Evaluation of groundwater renewability in the Henan Plains, China

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The sustainability of groundwater resources in the Henan Plains, located in the eastern portion of central China, has been threatened by both increasing industrial and agricultural pumping and periods of drought occurring since the 1990s. Therefore, there is an urgent need to improve water resources management in the Henan Plains. However, the recharge and annual renewal rate are very difficult to be calculated when based only on traditional hydrogeological methods because of inadequate hydrometeorologic data. In this study, tritium concentrations in groundwater and reconstructed ³H concentration time series from 1953~2009 in precipitation were used to determine the annual groundwater renewal rate. The ³H concentrations mostly ranged from 2.91 to 40.30 TU in the shallow groundwater with a mean ³H concentration of 19.13 TU, which suggested that the shallow groundwater was recharged from modern precipitation after 1953 in the study area. Three exceptionally low ³H concentration (less than 1 TU) wells were sampled in Xinxiang, Puyang and Zhengyang which indicated that those wells contained deep old groundwater recharge before 1953 as a result of over-pumping. High renewal rates (more than 4%/a) of groundwater are located mainly in the recharge areas such as the Yellow River nearby and the pediments of Taihang Mountain, Songqi Mountain, Funiu Mountain, Dabie Mountain, where the groundwater extraction volume could be increased. Moderate renewal rates (2~4%/a) of groundwater are mainly in the runoff areas where the groundwater extraction volume can be kept at current levels. Low renewal rates (1~2%/a) of groundwater are located mainly in the discharge areas in the eastern regions of Nanle, Puyang, Shangqiu, Luyi where the groundwater extraction volume should be reduced. The lowest renewal rates of (less than 1%/a) groundwater are in Fanxian, Xinxiang, Yongcheng, Zhengyang and Xixian, where the groundwater extraction volume should be restricted.

Keywords: renewal rate, ³H, shallow groundwater, reconstruction of tritium in precipitation, the Henan Plains, China

INTRODUCTION

Shallow groundwater is the important water resources for industry, agriculture and domestic use (Ministry of Water Resources Division, Nanjing Hydraulic Research Institute, 2004) in the Henan Plains of China. Nowadays, the sustainability of groundwater resources is threatened by both increasing industrial and agricultural pumping and periods of drought occurring since the 1990s. Because of over pumping of shallow groundwater, water shortage has already occurred in Henan Plains and a series of environmental geological problems such as regional groundwater level decline (Lan and Liu, 2005), land subsidence (Miao, 2010) and ground fissure (Gao, 2008) have emerged in many cities in Henan Plains, such as Anyang, Hebi, Puyang, Xinxiang, Zhengzhou, Zhengyang and Xixian (Institute of Geological Environment Monitoring of Henan Province, 2006; Institute of

Geological Survey of Henan Province, 2007). Therefore, there is an urgent need to improve water resources management in Henan Plains. Hydrogeological information such as total resources and renewal rate of groundwater (i.e., the ratio between the annual recharge and the total reserve) is essential for improving water resources management (Le Gal La Salle *et al.*, 2001).

Estimations of the recharge and annual renewal rate are very difficult, when based only on traditional hydrogeological methods such as water budget, groundwater balance or Darcy's law, because these methods often require large volumes of hydrometeorologic data collected over considerable time span and hydrological parameters which are generally inadequate or unreliable in many regions (Wood and Imes, 1995; Wood and Sanford, 1995; Wood, 1999; Flint *et al.*, 2002; Edmunds *et al.*, 2002). Thus, isotope tracers have been proven to be extremely useful in the research of groundwater renewability (Le Gal La Salle *et al.*, 2001; Ma and Hou, 2005). In recent years, ³H is considered to be an ideal tracer in the ground water renewal rate calculation, because ³H participates in water cycle as a component of water molecule

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(Clark and Fritz, 1997; Gat *et al.*, 2000). Tritium's half-life allows it to be used as a dating tool for relatively young water, i.e., water recharged less than 50 years ago (Clark and Fritz, 1997). However, observations of tritium concentration in precipitation are generally scarce. So, the utilization of tritium concentration is strongly limited by our knowledge of the natural distribution of tritium in precipitation over both space and time. Fortunately, the methods of reconstructing the tritium concentration time series in precipitation are well documented (Weiss and Roether, 1980; Guan, 1986; Lian, 1990; Doney *et al.*, 1992; Celle-Jeanton *et al.*, 2001; Ba and Xu, 2010; Zhang *et al.*, 2011). A simpler approach to obtain isotopic data for a location where no data is available would be to interpolate existing data from other neighboring locations. Despite its lack of the physical basis that a numerical model provides, interpolation has been frequently used in environmental sciences. Isotopic hydrology literature has several examples to offer, utilizing a large variety of interpolation methods (e.g., Lian, 1990; Longinelli and Selmo, 2003; Gibson *et al.*, 2005; Lykoudis *et al.*, 2010). All these methods are able to produce high-resolution gridded isotopic data sets as well as an estimate of the associated uncertainty (Lykoudis *et al.*, 2010).

In this study, we reconstructed the tritium time series of precipitation in Henan Plains and calculated the renewal rate of shallow groundwater using ^3H as a tracer. The results of this study can provide theoretical documentation for improving water resources management in Henan Plains.

STUDY AREA AND REGIONAL HYDROGEOLOGICAL SETTING

The Henan Plains is located at $112^{\circ}31'\sim 116^{\circ}40'$ E, $32^{\circ}00'\sim 36^{\circ}12'$ N, in the east of Henan Province, in middle eastern portion of China, with an area of about $8.53 \times 10^4 \text{ km}^2$. The Henan Plains is surrounded by mountains in the northwest, west and south and vast plains in the east (Fig. 1). Former Quaternary outcrops exist mainly in mountain areas, where fissure and karst formations are developed. Former Quaternary outcrops are Cambrian and Ordovician limestone of the Paleozoic with Permian and Carboniferous sandstone and shale secondly in the areas of Taihang Mountain and Songqi Mountain. In the areas of Tongbai Mountain and Dabie Mountain, the former Quaternary outcrops are metamorphic rocks of Archean, Proterozoic and Paleozoic.

The Henan Plains is overlain widely by unconsolidated formations of the Quaternary period, whose thickness follows a gradual increase from less than 100 m in pediment in the mountains to more than 180 m in the middle plain, and even more than 400 m in some places of eastern part of Henan Plains. The aquifer media consists

Fig. 1. Study area and groundwater sampling locations of ^3H samples.

mainly of sandy gravel and sand in the pediments of Taihang Mountain, Funiu Mountain and Songqi Mountain. The pediment of Dabie Mountain is cut into gullies by tributaries of Huaihe River. So the hypsography is remarkable in the pediment of Dabie Mountain. In addition, the aquifer media consists of medium-coarse sand and small amount of silt in the east of Puyang–Kaifeng–Xuchang and the west of Shangqiu–Zhecheng–Xiangcheng. The aquifer media consists mainly of silt, fine sand and mild clay in the east of Shangqiu–Zhecheng–Xiangcheng and Xincui, Xixian Huaibin areas.

According to the characteristics of aquifer media and the burial settings of groundwater, the unconsolidated formation of the Quaternary in the Henan Plains is classified as a shallow-buried aquifer (the confining bed depth is about 40~160 m), middle-buried aquifer (the lower confining bed depth 100~400 m) and deep-buried aquifer (the lower confining bed depth is 300~500 m). Most of the groundwater used in industry and agriculture comes from the shallow aquifer, for example, the pumping rate from shallow aquifer was $89.68 \times 10^8 \text{ m}^3/\text{a}$ which was 85.56% of the total pumping rate ($104.81 \times 10^8 \text{ m}^3/\text{a}$) in 1997 in the Henan Plains (Ministry of Water Resources Division, Nanjing Hydraulic Research Institute, 2004).

Table 1. The content of ^3H in the groundwater samples

Sample No.	^3H (TU)	Sample No.	^3H (TU)
GL2	23.00	GL19	15.57
GL3	27.26	GL20	20.10
GL4	38.23	A02	8.07*
GL5	29.3	A04	0*
GL7	11.62	B01	3.89*
GL8	5.48	B02	5.83*
GL9	0	B03	11.11*
GL11	29.80	B04	23.43*
GL12	23.57	B10	40.30*
GL13	15.61	B14	14.00*
GL14	33.47	B21	12.71*
GL15	15.63	B23	2.91*
GL16	33.47	B27	3.18*
GL18	30.80	B28	0.60*

*Calculated value.

Thus, the objective of this groundwater renewal rate evaluation is focused on shallow groundwater resources. The shallow groundwater system can be divided into three subsystems. They are northern plain groundwater system (I), central plain groundwater system (II), and southern plain groundwater system (III), according to the characteristics of the groundwater flow and the watershed which it belongs to (Fig. 1).

Precipitation is the main source of recharge for shallow groundwater, with small amounts of recharge from the bedrock fissure water and the karstic water in pediment of mountains in Henan Plains. Otherwise, groundwater nearby the Yellow River can be recharged by the Yellow River water by the lateral seepage because the Yellow River is a ground suspended river whose water level is higher than groundwater level. According to Cui *et al.* (2004), only groundwater within 5.0~23.0 km from the banks of the Yellow River can be recharged by the water from the Yellow River. Otherwise, pumping is the main discharge of shallow groundwater in the Henan Plains, besides a small amount of evaporation, runoff to the down gradient and leakage to the deep-buried aquifer.

Groundwater flow in the shallow aquifer is influenced primarily by regional topography. Hydraulic head in the shallow groundwater decreases from west to east (i.e., from the pediment of mountains to the eastern plain) on the whole. However, in the nearby of watersheds, groundwater flows from the watershed to the two opposite directions separated by watersheds and both of the flow directions are right-angled with the watershed (Fig. 1). The hydraulic gradient and permeability of aquifer both follow a gradual decrease trend from the pediment of mountains to the eastern plain.

FIELD SAMPLING AND ANALYTICAL METHODS

Sixteen shallow groundwater samples (Fig. 1) were collected for ^3H concentration measurements from domestic wells in April, 2009. Renewal of the water column was obtained by half hour pumping before sampling in order to obtain representative water of the aquifer. The tritium concentrations (Table 1) were measured by counting of scintillations of phase liquid in State Key Laboratory of Earthquake Dynamics in Institute of Geology of China Earthquake Administration and expressed in tritium unit (TU) with an uncertainty of ± 0.5 TU.

Considering that the tritium concentration is influenced only by radioactive decay with no reaction with aquifer media (Tian *et al.*, 2007), 12 additional tritium concentration data were collected to complement the tritium data in the northern plain groundwater subsystem which were sampled in April, 2001. To allow comparison of tritium concentration in different years, the ^3H concentration in shallow groundwater samples which were sampled in 2001 must be regulated to 2009 using radioactive decay formula (Eq. (1)) before calculating the renewal rate.

$$A_{2009} = A_{2001}e^{-\lambda \times 8} \quad (1)$$

where A_{2001} is the tritium concentration of groundwater in 2001; A_{2009} is the calculated tritium concentration of groundwater in 2009; λ is the radioactive constant ($5.58 \times 10^{-2} \text{ a}^{-1}$).

METHODS

Model of well-mixed reservoir

Well-mixed reservoir model, applied by Le Gal La Salle *et al.* (2001), assumes that a complete mixing of groundwater issued from successive recharge episodes occurs within the aquifer. This model can be used in Henan Plain based on the following two reasons. One is that the shallow aquifer media consists mainly of sandy gravel, medium-coarse sand on the whole except for silt, fine sand and mild clay in a small part of study area; therefore, it is easy for the shallow groundwater to be recharged by precipitation. The other is that the shallow groundwater flows very slowly because of the small hydraulic gradient (about 1/3300 on average) in Henan Plains; so a mixing of groundwater issued from successive recharge episodes can be occurred within the aquifer.

For the model of a well-mixed reservoir with annual time steps and the radioactive decay of ^3H in solution, the annual ^3H concentration of groundwater is calculated as follows:

$$A_{gi} = (1 - R_i)A_{gi-1}e^{-\lambda} + R_iA_{oi} \quad (2)$$

Table 2. Recorded ^3H concentration of precipitation in Zhengzhou station by IAEA

Year	1986	1987	1988	1989	1990	1991
^3H (TU)	38.15	52.74	19.78	25.38	19.53	20.10

Fig. 2. Distribution of monitoring stations around Zhengzhou station.

where A_g is the ^3H concentration of groundwater; A_o is the ^3H concentration of the input water; λ is the radioactive constant ($5.58 \times 10^{-2} \text{ a}^{-1}$); i is the time by year, ranging from 0 to 56 (corresponding to the calendar year 2009–1953); R_i is the annual renewal rate. For the model, the annual recharge is firstly assumed to be proportional to the annual rainfall. Therefore, the annual renewal rate, R_i is given by the mean renewal rate, R weighted by the annual rainfall, P_i , so $R_i = RP_i/P_m$, where P_m is the annual mean rainfall.

The ^3H concentration of the input water (precipitation) A_o is 10 TU before 1953 (Wang, 1991), then

$$A_{g1953} = 10 / (\lambda / R + 1). \quad (3)$$

Reconstruction of tritium time series in precipitation

As the main recharge of shallow groundwater in the Henan Plains, precipitation is the main input source of ^3H in groundwater. According to the locations of the monitoring stations for ^3H concentration in precipitation in China sited by International Atomic Energy Agency (IAEA), the ^3H concentration in precipitation at Zhengzhou station was chosen to represent the ^3H concentration of precipitation in study area. Zhengzhou station is the only station in study area. However, since only records of ^3H concentrations of precipitation between 1986–1991 at Zhengzhou station exist (Table 2), the ^3H concentration of precipitation in other years between 1953–2009 must be reconstructed in order to calculate

Table 3. Coefficients for the interpolation equation of ^3H concentration in precipitation and correlation coefficients

Year	A_i	B_i	C_i	Correlation coeff.
1969	−2.536	10.870	60.610	0.957
1970	−1.755	9.235	9.082	0.876
1971	−3.211	7.880	230.395	0.812
1972	−2.129	4.430	172.023	0.933
1973	−0.387	5.532	−94.117	0.961
1974	−1.127	5.303	9.739	0.949
1975	−1.088	4.522	22.044	0.942
1976	−1.085	3.428	49.895	0.954

Table 4. The reconstructed ^3H concentration time series in precipitation from 1953 to 2009

Year	^3H (TU)	Year	^3H (TU)
1953	24.07	1982	36.75
1954	182.53	1983	32.33
1955	33.13	1984	30.18
1956	119.56	1985	29.51
1957	79.64	1986	38.15*
1958	364.12	1987	52.74*
1959	281.92	1988	19.78*
1960	102.84	1989	25.38*
1961	145.91	1990	19.53*
1962	609.88	1991	20.10*
1963	1766.69	1992	20.81
1964	937.57	1993	19.27
1965	479.96	1994	20.37
1966	348.14	1995	17.85
1967	204.69	1996	18.13
1968	139.60	1997	21.63
1969	149.80	1998	20.11
1970	130.27	1999	19.10
1971	139.06	2000	21.75
1972	83.87	2001	18.93
1973	53.97	2002	17.06
1974	65.78	2003	16.92
1975	55.40	2004	17.12
1976	45.60	2005	19.17
1977	52.90	2006	15.79
1978	52.72	2007	18.97
1979	38.17	2008	8.21
1980	38.11	2009	7.00
1981	41.48		

*Observed data at Zhengzhou station.

the renewal rate of groundwater.

Interpolation is a kind of multivariate statistical analysis method which can effectively analyze particular spatial distribution and variation trends of an attribute data (Shaw, 1977; Sun *et al.*, 2003). In this study, taking the position of monitoring stations and the recorded ^3H concentrations in precipitation into account, we used inter-

Fig. 3. ^3H concentration time series of precipitation at Ottawa station.

polution (Eq. (4)) to calculate the ^3H concentrations in precipitation from 1969 to 1976 at Zhengzhou station.

$$T_i(x, y) = A_i x + B_i y + C_i \quad (4)$$

where x and y are longitude and latitude of the monitoring station respectively; $T_i(x, y)$ is the ^3H concentration of precipitation in No. i year at the point of (x, y) ; A_i , B_i and C_i are the coefficients in the interpolation equation.

First, we calculated the coefficients: A_i , B_i and C_i in interpolation equation for ^3H concentration of precipitation between 1969~1976 at Zhengzhou station by the Least square method. In the calculation, the longitude and latitude coordinates and the ^3H concentrations in precipitation from 1969 to 1976 are those at Pohang station, Tokyo station, Irkutsk station, Novosibirsk station, Yakutsk station and Hong Kong station. Those monitoring stations are distributed around Zhengzhou station (Fig. 2). The correlation coefficient test of significance showed that the correlativity was high between observed data and calculated data for every year (Table 3).

Substituting A_i , B_i and C_i (Table 3) and the coordination by longitude and latitude of Zhengzhou station into Eq. (4) produced the ^3H concentration of precipitation between 1969~1976 at Zhengzhou station (shown in Table 4).

The ^3H concentrations in precipitation for 1953~1968, 1977~1985 and 1992~2007 at Zhengzhou station (Table 4) were reconstructed on linear regression equations (Eq. (5)) by data at Ottawa where ^3H was measured in precipitation for long period from 1953 to 2007 (Fig. 3). The ^3H concentrations in precipitation (including recorded and reconstructed between 1969~1976) at Zhengzhou station had a distinct relativity with that at Ottawa station (the correlation coefficient was 0.97).

$$y = 0.6064x + 8.0747, \quad R = 0.97 \quad (5)$$

Fig. 4. Curve of renewal rate vs. ^3H in groundwater.

where x is the ^3H concentration of precipitation at Ottawa station; y is that at Zhengzhou station; R is correlation coefficient.

The range of ^3H concentration time series for precipitation in Ottawa station is from 1953 to 2007 with a lack of data from 2008~2009. So the linear regression equation (Eq. (6)) between ^3H concentration and time at Zhengzhou station (the correlation coefficient was 0.86) was constructed to calculate the ^3H concentration of precipitation by the least square method at Zhengzhou station for years 2008~2009 (Table 4).

$$y = -1.2109t + 2439.7, \quad R = 0.86 \quad (6)$$

where t is the time; y is the ^3H concentration of precipitation at Zhengzhou station; R is correlation coefficient.

Calculation of renewal rate

For a series of given R values (for example $R = 1 \sim 100$),

Table 5. Renewal rate of the groundwater

Sample No.	Renewal rate (%/a)
GL2	4.91
GL3	4.91
GL4	4.91
GL5	4.91
GL7	4.91
GL8	0.78
GL9	0.01
GL11	4.91
GL12	4.91
GL13	4.91
GL14	4.91
GL15	4.91
GL16	4.91
GL18	4.91
GL19	4.91
GL20	4.91
A02	1.39
A04	0.02
B01	0.51
B02	0.85
B03	3.07
B04	4.91
B10	4.91
B14	4.91
B21	4.91
B23	0.36
B27	0.40
B28	0.07

a series of A_g can be calculated accordingly by Eq. (2) and Eq. (3). Then the $A_g \sim R$ curve of the study area was made to calculate the groundwater renewal rate on the basis of the ^3H concentration of groundwater samples.

According to the above method, the relation curves of ^3H output concentration (A_g) and mean renewal rate of shallow groundwater in 2009 in the study area were constructed following the model of a well-mixed reservoir (Fig. 4).

The groundwater annual renewal rate (shown in Table 5) of every sample can be determined by the curve of Fig. 4 according to the ^3H concentration of each groundwater sample.

RESULTS AND DISCUSSION

^3H concentration in shallow groundwater

The natural background activity of ^3H in precipitation prior to 1952 was about 10 TU (Wang, 1991). As a result of radioactive decay, groundwater derived from precipitation that fell before the onset of atmospheric testing of nuclear weapons in 1953 (pre-bomb) would have contained not more than 0.45 TU in 2009. In the study area, the ^3H concentrations mostly ranged from 2.91 to

Fig. 5. The isogram of groundwater renewal rate.

40.30 TU in the shallow groundwater with a mean ^3H concentration of 19.13 TU which was much greater than 0.45 TU. The range of ^3H concentration in groundwater suggested that the shallow groundwater was recharged from modern precipitation after 1953 in study area. Three exceptionally low values (less than 1 TU) were measured in three samples: GL9, A04 and B28 located in Zhengyang, Xinxiang and Puyang respectively. According to Ministry of Water Resources Division, Nanjing Hydraulic Research Institute (2004), Xinxiang city had the highest rates of both groundwater pumping ($27.22 \times 10^8 \text{ m}^3/\text{a}$) and module of groundwater yield ($33 \times 10^4 \text{ m}^3/\text{km}^2 \cdot \text{a}$) in 2003 in Henan Plains. And according to Zhang *et al.* (2001), land subsidence was very severe in Puyang because of over pumping of groundwater, the accumulated ground subsidence had been 41~57 mm from 1997 to 2001, with the area of land subsidence at about 140 Km^2 in 1997. Therefore, those low values of ^3H concentration in groundwater could indicate that the wells contained deep old groundwater recharge from before 1953 resulting from over-pumping of shallow groundwater.

Estimates of groundwater renewal rate

The calculated renewal rate of shallow groundwater in Henan Plains varies between 0.01~4.91%, with a mean

of about 3.42% (Table 5). This relatively large range of renewal rate in shallow groundwater is probably due to the variability of the hydraulic conductivity and the recharge of deep groundwater with low ^3H concentration under the influence of over pumping in some low renewal rate locations.

In this paper, the interpolation in space is used to construct the isogram of renewal rate, based on calculated renewal rate for 28 samples in order to understand the spatial distribution law of the renewal rate in shallow groundwater (Fig. 5).

On the whole, the renewal rate in shallow groundwater decreases from the pediments of Taihang Mountain, Funiu Mountain and Songqi Mountain to the eastern plain in the direction of groundwater flow. Groundwaters in the pediments of mountains and near the Yellow River are characterized by high renewal rates of more than 4%/a. In the east and northeast along Nanle, Puyang city and Minquan, Zhecheng and Luyi, groundwater is characterized by low renewal rates of less than 2%/a. Between high and low renewal rates groundwater, the renewal rate is from 2%/a to 4%/a. The above distribution law of renewal rate in shallow groundwater just shows a good match with the hydrogeology settings in the study area. The high renewal rates of groundwater are just distributed mostly in the recharge areas of groundwater while low renewal rates are distributed in the discharge areas. In pediments of mountains in the west, groundwater receives lateral recharge from mountain areas while groundwater in the two laterals of the Yellow River receives lineal recharge from Yellow River. Otherwise, the main lithology of the aquifer media is sand and sandy gravel which are coarse enough and easy to be recharged by precipitation in the pediments of Taihang Mountain, Funiu Mountain and Songqi Mountain. In addition, the above areas also have a relatively high hydraulic gradient of 1/1000~1/1500 and high hydraulic conductivity of 700~1000 m^2/d . In the discharge areas with low renewal rates, the main lithology of the aquifer media is sandy loam, clay, and medium-fine sand with a low hydraulic conductivity of 50~300 m^2/d and low hydraulic gradient of 1/4000~1/6000 (The NO. 1 Hydrogeological Party in Bureau of Geology and Mineral Resources in Henan Province, 1987).

It is evident from the isogram of renewal rate (Fig. 5) that the groundwater in Xinxiang, Zhengyang and Xixian is also located in the recharge area, but it is characterized with extremely low renewal rate of less than 1%/a. This suggests that the groundwater has a weak renewability influenced by over pumping of groundwater as discussed above.

In addition, the areas with high groundwater renewal rates (greater than 4.0%/a) and low groundwater renewal rates (smaller than 2%/a) are 41% and 23% of the whole subsystem area respectively in the northern groundwater

system. Moreover, the areas with the high and low groundwater renewal rates are 41% and 19% of the subsystem area respectively in the central groundwater system. The areas with the high and low groundwater renewal rates are 71% and 9% of the subsystem area respectively in the southern groundwater system. The above evidence indicates that the groundwater renewability in southern groundwater system is stronger than that in the other two systems. This results from the following two reasons. One is that the annual precipitation has a decrease trend from south to north in Henan Plains. It is 1000~1300 mm in the south of Huaihe River which is about two times of that in the north areas of Henan Plains. The other is that the groundwater hydraulic gradient (1/2500) in the southern groundwater system is greater on average than that in the other two systems. The hydraulic gradients are 1/3500 and 1/4000 in the northern and central groundwater systems respectively. Therefore, the shallow groundwater in the southern groundwater system can not only get more recharge from precipitation but also have a relatively greater flow rates than groundwater in the other two groundwater systems. These all contribute to the greater renewability of shallow groundwater in the southern groundwater system.

Renewal rate as an indicator on groundwater pumping

Considering that the groundwater is characterized as higher renewal rate (more than 4%/a) in the pediments of Taihang Mountain, Songqi Mountain, Funiu Mountain, Dabie Mountain and Weishi, Zhoukou, Xiangcheng, Luohe, Runan, Pingyu, the volume of groundwater pumping can be increased. Especially before rainy periods (from July to September), enough space in aquifer could be provided by increasing pumping so as to accept more recharge of precipitation in rainy periods. The groundwater renewal rate is more than 4%/a near the Yellow River. Therefore, we can also make good use of the characteristics of ground suspended river of the Yellow River to induce much more river water by increasing the volume of groundwater pumping near the Yellow River. By doing so, not only more recharge from the Yellow River is induced, but also the highly turbid waters of the Yellow River may be refined by flowing through the aquifer. In addition, groundwater pumping should be reduced because of weak renewability (the renewal rate less than 2%/a) in Nanle, Puyang, Shangqiu, Luyi in order not to cause some environmental problems such as regional groundwater level decline, and land subsidence. Groundwater pumping should be restricted in Fanxian, Xinxiang Yongcheng, Zhengyang, and Xixian in order to avoid the deterioration of land subsidence, because the renewal rates of groundwater are less than 1%/a. In other places not mentioned above in study area, groundwater pumping can be kept at current extraction rates.

CONCLUSIONS

Tritium concentrations in groundwater and reconstructed ^3H concentration time series from 1953~2009 in precipitation can be used to determine the annual groundwater renewal rate. It has been demonstrated, based on the spatial distribution of groundwater renewal rate, that groundwater in the study area are classified into four groups. They are high renewal rate (more than 4%/a) areas, moderate renewal rate (2~4%/a) areas, low renewal rate (1~2%/a) areas and extremely low renewal rate (less than 1%/a) areas. The high renewal rate groundwater is located mainly in the recharge areas, such as the pediments of mountains and nearby the Yellow River. This group highlights the significant roles of lateral runoff from the pediment of mountains and lineal recharge of Yellow River water to two lateral ground waters. The middle renewal rate groundwater is mainly in the runoff areas. Low renewal rates of groundwater are located mainly in the discharge areas, such as Nanle, Puyang in the northern groundwater subsystem, east of Zhecheng, Luyi in the middle groundwater subsystem. Extremely low renewal rates of groundwater are located in Fanxian, Xinxiang, Yongcheng, Zhengyang and Xixian. This group highlights the influence of groundwater over-pumping. The distribution of groundwater renewal rate matches well with the hydrogeological settings in the study area.

The distribution of groundwater renewal rate indicates that pumping rate can be increased along the Yellow River and in the pediments of Taihang Mountain, Songqi Mountain, Funiu Mountain, Dabie Mountain and Weishi, Zhoukou, Xiangcheng, Luohe, Runan, Pingyu; while the groundwater pumping should be reduced in Nanle, Puyang, east of Zhecheng, Luyi, and be restricted in Fanxian, Xinxiang, Yongcheng, Zhengyang and Xixian. Other places not mentioned above in study area can keep the current pumping rate.

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