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Using EARTH Model to Estimate Groundwater Recharge at Five Representative Zones in the Hebei Plain, China

Bingguo Wang*, Menggui Jin, Xing Liang
School of Environmental Studies, *China University of Geosciences*, *Wuhan* 430074, *China*; *State Key Laboratory of Biogeology and Environmental Geology*, *China University of Geosciences*, *Wuhan* 430074, *China*

ABSTRACT: Accurate estimation of groundwater recharge is essential for efficient and sustainable groundwater management in many semi-arid regions. In this paper, a lumped parameter model (EARTH) was established to simulate the recharge rate and recharge process in typical areas by the observation datum of weather, soil water and groundwater synthetically, and the spatial and temporal variation law of groundwater recharge in the Hebei Plain was revealed. The mean annual recharge rates at LQ, LC, HS, DZ and CZ representative zones are 220.1, 196.7, 34.1, 141.0 and 188.0 mm/a and the recharge coefficients are 26.5%, 22.3%, 7.2%, 20.4%, and 22.0%, respectively. Recharge rate and recharge coefficient are gradually reduced from piedmont plain to coastal plain. Groundwater recharge appears as only yearly waves, with higher frequency components of the input series filtered by the deep complicated unsaturated zone (such as LC). While at other zones, groundwater recharge series strongly dependent on the daily rainfall and irrigation because of the shallow water table or coarse lithology.
KEY WORDS: EARTH model, groundwater recharge, Hebei Plain.

0 INTRODUCTION

In arid and semi-arid areas, where potential evapotranspiration equals or surpasses average precipitation, recharge is difficult to estimate (Sekhar et al., 2004; De Vries and Simmers, 2002). Hebei Plain, a semi-arid area, is one of the most important agricultural areas in China, but water shortages limit the local agricultural development. As is common in semi-arid regions, water resource is critical to economic development (De Vries and Simmers, 2002). The local agricultural development mainly depends on the irrigation. Groundwater is the main irrigation source, about 70% of the total water supply. Due to groundwater over-exploitation, groundwater level declined rapidly and the rate of decline was more than 1 m/a in the past decades. In order to solve the water shortage problem, water-saving agricultural practices have been practiced since the 1990s, which certainly influence the soil moisture regime and recharge processes (Jin et al., 2000, 1998). Therefore, accurate estimation of the current rate of groundwater recharge is essential for efficient and sustainable groundwater management in the semi-arid region.

Groundwater recharge may be estimated by several methods (Nimmo et al., 2005; Scanlon et al., 2002; Simmers et al., 1997), such as the water-balance, Darcian approach, lysimeter, water table fluctuation, tracer techniques (Lin et al., 2013; Wang et al., 2008), and also modeling water transport through the unsaturated zone, which is subject to this paper. The type of model used is determined by mainly two factors: the natural environment (climatic, geology and geomorphology) and the available information and data. By its nature, the geology and geomorphology of the study area will exert a fundamental influence on infiltration and percolation. The geology in the study area may be represented schematically by a sand aquifer, overlaid by an unsaturated zone of different thickness (from several meters to 30 m) consisting of inter-bedding of clay and sand. However, it is hard to determine the actual recharge by the numerical techniques under the condition of the deep groundwater tables. Therefore, attention is focused on the lumped parametric approach (EARTH model), instead of the more sophisticated deterministic method.

In this paper, EARTH model was used to evaluate the actual groundwater recharge of the representative zones in the Hebei Plain under semi-arid climatic conditions. Additional objectives are to analyze spatial and temporal distribution of groundwater recharge in the Hebei Plain.

1 BACKGROUND OF THE STUDY AREA

Hebei Plain, adjacent to Beijing and Tianjin municipalities, is a part of the North China Plain. The southern boundary is Henan Province and the eastern boundary is Bohai Bay of the Pacific Ocean (Fig. 1). The total area of Hebei Plain is 73 000 km^2, 40 000 km^2 of which is cultivated land. The population totals 50 million. The plain has very flat topography, deep soil, and abundant sunshine, and is one of the most important agricultural areas in China. Because of monsoonal influences, rainfall and runoff are highly variable, with 60%–70% of the annual precipitation (500–600 mm) and runoff concentrated between June and August. This variability produces a spectrum of

*Corresponding author: bgwang@cug.edu.cn

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natural disasters such as spring droughts, autumn floods, soil salinization and alkalization, and saline groundwater, all of which limit the development of agriculture in the area. In addition, with increased intensity of agriculture since the 1980s, groundwater over-extraction has led to a reduction of volume of fresh unconfined groundwater and continued lowering of piezometric levels of deep fresh confined water. These developments have resulted in serious environmental problems such as seawater intrusion, saline connate water invasion into fresh groundwater, land subsidence and groundwater pollution (Yang et al., 2012). Consequently, socio-economic and agricultural impacts of water shortages and environmental degradation are increasing in severity (Lu et al., 2011).

In this region, the key issue for agricultural development is to develop and manage the limited water resources in such a way that they can be used on a sustainable basis. Current water-saving agricultural practice in the area certainly influence the soil moisture regime and recharge processes and are directly reflected by differences in net groundwater recharge (Jin et al., 2000, 1998).

According to the hydrogeologic conditions and the character of the groundwater system, representative zones from the piedmont to coastal plain were selected for particular research. They are (1) the Luquan (LQ) and Luancheng (LC) representative zone on the piedmont plain; (2) the Hengshui (HS) and Dezhou (DZ) representative zone on the alluvial and lacustrine plain; and (3) the Cangzhou (CZ) representative zone on the coastal plain (Fig. 1). General features of the representative zones are listed in Table 1.

Table 1 General feature of the representative zones (Lu et al., 2011)

Geomorphologic setting	Representative zone (code)	Water table depth (m)	Lithology of the vadoze zone	Mean annual rainfall (mm/a)
Alluvial and pluvial plain	Luquan (LQ)	10–25	Silt and fine sand	547
	Luancheng (LC)	30–35	Silty and silt clay	537
Alluvial and lacustrine plain	Hengshui (HS)	3–5	Clay, silty clay and silt	511
	Dezhou (DZ)	2–6	Silty and silt clay	522
Alluvial and coastal plain	Cangzhou (CZ)	1–4	Silt and silty clay	554

2 OUTLINE OF THE EARTH MODEL

Methods of recharge modelling can be classified into two distinct groups: direct methods and indirect methods. The direct method describes recharge mechanisms as percolation, soil moisture distribution, evapotranspiration etc. to come to an estimate of recharge. It approaches the problem 'from the top'. The indirect method uses fluctuations of the groundwater table as indicator of the amount of actual recharge (Das Gupta and Paudyal, 1988; Johansson, 1987). EARTH model, developed by Van der Lee and Gehrels (1990), for use in the GRES (groundwater recharge evaluation study) project, is a combination of the two methods. The first three modules, MAXIL, SOMOS and LINRES are together the 'direct' part of the model (Fig. 2). It determines recharge using physical processes above the groundwater table. This part is calibrated with the measured time series of soil moisture. SATFLOW, the last module, is the indirect part of the model and calculates the groundwater level with the estimated recharge of the direct part (Van der Lee and Gehrels, 1990). Some researchers also used similar model to study groundwater recharge and discharge. Pozdniakov and Shestakov (1998) applied a lumped-parameter model of groundwater balance to estimate of discharge variability in comparison with the variability of recharge in a river valley in the territory of Tajikistan. Wang et al. (2010) used tank models to estimate delayed recharge through thick vadose zone.

The first module MAXIL (MAXimum Interception Loss) represents plant surface retention loss. The fraction of precipitation that reaches the surface and infiltrates is defined as precipitation excess, that is

$$P_{exc}=P-Maxil, \text{ while } P>Maxil \tag{1}$$

SOMOS (SOil MOisture Storage) is a reservoir with capacity S_m within a thickness of approximately the root zone. In this module infiltration water (P_{exc}) is divided into different components: actual evapotranspiration (ET_a), percolation (R_p), ponding and/or runoff (Q_s) and change in soil moisture storage ($\mathrm{d}S/\mathrm{d}t$). The general water balance is thus

$$\frac{\mathrm{d}S}{\mathrm{d}t}=P_{exc}-ET_a-R_p-E_0(SUST)-Q_s \tag{2}$$

Equation (2) is solved numerically using the implicit method, where ET_a and R_p are calculated by

$$ET_a=ET_p\frac{S-S_r}{S_m-S_r} \tag{3}$$

$$R_p=K_s\frac{S-S_{fc}}{S_m-S_{fc}} \quad (R_p>0, \text{ while } S>S_{fc};\ R_p=0, \text{ while } S<S_{fc}) \tag{4}$$

Equations (3) and (4) contain the actual soil moisture content (S), maximum soil moisture content (S_m), residual soil moisture content (S_r), soil moisture at field capacity (S_{fc}), crop potential evapotranspiration (ET_p) and saturated conductivity (K_s). At the beginning of time step t the amount of water stored in SOMOS will be ($S_{t-1}+P_{exc}$). During time step t the amount of water will be reduced by mainly the components ET_a and R_p. Exceeding the maximum storage capacity of SOMOS ($S>S_m$) results in ponding (surface storage) and optionally surface runoff. By taking the actual soil moisture storage during the

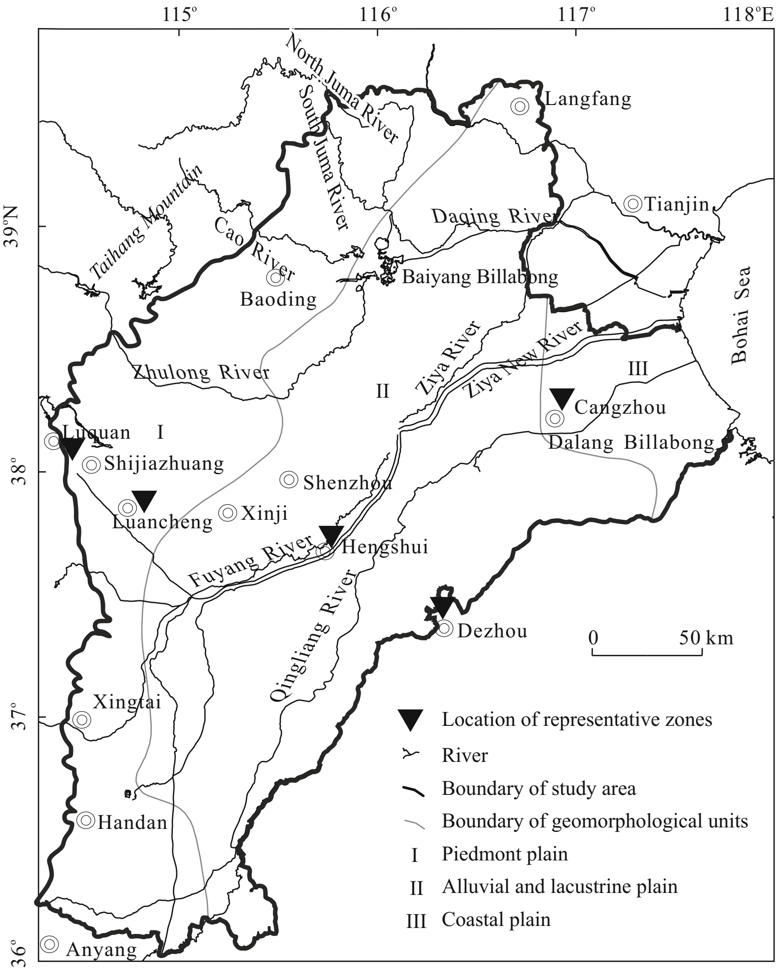

Figure 1. Map of Hebei Plain and locations of representative zones.

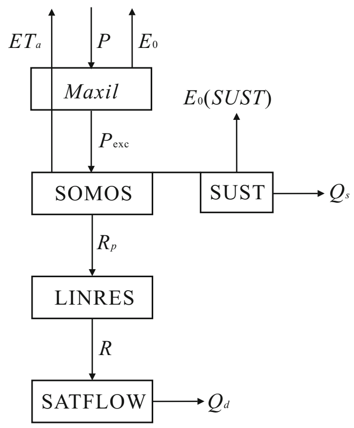

Figure 2. Flow chart of the EARTH model (Van der Lee and Gehrels, 1990).

time step an overestimation of ET_a and R_p is avoided. After this module calculation the percolation rate R_p is obtained.

LINRES (LINear REServoir routing) is a module to redistribute R_p in time in the deep unsaturated zone beneath the root zone using a parametric transfer function. This function emulates a series of linear reservoirs and creates a time lag and attenuation of the input pulse. Each algebraic equation (e.g., one reservoir) of the numerical transfer function yields

$$Y_{i,t} = Y_{i,t-1} - \frac{\Delta t}{f}\left(Y_{i,t} + Y_{i-1,t}\right) \qquad i=1,2,\ldots,n \tag{5}$$

where Y is output of R_p for the i reservoir (i=1,2,…,n) at t time; Δt is time step; and f is unsaturated recession constant. This implicit numerical solution is unconditionally stable (Van der Lee and Gehrels, 1990). With the following boundary condition for the first reservoir

$$Y_1 = R_p - f \cdot Y' \tag{6}$$

the set of equation can be solved sequentially. For n equations (or reservoirs) the output at time t is given by

$$Y_{n,t} = \frac{f}{1+f}\sum_{i=0}^{n}\frac{1}{1+f}Y_{n-i,t-1} = R_t \tag{7}$$

with

$$Y_{0,t-1} = R_p\frac{1+f}{f} \tag{8}$$

where R_t is the recharge (mm/d), f is the unsaturated recession constant, n is the number of reservoirs, Y_n refers to the result from the previous time step, Y_0 is the upper boundary condition and R_p is the percolation (mm). The solution requires that two parameters (n and f) should be known. Determination of the two parameters is performed with an iterative least square technique, which compares the estimated output of the system with measurements of groundwater level fluctuations.

SATFLOW (SATurated FLOW module): the lower boundary of EARTH is defined by a simple one-dimensional, parametric, groundwater model whose parameters have a semi-physical meaning. The equation is given by

$$S_{to}\frac{\mathrm{d}h}{\mathrm{d}t}=R_t-\frac{h_t}{RC}S_{to} \tag{9}$$

Where h_t is groundwater level at t time; dh/dt *is* derivative of h; RC is saturated recession constant (d); S_{to} is storage coefficient. This is intrinsically a linear function, and can be solved numerically from

$$h_t=h_{t-1}-\frac{\Delta t}{RC}h_t+\frac{\Delta t}{S_{to}}R_t \tag{10}$$

the shape of the recession curve depends on the water yielding properties of the aquifer material, the transmissivity and the geometry. The recession coefficient is interpreted directly from groundwater level measurements.

The first two modules, MAXIL and SOMOS, represent “the agro-hydro-meteorological zone” of the modelled space. Vegetational and atmospheric influences are buffered in this zone. Precipitation is redistributed into evapotranspiration, percolation and soil moisture storage. The last two modules, LINRES and SATFLOW, stand for the “hydro-geological zone” of the modelled space. LINRES represents deep percolation, flow from the lower boundary of the root zone to the groundwater table. SATFLOW is the model of saturated flow and predicts the groundwater level with an estimated aquifer recharge, the outcome of LINRES. An important aspect is that the calculated recharge can be optimized by both the measured soil moisture and the measured groundwater level.

3 MODEL APPLICATION

3.1 Available Data Sets

Input data sets include rainfall (or irrigation), potential evapotranspiration, soil moisture storage and groundwater level. Available data sets of the different representative zones were given in Table 2.

Precipitation record from the local standard weather station and the crop potential evapotranspiration on daily basis were available. The crop potential evapotranspiration was calculated by crop coefficient

$$ET_p=K_c\cdot ET_0 \tag{11}$$

where ET_0 is the reference crop potential evapotranspiration, which was calculated by Penmen-Monteith Formula; K_c is crop coefficient, and the crop coefficient of winter wheat and summer maize at representative zones was given in Table 3.

Volumetric soil moisture was measured with a neutron probe (IH-II, Institute of Hydrology, UK) in access tubes down to 340 cm (0–100 cm at 10 cm intervals, 100–220 cm at 20 cm intervals, 220–340 cm at 40 cm intervals at LC representative zone) or 300 cm (0–50 cm at 10 cm intervals, 50–110 cm at 20 cm intervals, 110–260 cm at 30 cm intervals and 260–300 cm at 40 cm intervals at HS representative zone) at about every 2 or 3 days. Soil water potential was also measured with the tensions (WM-1, Institute of Hydrogeology and Engineering Geology,

Table 2 Available data sets of the different representative zones

Representative zones	Period of the data sets			
	Rainfall and irrigation	Potential evapotranspiration	Soil moisture storage	Groundwater level
LQ	2003.01.01–2005.09.30	2003.01.01–2005.09.30	.	2003.01.01–2005.08.26, every fortnight
LC	2002.01.01–2005.08.31	2002.01.01–2005.08.31	2002.11.12–2006.02.20	2001.06.05–2005.09.21, every fortnight
HS	1999.10.01–2002.06.05	1999.10.01–2002.06.05	1999.10.26–2002.05.07	1999.10.26–2002.06.05, every fortnight
DZ	1999.10.01–2004.12.31	1999.10.01–2004.12.31	.	1999.10.01–2004.12.31, every fortnight
CZ	2003.08.01–2005.09.30	2003.08.01–2005.09.30	2004.04.15–2005.09.10	2003.08.01–2005.09.30, every fortnight

Table 3 Crop coefficient of winter wheat and summer maize at representative zones (Wang, 2008)

Representative zone	Month											
	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
LQ & LC	0.43	0.38	0.57	1.23	1.42	0.48	1.07	1.59	0.9	0.6	0.82	0.86
HS, DZ & CZ	0.20	0.20	0.93	1.69	1.12	1.08	0.84	0.94	1.34	0.56	0.56	0.20
Memo	Winter wheat					Summer maize				Winter wheat		

Chinese Academy of Geological Sciences, China) at the same depth and intervals as the soil moisture. For DZ & CZ representative zones, volumetric soil moisture was measured by soil moisture probe monthly. The soil moisture storage could be calculated according to the observed soil water from the neutron probe and the depth of equivalent root zone (the location was almost at the deepest zero flux plane, which can be determined by the soil water potential data).

3.2 Calibration of the Model

Except the data sets above, some parameters are also needed, such as $IL_{\max}$ (maximum interception loss, mm), S_{smax} (maximum surface storage, mm), S_m (maximum soil moisture content, mm), S_r (residual soil moisture content, mm), S_i (initial soil moisture content, mm), S_{fc} (soil moisture at field capacity, mm), K_s (saturated conductivity, mm/d), f (unsaturated recession constant, d), n (number of reservoirs), RC (saturated recession constant, d), S_{to} (storage coefficient), H_i (initial groundwater level, m) and H_0 (local base level, m).

From field observation no surface runoff occurs during normal rain periods, modelling results have also demonstrated with a maximum surface storage (S_{smax}) of 2.0 mm. Maximum interception loss is considered as 1.8 mm. The depth for soil moisture storage calculations is 2 m, since the total soil water potential observation data show that the deepest zero flux plane lies at about this depth. S_m *and* S_r were determined by water retention curves, and S_{fc} are was obtained by the field irrigation tests. S_i, H_i, H_0 and RC are read from the soil moisture and groundwater level data set respectively. Saturated conductivity for the unsaturated zone (K_s) was determined by the double ring infiltration tests and storage coefficient (S_{to}) was determined from water table fluctuation method at HS, DZ and CZ the field tests or empirically estimated at LQ and LC. The unsaturated recession constant (f) and the number of reservoirs (n) were identified from the EARTH model. The two parameters affect the shape of LINRES output pulse, which directly affect the simulated groundwater level. The unsaturated recession constant (f) smoothes the input out in time (Fig. 3a), while the number of reservoirs (n) determines the place in time of the weighed center (Fig. 3b).

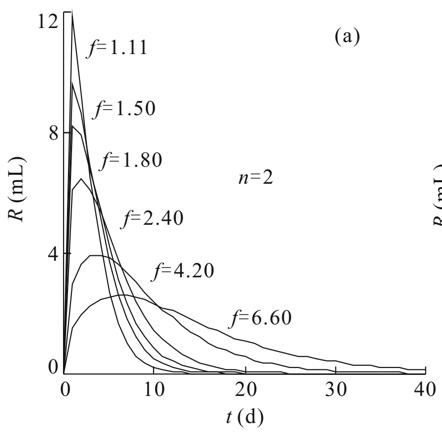

Figure 3. When n or f is constant, another parameter' effect on the output (with an input of 50 mL water).

The simulation periods were determined according to the available data sets. The time step was chosen as small as possible, i.e., one day, reminding the short duration/high intensity character of the rainy events in semi.arid climates. The model was only calibrated on the water table fluctuations at LQ and DZ for short of soil moisture data sets. A rough fit was obtained between measured and calculated groundwater levels (Figs. 4–5). According to the study results from Van der Lee and Gehrels (1990), the model could be calibrated on groundwater level data only when there is an adequate estimate of the soil retention capacity (S_{fc}–S_r). While at LC, HS and CZ, the model was calibrated on both soil moisture and water table fluctuations, which led to better results. The simulated results for groundwater levels reasonably fit the measured data (Figs. 6–11). It demonstrates the reliability of the reservoirs LINRES and SATFLOW, or the unsaturated and saturated water transport. The simulated recharge rates series in typical zones were given from Figs. 12–16. The identified parameters were given in Table 4.

3.3 Results and Discussion

The simulated results are summarized in Table 5. The mean annual recharge rates at LQ, LC, HS, DZ and CZ representative zones are 220.1, 196.7, 34.1, 141.0 and 188.0 mm/a and the recharge coefficients (indicate the recharge from the rainfall or irrigation, and its formula is $R_d \times \Delta t/(P+I) \times 100\%$) are 26.5%, 22.3%, 7.2%, 20.4% and 22.0%, respectively (Table 5).

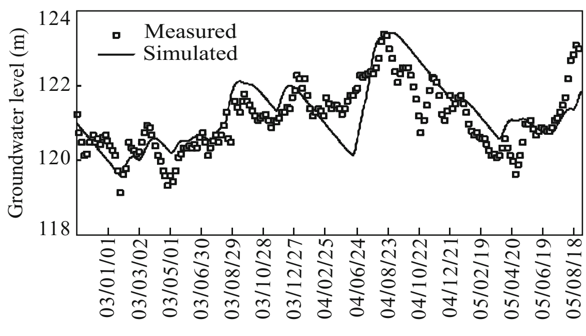

Figure 4. Measured and simulated groundwater level at LQ.

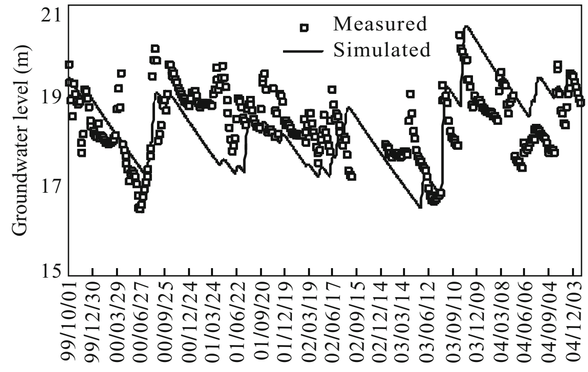

Figure 5. Measured and simulated groundwater level at DZ.

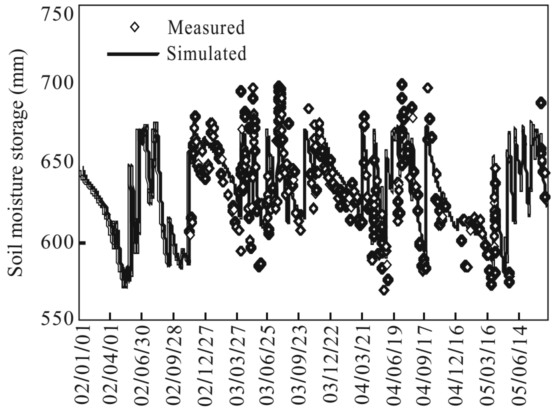

Figure 6. Measured and simulated soil moisture storage at LC.

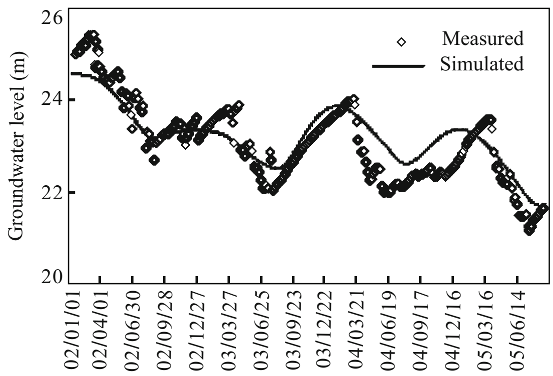

Figure 7. Measured and simulated groundwater level at LC.

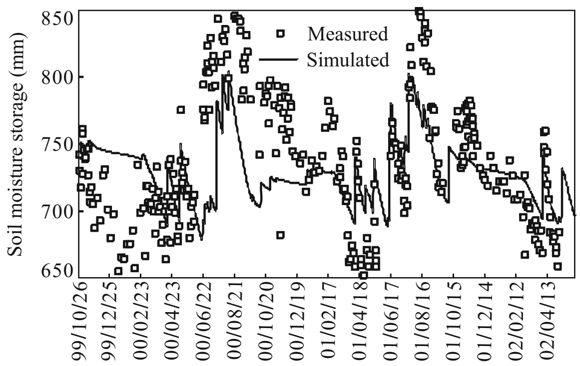

Figure 8. Measured and simulated soil moisture storage at HS.

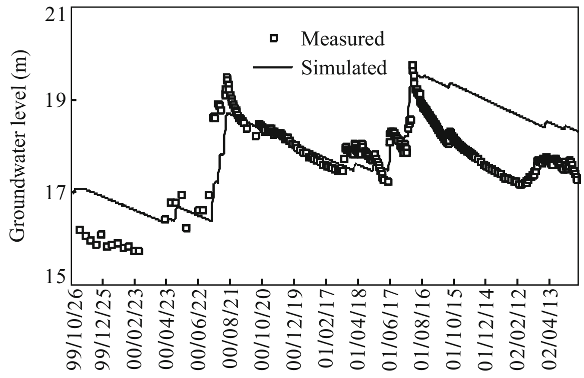

Figure 9. Measured and simulated groundwater level at HS.

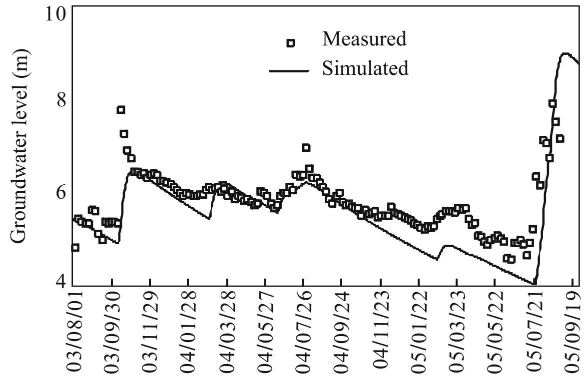

Figure 10. Measured and simulated groundwater level at CZ.

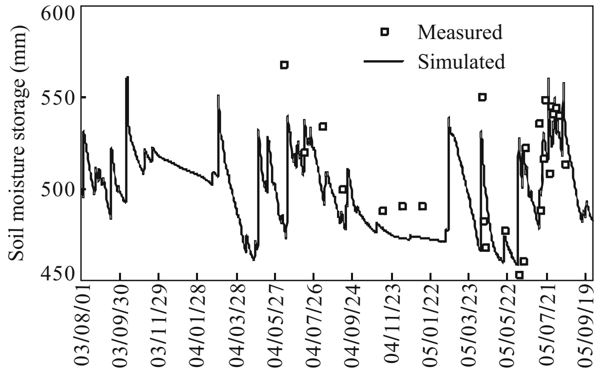

Figure 11. Measured and simulated soil moisture storage at CZ.

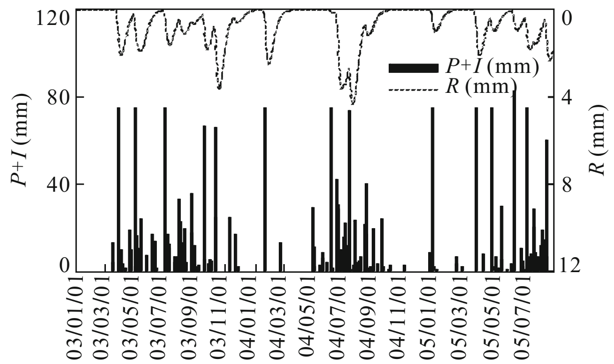

Figure 12. Simulated recharge and P+I at LQ.

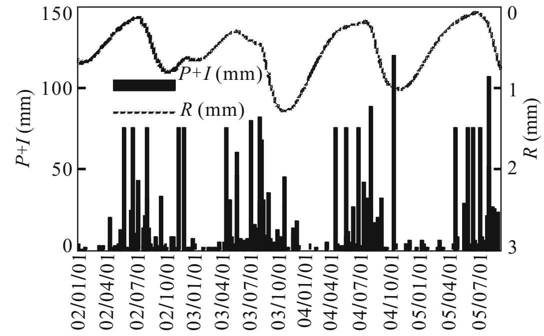

Figure 13. Simulated recharge and P+I at LC.

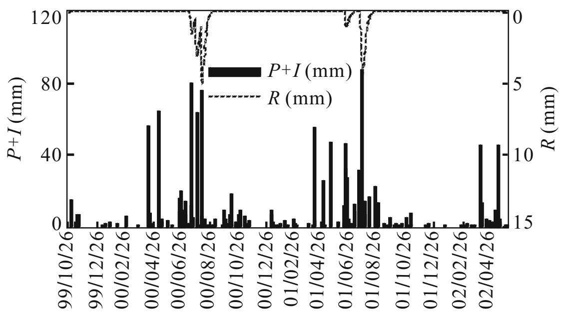

Figure 14. Simulated recharge and P+I at HS.

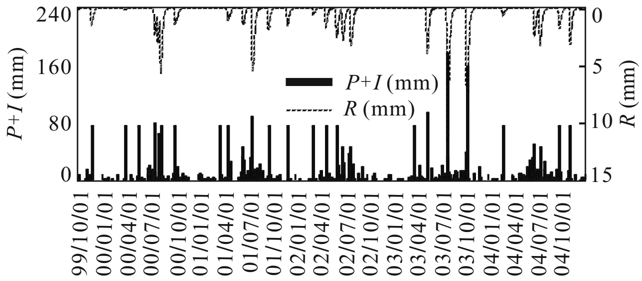

Figure 15. Simulated recharge and P+I at DZ.

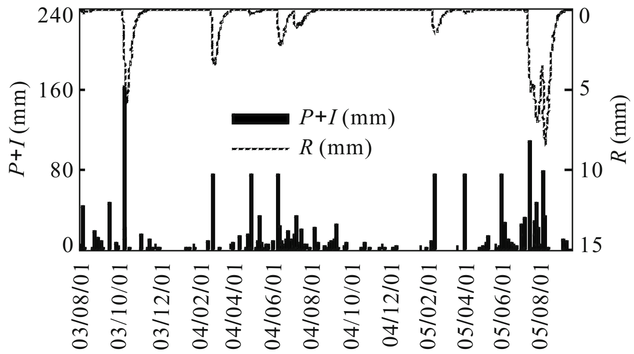

Figure 16. Simulated recharge and P+I at CZ.

Table 4 Parameters for the EARTH model simulation at representative zones

Representative zones	IL_{max}	S_{smax}	S_m	S_r	S_i	S_{fc}	K_s	f	n	RC	S_{to}	H_i
LQ	1.8	2	600	470	530	580	600	6	2	7 200	0.08	120.53
LC	1.8	2	710	570	650	670	420	42	3	8 000	0.05	26.0
HS	1.8	2	850	650	742	830	240	2	1	3 600	0.02	16.50
DZ	1.8	2	630	500	530	590	450	3	2	2 000	0.04	19.39
CZ	1.8	2	540	410	460	500	480	4	2	640	0.04	4.79

Memo: IL_{max}. maximum interception loss (mm); S_{smax}. maximum surface storage (mm); S_m. maximum soil moisture content (mm); S_r. residual soil moisture content (mm); S_i. initial soil moisture content (mm); S_{fc}. soil moisture at field capacity (mm); K_s. saturated conductivity (mm/d); f. unsaturated recession constant (d); n. number of reservoirs; RC. saturated recession constant (d); S_{to}. storage coefficient; H_i. initial groundwater level.

Comparing the simulation results at the different representative zones (Table 5), the mean annual recharge rate and the recharge coefficient at HS are only 34.1 mm/a and 7.2%, respectively, the minimum of all the representative zones. It may be resulted from the scarce rainfall during the simulation period (annual rainfall is only about 440 mm in 2000 and 2001). Furthermore, the study area during the simulation period was carrying out soil water control test and the irrigation quota is only 450–600 m^3/ha. Research also shows that the irrigation quota in less than 450 m^3/ha almost do not lead to recharging. The mean annual recharge rate at LQ is the largest (220.1 mm/a), and the infiltration recharge coefficient is up to 26.5%, which may be attributed to a more homogeneous silt soil at LQ.

Average groundwater recharge for years can only reflect the groundwater recharge roughly, not reflect the influence of groundwater recharge from different hydrological years. Based on this, according to the yearly simulation results (Table 5), the groundwater recharge rates and infiltration recharge coefficients in particular years were selected to analyze the spatial distribution rule of the groundwater recharge in Hebei Plain. From the Figs. 17–18 we can see the recharge rate (R_a) and infiltration recharge coefficient (R_c) in 2004, LQ is the largest, followed by LC and DZ, and CZ is the smallest. The result shows that the infiltration recharge rates and the infiltration recharge coefficients reduce progressively from piedmont plain to coastal plain. The recharge rate (R_a) and infiltration recharge coefficient (R_c) at DZ and LC in 2003 were higher than other zones, this may be ascribed to the abundant rainfall. The rainfall at DZ was up to 796.6 mm in 2003, especially, there are two heavy rains, 177.3 mm on July 30 and 159.2 mm on October 11. Maybe there are some other factors which effect the spatial distribution of the groundwater recharge, such as groundwater table depth and vadose zone lithology. Groundwater table depth at LQ and LC is over 10 m, which results in almost no evaporation from phreatic water. Vadose zone lithology at LQ is silt and fine sand, which maybe results in more recharge. While at LC, HS, DZ and CZ, vadose zone is mainly composed of alternation of silt and silty clay, which maybe reduce recharge.

According to the complete year simulation results (Table 5), the groundwater recharge rates at particular representative zones (LC and DZ, stand for the deep water table and shallow water table) were selected to analyze the temporal distribution rule of the groundwater recharge in Hebei Plain. From Fig. 19 we can see the recharge rate (R_a) at LC in different years, that in 2003 is the largest, followed by 2004 and 2002, and that in 2001 is the smallest, which indicate the correlation between the recharge rate and the rainfall or irrigation. But the groundwater

Table 5 The simulation results for the EARTH model at representative zones

Representative zone	Simulation periods	Δt (d)	P (mm)	I (mm)	P+I (mm)	R (mm)	R_d (mm/d)	R_a (mm/a)	R_c (%)
LQ	03.01.01–03.12.31	365	619.3	225	844.3	231.6	0.63	231.6	27.4
	04.01.01–04.12.31	366	536.5	225	761.5	229.8	0.63	229.8	30.2
	05.01.01–05.08.31	243	308.0	300	608.0	126.0	0.52	189.2	20.7
	03.01.01–05.08.31	974	1 463.8	750	2 213.8	587.4	0.60	220.1	26.5
LC	02.01.01–02.12.31	365	397.1	375	772.1	179.7	0.49	179.7	23.3
	03.01.01–03.12.31	365	581.3	315	896.3	257.4	0.71	257.4	28.7
	04.01.01–04.12.31	366	501.0	345	846.0	214.0	0.58	214.0	25.3
	05.01.01–05.08.31	243	342.1	375	717.1	70.6	0.29	106.0	9.8
	02.01.01–05.08.31	1 339	1 821.5	1 410	3 231.5	721.7	0.54	196.7	22.3
HS	99.10.26–99.12.31	92	35.8	0	35.8	0	0.00	0.0	0.0
	00.01.01–00.12.31	366	442.2	120	562.2	57.8	0.16	57.8	10.3
	01.01.01–01.12.31	365	441.4	100.5	541.9	33.8	0.09	33.8	6.2
	02.01.01–02.06.05	156	46.2	90	136.2	0	0.00	0.0	0.0
	99.10.26–02.06.05	979	965.6	310.5	1 276.1	91.6	0.09	34.1	7.2
DZ	99.10.01–99.12.31	92	35.8	75	110.8	14.0	0.15	55.5	12.6
	00.01.01–00.12.31	366	442.2	225	667.2	119.9	0.33	119.9	18.0
	01.01.01–01.12.31	365	441.4	300	741.4	124.1	0.34	124.1	16.7
	02.01.01–02.12.31	365	328.8	225	553.8	119.5	0.33	119.5	21.6
	03.01.01–03.12.31	365	796.6	75	871.6	250.0	0.68	250.0	28.7
	04.01.01–04.12.31	366	467.5	225	692.5	113.6	0.31	113.6	16.4
	99.10.01–04.12.31	1 919	2 512.3	1 125	3 637.3	741.1	0.39	141.0	20.4
CZ	03.08.01–03.12.31	153	384.3	0	384.3	75.5	0.49	180.2	19.7
	04.01.01–04.12.31	366	447.8	225	672.8	89.3	0.24	89.3	13.3
	05.01.01–05.09.30	273	570.5	225	795.5	243.0	0.89	324.9	30.6
	03.08.01–05.09.30	792	1 402.6	450	1 852.6	407.9	0.52	188.0	22.0

Notes: Δt. days of the simulation periods (d); P. precipitation (mm); I. irrigation (mm); R_d. mean daily recharge rates (mm/d); R_a. mean annual recharge rates (mm/a); Rc. recharge coefficient and its formula is $R_d \times \Delta t/(P+I) \times 100\%$; *. stand for simulation periods of Jan. to Aug. in 2005.

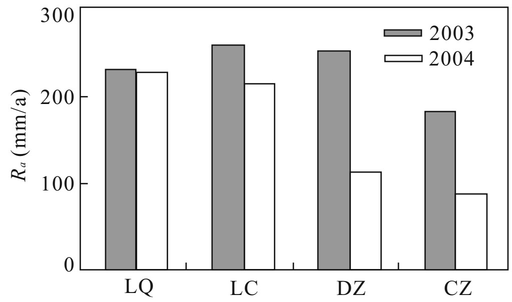

Figure 17. The annual recharge rate at different representative zones in 2003 and 2004.

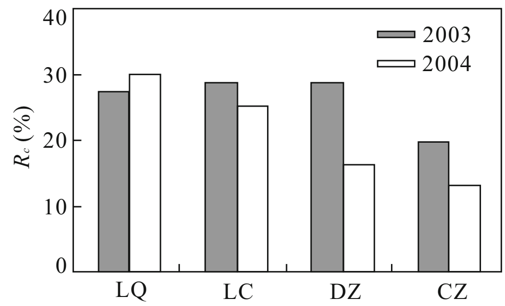

Figure 18. The infiltration recharge coefficient at different representative zones in 2003 and 2004.

recharge rates at DZ for different years have no upper rules (Fig. 20). The groundwater recharge rate in 2003 is the largest, which is similar to LC. But other years almost have the same recharge rates. The rule also reflects the change law of the rainfall and irrigation. From Fig. 7 we can see the output groundwater level series appear as only yearly waves, with higher frequency components of the input series filtered by the deep unsaturated zone (thickness over 30 m), and the groundwater recharge also shows yearly waves (Fig. 13). Under shallow water table depth, the relationship between precipitation (or irrigation) and recharge is remarkable. But there is an obvious time.lag from Figs. 14–16.

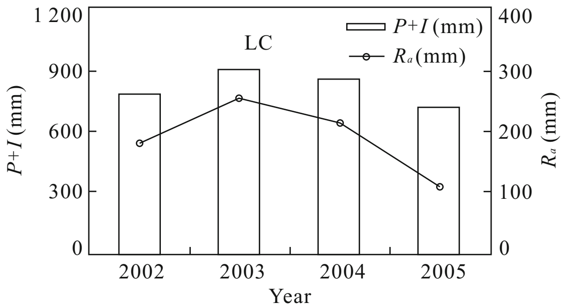

Figure 19. The annual recharge rates at LC from 2002 to 2005.

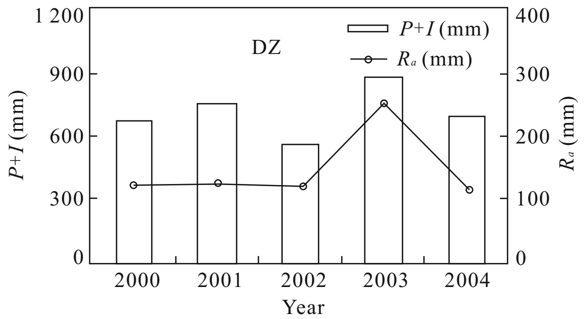

Figure 20. The annual recharge rates at DZ from 2000 to 2004.

On the basis of above, all the simulated recharge rate and the rainfall and irrigation at different representative zones from the complete year were used to study the effect of the rainfall and irrigation on the recharge rate by correlation analysis method. Research results showed that the correlation coefficient between the recharge rate and the rainfall and irrigation was more than 0.9 (Fig. 21), which is significant positive correlation at the 0.05 level (2.tailed). The correlation equation was given as follows: R=0.57(P+I)–255.50. It demonstrated that the rainfall and irrigation was the main determinants of the yearly recharge rate.

From Fig. 7 and Fig. 13 we can see the output groundwater level and recharge series appear as only yearly waves, with higher frequency components of the input series filtered by these modules, which is not related to daily rainfall and irrigation. This might be reasonable because of the deep complicated unsaturated zone (thickness over 30 m at LC during the simulating periods). We can also see a long time-lag between precipitation and recharge to the saturated zone from Fig. 13. However, at DZ representative zone (water table depth is about 1–4 m), the output recharge series strongly dependent on the daily rainfall and irrigation, which is apparent in many peaks (Fig. 15). Furthermore, the same amount of rainfall or irrigation may result in different recharge rates, which indicates the common effect of soil water, water table depth, potential evapotranspiration and so on.

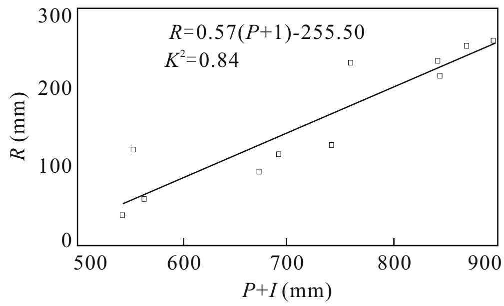

Figure 21. The correlative between the annual recharge rate (R) and P+I.

4 CONCLUSIONS

EARTH model makes full use of the information of the vadose zone and saturated zone, the actual or potential recharge was estimated on a lumped parametric approach under semi-arid climatic conditions and different groundwater tables. Calibration of the model on soil moisture or groundwater data is preferable.

The modelling results indicate the spatial and temporal variation law of groundwater recharge in the Hebei Plain. The mean annual recharge rates at LQ, LC, HS, DZ and CZ representative zones are 220.1, 196.7, 34.1, 141.0 and 188.0 mm/a and the recharge coefficients are 26.5%, 22.3%, 7.2%, 20.4% and 22.0%, respectively. Recharge rate and recharge coefficient is gradually reduced from piedmont plain to coastal plain, and the annual precipitation and irritation is the determinants of recharge rate.

Groundwater recharge appears as only yearly waves, with higher frequency components of the input series filtered by the deep unsaturated zone (thickness over 30 m). Under shallow water table depth, the relationship between precipitation (or irrigation) and recharge is remarkable. But there is an obvious delay response.

In addition to precipitation and evapotranspiration, seasonal groundwater extraction for irrigation also has a significant impact on groundwater level fluctuations. In Hebei Plain, groundwater is an important source of irrigation water. In this paper the irrigation water at Luquan and Dezhou comes from surface water engineering, while at Hengshui and Cangzhou (because the phreatic water is saline water) it comes from deep fresh ground groundwater. Deep groundwater pumping in these zones maybe has little effect on the phreatic water table. So, pumping influence at HS and CZ water was neglected. In the future study, the role of groundwater pumping on the water table (especially for well irrigation zones in piedmont plain) should be considered to further calibrate to obtain the better results in the future simulation.

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