16 050
(R-D-E-Q)/10^4 m^3	–154	–1 262	–1 416
ΔS/10^4 m^3	–684	–1 650	–2 334
Relative error/%	–3.71	–6.88	–4.61

is imbalanced, and the imbalance yield of the deep aquifer is up to 1 262 × 10^4 m^3, accounting for 89% of the total imbalance yield. A similar phenomenon can be measured by the change in groundwater level of the representative observation wells, and the groundwater storage exhibited a declining trend of 1 650 × 10^4 m^3, which was larger than the total imbalance yields during the representative period (2007–2014).

Entire portions of Baotou City rely on groundwater as the primary source of the domestic water supply. With population growth and rapid urbanization, the groundwater level of most observation wells has continuously decreased due to the increasing pumping intensity as shown in Fig. 7.

For shallow aquifers (Fig. 7a), the Wanshuiq unit has the highest pumping intensity (11.40 × 10^4 m^3) followed by the Sanheh unit (8.38 × 10^4 m^3). The two geological units are located in a main agricultural area that uses groundwater extraction, and the rate of decline in the groundwater level was greater than 1.5 m per year at some representative observation wells (No. S10); this can result in negative impacts on the geological and environmental systems.

For the deep aquifer (Fig. 7b), the Kundul unit has the highest groundwater pumping intensity (16.94 × 10^4 m^3), followed by the Liubaoy unit (12.88 × 10^4 m^3). The decline in the groundwater level is widely apparent in most geological units, and the area of serious depression affected by groundwater over-exploitation (the rate of decline is greater than 1 m/y) has been estimated at 585 km^2, accounting for 31% of the Baotou Plain area.

4.5. The sustainable yield of the groundwater system

A numerical groundwater model based on the water budget was used to simulate and quantify the responses of the recharge, discharge, and evapotranspiration variables to the given groundwater pumping scenarios.

If the rainfall intensity is relatively large, the recovery of the groundwater storage varies little during an excessive pumping period, such as from 2011 to 2012 for the shallow aquifer (Table 3). The simulation results show that sufficient rainfall supports an excessive pumping pattern and causes a slow and disproportionate groundwater storage recovery and water level rise in the shallow aquifer. The annual

Table 3
Estimation of the sustainable yield of the groundwater system from 2007 to 2014

Year	Shallow (×10^8 m^3)							Deep (×10^8 m^3)					
	R	D	E	ΔS	$\overline{Q}_{safe}$	$\overline{Q}$	$\overline{Q}_{safe}-\overline{Q}$	R	D	ΔS	$\overline{Q}_{safe}$	$\overline{Q}$	$\overline{Q}_{safe}-\overline{Q}$
2007	1.13	0.03	0.34	–0.07	0.70	0.79	–0.09	0.52	0.02	–0.20	0.30	0.54	–0.24
2008	1.53	0.04	0.38	–0.12	0.99	0.82	0.17	0.54	0.02	–0.15	0.38	0.65	–0.27
2009	1.32	0.03	0.34	–0.05	0.90	0.84	0.06	0.42	0.01	–0.12	0.28	0.62	–0.33
2010	1.45	0.04	0.35	–0.05	1.01	0.88	0.13	0.49	0.02	–0.18	0.29	0.73	–0.43
2011	1.07	0.04	0.32	–0.08	0.63	1.01	–0.39	0.35	0.02	–0.21	0.12	0.77	–0.64
2012	2.01	0.05	0.45	–0.08	1.43	0.97	0.47	0.94	0.02	–0.13	0.79	0.75	0.04
2013	1.14	0.04	0.33	–0.07	0.70	0.93	–0.23	0.61	0.02	–0.19	0.41	0.72	–0.30
2014	1.78	0.04	0.41	–0.03	1.30	0.97	0.33	0.63	0.02	–0.15	0.46	0.77	–0.31
Average	1.43	0.04	0.37	–0.07	0.96	0.90	0.06	0.56	0.02	–0.16	0.38	0.69	–0.31

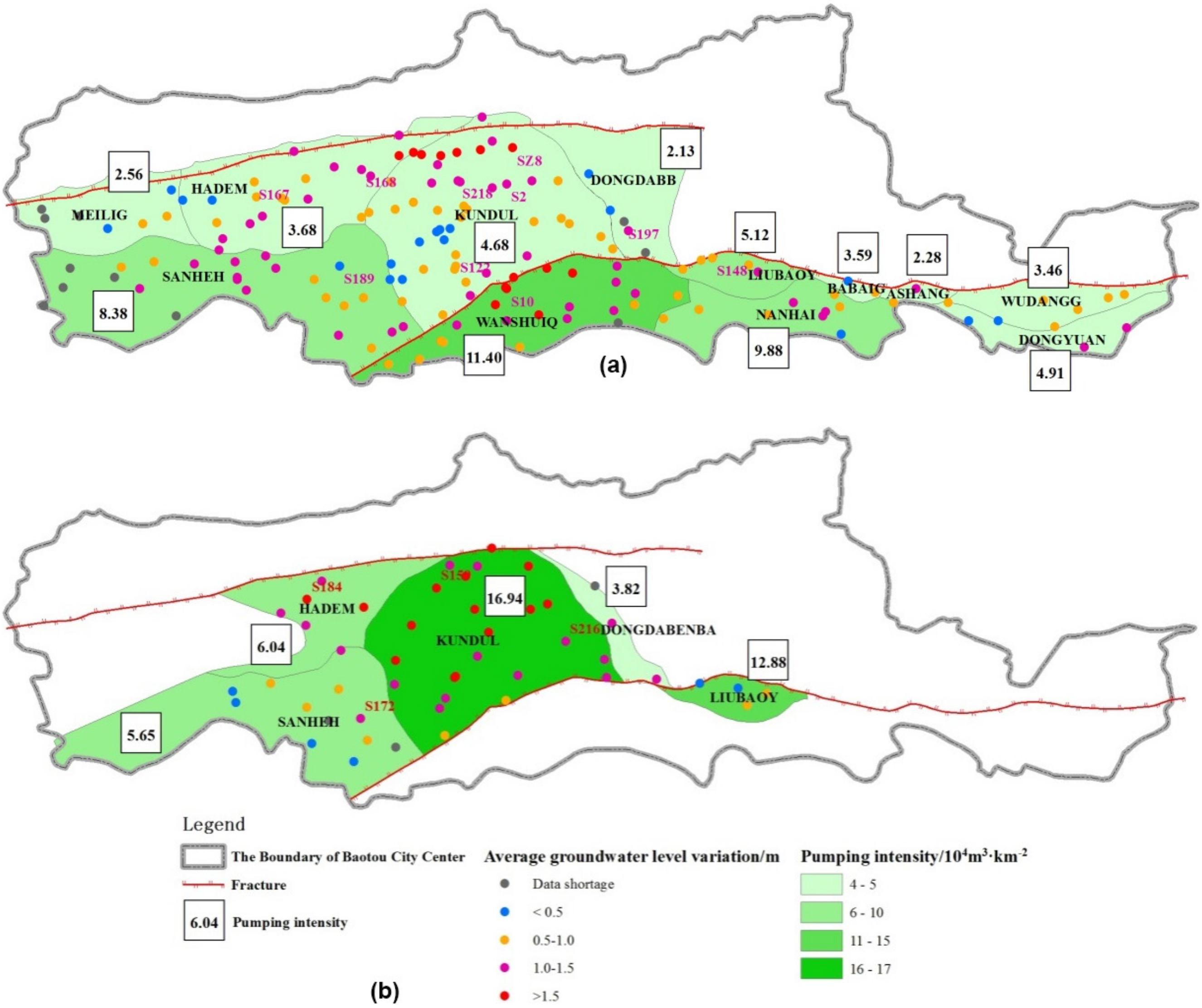

Fig. 7. The average groundwater level variation and pumping intensity for the shallow (a) and the deep (b) aquifers.

rainfall intensity was much lower in 2011 (224 mm) than in 2012 (422 mm), and the recharge varied from $1.07 \times 10^8\,m^3$ to $2.01 \times 10^8\,m^3$, but the groundwater storage was approximate equal to $-0.08 \times 10^8\,m^3$ in the shallow aquifer for both years. The slow storage recovery indicated that the declining trend of the groundwater level was controlled effectively by a short-duration and heavy-intensity inter-annual rainfall; the discrepancy between recharge and pumping was less obvious due to the greater boost of the sustainable yield for the shallow aquifer in wet years than in drought years.

In addition, the increase in the recharge of the groundwater system was found to have a notable effect on the groundwater storage for the deep aquifer, and the added dynamic annual sustainable yield could also not support a long-term excessive pumping development.

Overall, the attributed groundwater sustainable yield attributed to average, wet, medium, and dry rainfall was estimated at $9561 \times 10^4\,m^3$, $12897 \times 10^4\,m^3$, $8967 \times 10^4\,m^3$, and $5943 \times 10^4\,m^3$, respectively, for the shallow aquifer and $3803 \times 10^4\,m^3$, $5560 \times 10^4\,m^3$, $3562 \times 10^4\,m^3$, and $1544 \times 10^4\,m^3$, respectively, for the deep aquifer during the representative period of 2007–2014 (Table 4).

4.6. Comparison of the traditional and modified results

When comparing the sustainable yield based on the second national water resources assessment achievement from the Water Conservancy Bureau and the estimated results of the dynamic assessment introduced in this work, we find that the constant value of the sustainable yield is $108 \times 10^6\,m^3$ for shallow aquifers and $41 \times 10^6\,m^3$ for deep aquifers in Baotou Plain with the traditional method; however, in severe drought years (such as 2011), the pumping is lower than the sustainable yield by the traditional method and could not match the change of the groundwater level, thereby causing the shallow groundwater level to show a declining trend (Table 5).

Table 4
The estimation on the sustainable yield of geological units with different rainfall

Geological units	Shallow sustainable yield				Deep sustainable yield			
	Average annual rainfall (264 ± 25 mm)	Wet period (307 ± 25 mm)	Median rainfall period (251 ± 25 mm)	Drought period (209 ± 25 mm)	Average annual rainfall (264 ± 25 mm)	Wet period (307 ± 25 mm)	Median rainfall period (251 ± 25 mm)	Drought period (209 ± 25 mm)
MEILIG unit	558	942	526	448				
HADEM unit	1167	1856	1073	965	343	440	323	171
KUNDUL unit	1434	1673	1328	731	2063	3217	1946	767
DONGDABB unit	669	760	620	451	195	251	177	67
LIUBAOY unit	332	432	306	269	573	767	551	278
BABAI Unit	224	303	211	189				
ASHAN unit	135	211	127	97				
WUDANG unit	581	780	550	477				
SANHEH unit	1839	2757	1759	1211	629	885	566	261
WANSHUIQ unit	1335	1627	1277	527				
NAHAI unit	919	1059	849	362				
DONGY unit	368	496	340	217				
Total	9561	12897	8967	5943	3803	5560	3562	1544

Table 5
The comparison of the estimated sustainable yield between the traditional and modified method in 2011

Aquifer	Rainfall (mm)	Sustainable yield ($\times 10^6$ m^3)		Actual pumping ($\times 10^6$ m^3)	Water level change (m)
		Tradition method	Modified method		
Shallow	224	108	63	101	–0.23
Deep	224	41	12	77	–0.57

As seen in Table 5, the traditional method could not reflect the actual storage and recharge capacity in the groundwater flow system such that the current pumping pattern is judged as proper but is inconsistent with the change in groundwater level for the shallow aquifer. As we know, there is a strong relationship between the sustainable yield and the groundwater level, but the groundwater level increasing or decreasing is a comprehensive action affected by many factors, such as land use and the interaction between surface water and groundwater. Therefore, the future modified direction of the dynamic sustainable yield should consider the coupled effect of both the underlying surface conditions and environmental state for different geological units.

5. Conclusion

Pumping from an aquifer will always cause a decline in the groundwater level, which induces recharge, and discharge patterns and change the groundwater flow system from a control based on natural conditions to a control based on both natural conditions and human activities.

The traditional method for estimating the sustainable yield often focuses on a value based on the total natural recharge plus a coefficient for allowance pumping; this approach does not reflect the dynamic changes in the new recharge and discharge variables due to a groundwater level decline in the aquifer. When the groundwater extraction is less than the sustainable yield in an aquifer, the total recharge due to the rainfall is sufficient to meet the water demand for a healthy and steady socio-economic development without generating any negative consequences. However, when the groundwater extraction is greater than the sustainable yield, the decline in the groundwater level due to excessive pumping will result in a depletion of the groundwater storage and will eventually alter the relative steady balance of the groundwater flow systems under natural conditions.

Compared with the sustainable yield, the present groundwater pumping must be reduced to a proper level, and the reduced groundwater withdrawal must be replaced by engineering measures, such as water conservation, water imports, and the use of alternative water sources (desalination, water recycling, etc.).

The future challenge is to link the predicted variation in the groundwater level and the variables for the aquifer's water budget to the impact on ecosystems and socio-economic developments. In addition, the effects of shallow to deep flow systems and the lag effect of rainfall under excessive pumping scenarios require detailed investigations.

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