Effects of irrigation on groundwater recharge under deep buried depth condition

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Abstract. In this paper the dynamic changes of the groundwater levels and soil moisture were studied to realize the groundwater recharge. The irrigation recharge coefficient was calculated based on groundwater level and soil moisture and verified by the numerical model with MODFLOW. The average groundwater recharge coefficient was 0.0875 the whole year. With the deep groundwater level in Jinghuiqu Irrigation district the results from changes of groundwater showed that the time of recharge was longer. The soil moisture had a similar trend with the groundwater level. Overexploitation without recharge of groundwater led the decreasing of groundwater level. The research may provide as a reference to increasing the surface water irrigation for development of groundwater ecological environment of the district.

1. Introduction

Human activities in irrigation districts, especially in large semi-arid irrigation districts, frequently affected the circulation and transformation of surface water and groundwater [1]. As a typical drainage well irrigation district in Northwest China, the of groundwater exploitation and recharge in the Jinghuiqu Irrigation District in Shaanxi province are always unbalanced, where the groundwater level declines with the increasing demand of water [2; 3]. The water-saving irrigation programme in Jinghuiqu Irrigation District also led to the less recharge to groundwater [4]. Therefore, the study on effects of irrigation on groundwater recharge under great buried condition and the numerical simulation of groundwater is of great importance to irrigation and groundwater sustainable use. In recent years, there were many researches on the influence of irrigation on groundwater recharge. The influence of irrigation on groundwater was analyzed under the condition of different groundwater depths at Hanwang test station in Xuzhou, China [5], and in the process of irrigation the smaller buried depth of the groundwater is, the greater amount of the groundwater recharge of irrigation it is. The irrigation under different groundwater depths also has a significant effect on wheat growth [6]. The seepage of irrigation water is an important source of groundwater in the irrigated farm region of arid area in Northwest China [7], where the amplitude of the seepage recharge coefficient of irrigated water was changeable from 0.3 to 0.9 according to the depth of groundwater level, and the infiltration rate increases with the decrease of groundwater level depth. Considering the various factors such as irrigation return flow, climate, water flow rate and management level, the utilization coefficient of irrigation water was calculated by dynamic space model to confirm groundwater recharge which contributed by irrigation [8]. In the Suibin Irrigation District of Heilongjiang Province, China, the groundwater level raised 2 m a year due to the surface water irrigation [9].

Generally in the above studies, the irrigation had an effect on groundwater level when the depth of groundwater was small. However, this paper aims to present the relationship between groundwater recharge and irrigation in deep groundwater irrigation area.

2. Methodology

2.1. Study area

The test region of Jinghuiqu Irrigation District of Shaanxi Province is located in Jingyang County, in Shaanxi Province, China. In the study area there is a branch canal in the north and a sub-main canal in the south whose total irrigation area is 483.58 hm^2.17 pumping wells were selected to irrigate and monitor the groundwater level (Fig. 1).

The study area has a temperate semi-arid climate. The mean annual precipitation is 502 mm with uneven distribution of years, and the mean annual evaporation is about 1125 mm. The soil texture of the test region is mainly composed of loam. The thickness of phreatic aquifer is 10-20 m, and the aquifer medium has coarse particles and strong permeability.

2.2. Research method

In order to realize the recharge of groundwater, the groundwater levels and soil moisture were semimonthly monitored. The soil moisture was measured by weighting. The coefficient of recharge from irrigation was respectively calculated based on groundwater levels and soil moisture. Then the results were verified and corrected by the groundwater flow numerical model with the Visual MODFLOW software developed by the US Geological Survey [10].

3. Changes of groundwater level and soil moisture

3.1. Changes of groundwater level

As shown in the Fig. 2 the groundwater buried depth (average values of the wells in study area) from Oct., 2013 to Sep., 2014 decreased 3 times and increased twice. From Oct. 10, 2013 to Dec. 10, 2013 the groundwater level had approximately risen by 1.0 m due to the first winter irrigation. The overall trend of the groundwater level from Dec. 20, 2013 to Apr. 10, 2014 declined about 1.9 m, the main factors were groundwater exploitation, evaporation and crops consumption. With the continuous precipitation and previous irrigation the groundwater level had increased about 1.1 m from Apr. 10 to May. 10. From Jun. 10 to Aug. 1 the groundwater level had a sharp decrease by about 3.4 m, this is mainly due to the great groundwater exploitation, high evaporation and water consumption of crops. After that the groundwater level had modestly recovered because of the hysteresis of irrigation infiltration.

3.2. Changes of soil moisture

As shown in the Fig. 3 the soil moisture was keeping at 10 %~30 % within 100 cm, and the change was similar to the variation of the groundwater level. The soil moisture in surface layer (0- 20 cm) was easier to be influenced by the precipitation, evaporation and irrigation., the changes of soil moisture in deeper soil layer was lagging behind and comparatively lower than in surface layer. However, the variation trend of soil moisture in different soil layer was similar. The soil moisture was

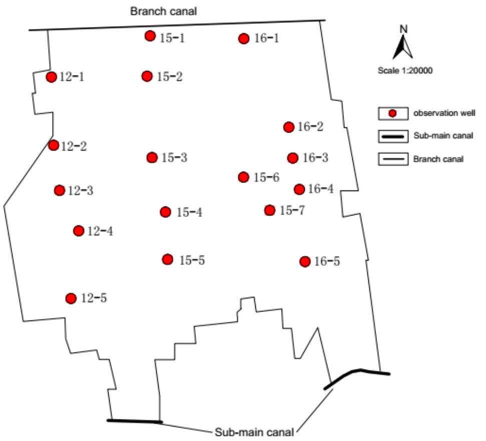

Figure 1. Study area

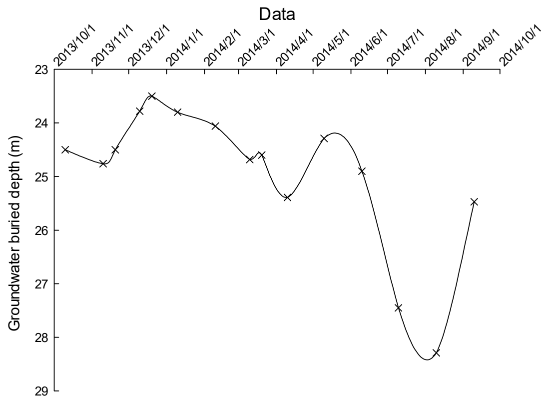

Figure 2. Groundwater buried depth dynamic change

increasing from Oct. 2013 to Nov. 2013 because of the first winter irrigation, and then decreasing with the fluctuations from Dec. 2013 to Jun. 2014. From Jul. 2014 to Oct. 2014 the soil moisture was increased by the influence of precipitation and irrigation.

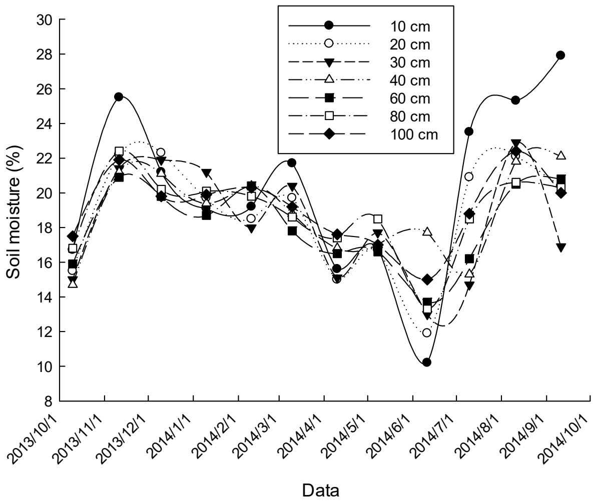

Figure 3. Soil moisture dynamic change

4. Calculation of irrigation recharge coefficient

4.1. Calculation of irrigation recharge coefficient based on the changes of groundwater depth

In order to calculate the irrigation recharge coefficient of groundwater the irrigation water amount, the soil moisture and the groundwater depth were analyzed in detail. Under water balance principle [11] the irrigation recharge coefficient based on the groundwater levels can be calculated as Eq. (1):

$$\beta = \frac{\mu \times \Delta h \times F}{I_g} \tag{1}$$

where β is the irrigation recharge coefficient; μ is specific yield, the empirical value of 0.07; Δh is amplitudes of groundwater level fluctuation; F is the test zone area (m2); I_g is the net irrigation water amount (m^3).

By the four times irrigation data including the first winter irrigation, the second winter irrigation, the spring irrigation and the summer irrigation, the irrigation recharge coefficient of groundwater was calculated in views of the precipitation and well irrigation. The total irrigation water is 448272 m^3 with the canal irrigation 265524 m^3 and the well irrigation 182748 m^3 during the first winter irrigation, and the irrigation recharge coefficient is 0.0870; the total irrigation water is 104309 m^3 with the canal irrigation 98746 m^3 and the well irrigation 5563 m^3 during the second winter irrigation, and the irrigation recharge coefficient is 0.0868; the total irrigation water is 777402 m^3 with the canal irrigation 337410 m^3 and the well irrigation 439992 m^3 during the spring irrigation, and the irrigation recharge coefficient is 0.0874; the total irrigation water is 573460 m^3 with the canal irrigation 405556 m^3 and the well irrigation 167904 m^3 during the summer irrigation, and the irrigation recharge coefficient is 0.0873. Taking the average of four values as the final result is 0.0871.

4.2. Calculation of irrigation recharge coefficient based on the soil moisture

The groundwater recharge of irrigation is generated through soil moisture movement in the vadose zone [12]. Assuming that there is no horizontal water exchange, the soil water balance equation is as follow [13]:

$$I + EG - ET - R_s - R_i = \Delta W \tag{2}$$

Where I is the total irrigation water; EG is the recharge of vadose zone from groundwater evaporation; ET is the evaporation of vadose zone; R_s is the surface runoff; R_i is the recharge from irrigation water infiltration; ΔW is the change of soil moisture.

There is generally no surface runoff in the test area due to the flat land and earth dam. Because of the deep groundwater level (>20 m) the recharge of soil moisture from groundwater evaporation is almost 0. For soil with high-permeability, the irrigation water soon infiltrates into the limit evaporation depth below, so the evaporation of vadose zone can be ignored. In the Eq. (2), the total irrigation water is a function of time, the other parameters are functions of time (t) and groundwater depth (Δ). Therefore, the Eq. (2) can be expressed as follow:

$$R_i(\Delta, t) = I(t) - W_2(\Delta, t_2) + W_1(\Delta, t_1) \tag{3}$$

Where t_2 is the time after the water irrigation; t_1 is the time before irrigation.

According to the measured soil moisture combined with the formula (3), the amount of recharge of groundwater from irrigation water infiltration is calculated in test area with the first winter irrigation data, the second winter irrigation data, spring irrigation data and summer irrigation data. The recharge coefficients of groundwater were 0.0869, 0.0864, 0.0874 and 0.0873, respectively. The average value is 0.0870.

Table 1. Calculation results of irrigation recharge coefficient

Irrigation period	Irrigation water (m^3)		Precipitation(m^3)	Change amount of groundwater (m^3)	Change amount of soil moisture (m^3)	Irrigation infiltration coefficient	
	Canal irrigation	Well irrigation				By groundwater level	By soil moisture
1st winter irrigation	265524	127332	45940	330676	145360	0.0870	0.0869
2nd winter irrigation	98746	5563	9332	138093	216287	0.0868	0.0864
Spring irrigation	337410	439992	29015	227585	14905	0.0874	0.0874
Summer irrigation	405556	167904	192949	284955	109634	0.0873	0.0873

5. Groundwater flow modelling

5.1. Generalization of the model

The aquifer system was the phreatic aquifer composed of Quaternary Holocene, Pleistocene medium-coarse sand and sand-gravel layer, which could be generalized single aquifer. The phreatic aquifer thickness was 10-20 m. The aquifer was with the coarse grain and strong penetration.

Influenced by water from the branch canal and main canal, groundwater level in the area had some spatial variability, the groundwater flow was unsteady. Therefore, the model was generalized as homogeneous and transversely isotropic three-dimensional unsteady flow.

As river boundaries (RIV) the branch canal and main canal were located in the north and south of the study area, respectively. The test area is flat with the lateral recharge from western upstream aquifers and discharged to the east. Therefore, the west and east boundaries were set as the general head boundaries (GHB).

5.2. The determination of initial parameters

According to the hydrogeological generalized model of the study area, the mathematical model could be expressed as homogeneous and isotropic three-dimensional unsteady groundwater flow model.
According to the characteristic of flow field, structure characteristics, hydraulic characteristics and boundary conditions, the discretization method of the finite difference was used to make the mesh generation. The study area was divided into 80 rows and 106 columns with the densified grids around the wells. Except the invalid cells there were 6155 effective cells in the model. The starting time and terminal time of the model was on Oct. 1, 2013 and Dec. 30, 2014 for 450 days. The data from Oct. 1, 2013 to Dec. 30, 2014 were for model identification, from Oct. 1, 2014 to Dec. 30, 2014 for model validation. A stress period was for 30 days with 10 days as a time step.

Based on previous pumping test and hydrogeology parameters second terrace of Jing River of Jinghuiqu Irrigation District, the permeability coefficient K is 25 m/d, the specific yield μ is 0.068.
The initial water level of groundwater was identified as observed water level on Oct., 2013.

5.3. Source term of simulation period

Unconfined aquifer mainly accepts precipitation infiltration recharge, canal seepage recharge, irrigation water infiltration and groundwater exploitation recharge, etc. Due to the relatively great buried depth of groundwater and the equal inflow and outflow, the evaporation and the lateral discharge were ignored, the discharge mainly included groundwater exploitation. The recharge intensity of groundwater was calculated as Table 2.

Table 2. Groundwater recharge rate of irrigation period in a year

Month	Rainfall infiltration recharge(mm)	Canals leakage recharge(mm)	Irrigation infiltration recharge(mm)	Groundwater exploitation recharge(mm)
Oct(2013)	1.05	5.20	3.09	3.08
Nov(2013)	2.02	2.85	1.69	0.21
Dec(2013)	0.00	2.12	1.26	0.10
Jan(2014)	0.01	0.88	0.52	0.19
Feb(2014)	0.98	5.48	3.25	0.46
Mar(2014)	0.14	4.76	2.82	0.71
Apr(2014)	4.23	0.00	0.00	0.19
May(2014)	2.70	0.00	0.00	0.27
Jun(2014)	1.65	9.96	5.90	2.65
Jul(2014)	4.97	2.35	1.39	3.76
Aug(2014)	10.92	0.00	0.00	4.39
Sep(2014)	16.64	0.00	0.00	0.26
Recharge rate(mm/a)	45.31	33.60	19.92	16.27

5.4. Identification and validation of the model

The initial groundwater level was determined as the values on Oct. 10, 2013. The aquifer parameters were calibrated based on the groundwater level, precipitation, irrigation water and groundwater exploitation, etc. The simulation period was 360 days, and terminal groundwater level was fitted with the observed water level on Sep. 2014.

The terminal groundwater level of model identification was simulated by MODFLOW, and the simulation errors were calculated in Table 3. As seen from the table 3 the relative errors of fitting were all less than 1%, and the groundwater level fitting result of more than 80% wells was less than 0.5%, which provided a better fit.

Table 3. Simulation errors of the groundwater flow model

Well number	Observed water level (m)	Simulated water level (m)	Absolute error (m)	Relative error (%)
12-1	397.09	396.36	-0.73	0.18
12-2	396.88	397.37	0.49	0.12
12-3	397.31	397.38	0.07	0.02
12-4	396.03	397.39	1.36	0.34
12-5	396.33	397.63	1.30	0.33
15-1	394.76	396.76	2.00	0.51
15-2	395.76	398.76	3.00	0.76
15-3	397.99	396.99	-1.00	0.25
15-4	396.18	394.98	-1.20	0.30
15-5	398.86	398.36	-0.50	0.13
15-6	400.3	400.8	0.50	0.12
15-7	401.52	402.52	1.00	0.25
16-1	392.2	393.7	1.50	0.38
16-2	392.36	393.16	0.80	0.20
16-3	394.18	394.48	0.30	0.08
16-4	395.56	395.36	-0.20	0.05
16-5	396.43	397.35	0.92	0.23

5.5. Model verification

In order to further validate the established numerical simulation model and the coefficient of recharge from irrigation obtained in the model during identification period， the numerical model was verified with the meteorological and dynamic observation data from Oct. 2014 to Dec. 2014 (Fig. 4). The fitting results showed that the errors of fitting more than 80% were less than 0.5, the calculated water level was observed to be in good consistency with the actual values, which indicated that the prediction model was reasonable with the correct aquifer generalization, hydrogeological parameters and boundary conditions generalization. Therefore, the irrigation recharge coefficient was finally determined to be 0.0875 by correction in the model.

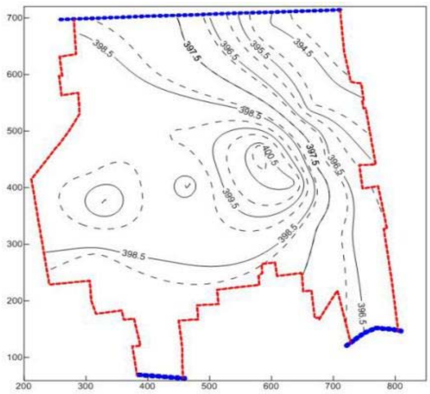

Figure 4. Simulated result of groundwater level in verification period

6. Conclusions

In this paper the changes of groundwater levels and soil moisture were studied in Jinghuiqu Irrigation District the whole year. The time of groundwater recharge from irrigation was different with different water levels, the deeper groundwater level is, and the longer recharge time is. During the fast growing period of crops the irrigation water mostly consumed by crops. The soil moisture had the similar trend with the groundwater level, whose recharge was ahead of the groundwater.

The coefficient of recharge from irrigation was affected by irrigation, water consumption of crops, precipitation and evaporation. The coefficients of recharge from irrigation calculated by groundwater level and soil moisture had similar results. By model validation of MODFLOW, the result was reliable which was ultimately determined the irrigation recharge coefficient as 0.0875. The over exploitation of groundwater led to the decreasing of groundwater levels, and to prevent this situation arise the irrigation of surface water should be appropriately increased in order to increase the recharge of groundwater.

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