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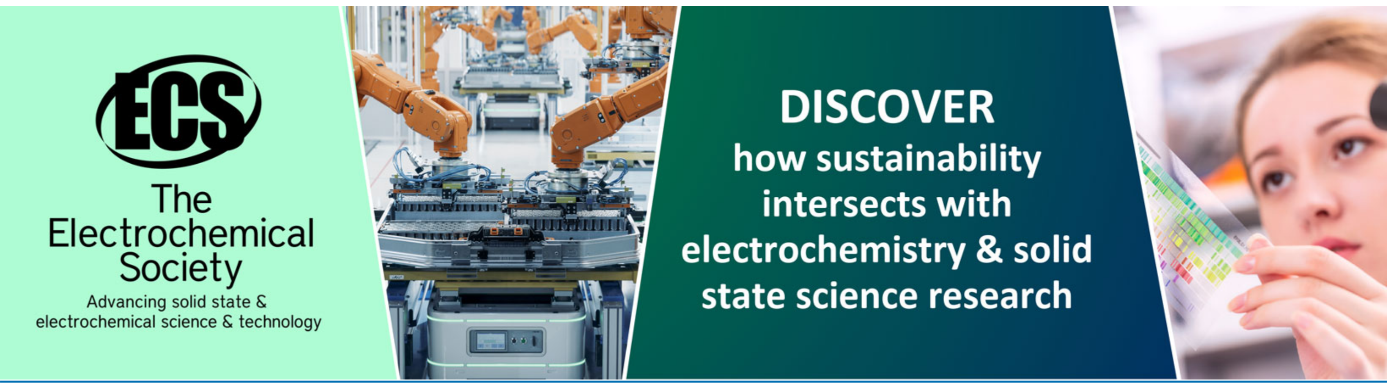

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Effect of managed aquifer recharge on drawdown cone in plain area of Linqing City, China

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Abstract. The Yellow River flood plain in northern of China, affected by the low precipitation and the large amount of well irrigation, is facing the ecological problems of serious groundwater overdraft and expansion of drawdown cone area. Taking Linqing city of Shandong Province as an experimental area, the technical scheme and parameters of Open channel-Underground perforated pipe-Shaft groundwater recharge system were designed by combining theoretical calculation and field test, and the effect of recharge was observed and analyzed. The results show that this project has increased groundwater amount of 52310.82m^3 by water diversion for 7 days compaired with existing canal system, accounting for 60.7% of the total groundwater recharge. This recharge technology can effectively increase the amount of groundwater replenishment and raise the groundwater table as well as scope of groundwater recharge. It has the advantages of no energy consumption, no land occupation, rechargeability, and drainage. Thus, it is of great significance to the recovery of groundwater drawdown cone area and the comprehensive treatment of drought and waterlogging.

1. Introduction

Linqing City is located in the Yellow River floodplain in northwestern of Shandong and is the most downstream of the Yellow River Diversion Irrigation Area. The average annual precipitation for many years is 530 mm, the total amount of water resources is 121.87 million m^3, the amount of shallow groundwater resources is 92.31 million m^3, and the amount of surface water resources is 29.56 million m^3. Groundwater extraction and water diversion from the Yellow River are the main water supply sources locally, which account for 53% and 40.2% of the total water supply respectively, accounting for 93.2% in total. Agricultural water consumption is still the largest, accounting for 81.03% of total water consumption.

As Linqing City is located in the downstream of the Yellow River Irrigation District, the diversion amount of Yellow River water is restricted. The current shallow groundwater overexploitation reaches 50.24 million m^3. The average groundwater depth has dropped from 4 m in the 1970s to about 10m now. The area of groundwater drawdown cone is about 30 km^2 and it seriously affected the local social production and ecological environment. In areas where groundwater resources cannot fully meet the needs of irrigation water, one of the solutions is to conduct managed aquifer recharge (MAR), that is, to recharge the aquifer on purposes[1-3]. But MAR projects also have some problems[4]. Although the surface seepage method has the advantages of large infiltration area and small investments, the recharge effects are not significant within a certain period of time. Well water injection has a good replenishment infiltration effect, but it is prone to clog, which will affect the overall recharge efficiencies. Although there are many studies on the clogging problem, it has not been fundamentally solved. In view of the current groundwater drawdown cone problems in the study area and the characteristics of containing fine-particle clay suspended solids in the downstream of Yellow River, an Open channel-Underground perforated pipe-Shaft system was proposed to increase the groundwater supply amount for agricultural irrigation and alleviate the geological problems caused by pumping. Meanwhile, field tests were conducted to verify the feasibility and recharge effect of this project.

2. Study area

The study area is located in Wanzhuang Village, Linqing City, which is located in the Yellow River floodplain of northwest Shandong and the downstream reaches of the Yellow River Irrigation District, belonging to the Chezhuanggou Basin. The study area is a well-canal combined irrigation area. In addition, Chezhuang ditch is connected with the three main canals of the Yellow River diversion, which has certain conditions for irrigation and replenishment of water from the Yellow River. At present, agricultural irrigation in the project area is seriously over-exploiting groundwater, and the groundwater depth reaches 17m, forming a large drawdown cone. The type of groundwater in the area is mainly loose layer pore water, shallow groundwater is fresh water, and deep groundwater is salt water. The shallow aquifer is the main water supply aquifer with the 60m thickness. The main replenishment method of shallow groundwater in this area is precipitation, followed by irrigation from the Yellow River, canal leakage replenishment and irrigation return water replenishment. The direction of groundwater runoff is basically the same as the slope of the terrain, flowing slowly from southwest to northeast, with a hydraulic gradient of 2/10000～4/10000. Artificial extraction is the main method of groundwater discharge in this area. According to the double-ring permeability experiment, the hydraulic conductivity coefficient K is 2.8 m/d, the effective porosity is 0.5, and the specific yield is 0.065. Combined with the results of geotechnical experiment and field double-loop permeability test, it can be concluded that the soil in this area is silt soil with good permeability and no continuous impervious layer. Therefore, the stratum and lithology in this area have good recharge conditions.

3. Open channel-Underground perforated pipe-Shaft System

3.1. System engineering design

The recharge control area of this project is 5.4 hm^2 and the bottom area of the filter tank is $4m^2$. Three underground water filtration pipe systems are arranged with a pipe distance of 90 m and a pipe length of 200m. The cross-sectional is shown in Figure 1. Each system consists of a filter tank, an underground perforated pipe and a shift (Figure 1 a, b, c). The inside of the filter tank is composed of geotextile, filter material, coarse sand cushion and storage tank; the underground perforated pipe is a plastic blind ditch with an inner diameter of 30cm and a pipe slope of 1/500; the depth of the shaft is 10m.

The open channel with water is a stable supply source and the water level provides pressure head, which can drive the filtration and recharge process without additional energy. Most of the engineering systems are buried under the ground, occupying less land. In addition, the underground perforated pipe has a certain slope, which can make the water leak into the ground through the pipe quickly, leading to high recharge efficiency. 20 cm thick gravel layers are laid outside the filter pipe to prevent sediment into the seepage areas so that slow down the clog of the filter pipe. Through manual pumping from shaft, huge water level difference between the shaft and open channel is formed, achieving the regular dredging by flowing water. Therefore, this project is both ecological and efficient during operation.

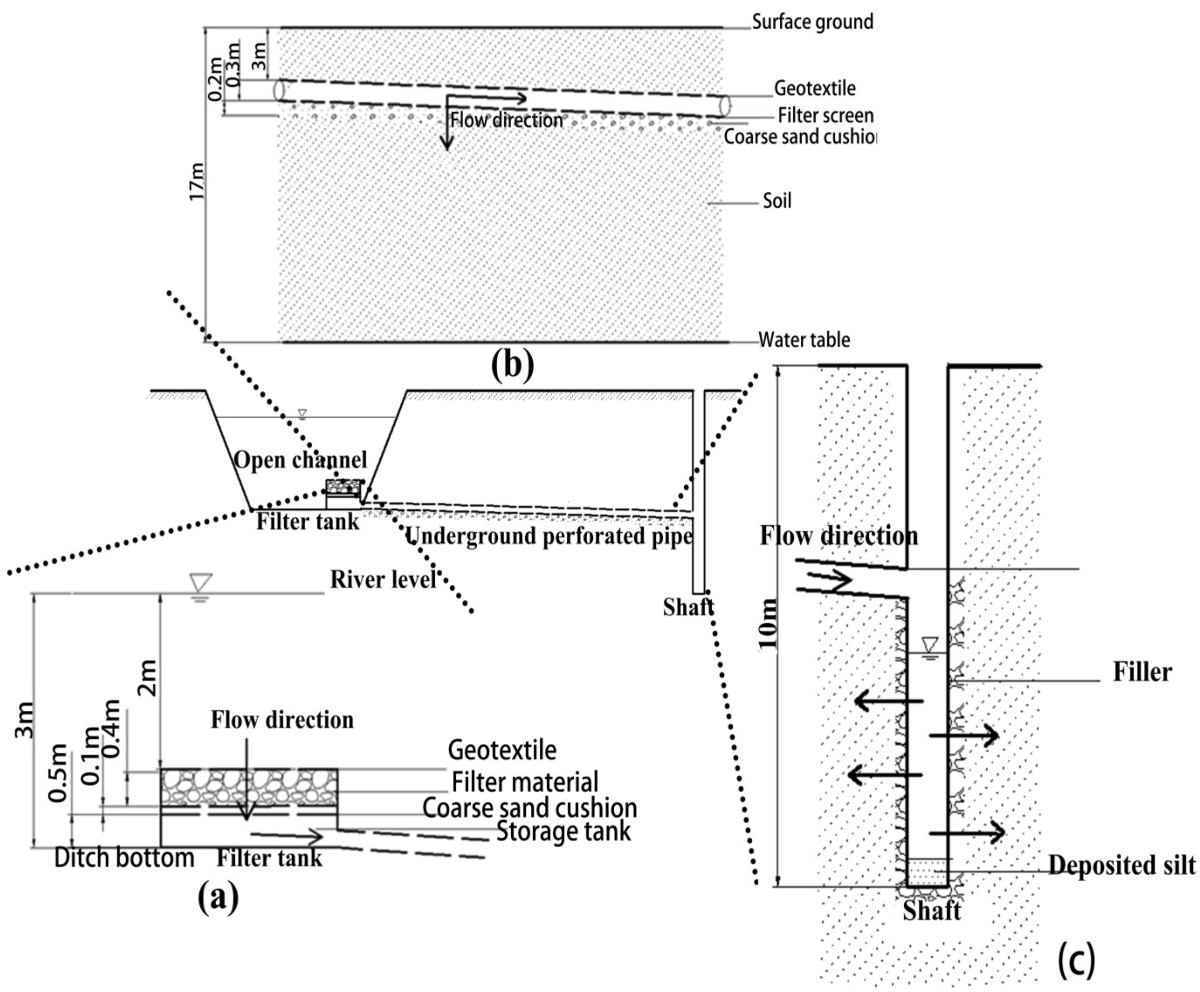

Figure 1. The cross section of project (a filter tank; b underground perforated pipe; c shaft).

3.2. Hydraulic parameter design

The leakage process of the recharge water is divided into three stages. The first stage is the unstable free leakage stage. The leakage water gradually moves from the bottom soil layer of the channel to the groundwater surface. The second stage is the stable free leakage, the leakage amount will not change with groundwater level rising. The third stage is the jacking leakage stage. After the mound of water rises to the bottom of the pipe, the leakage flow will gradually decrease as the nearby groundwater level rises.

3.2.1. Leakage of filter pipe

3.2.1.1.Unstable free leakage stage

The the wetting peak migration speed, vertical penetration time and unstable free leakage under the distance from the bottoem of the tube to the wet front are calculated by formula [5-6], see Table 1.

Table 1. Calculation results of unstable free leakage stage of pipe

L_f (m)	V (m/d)	T (d)	Q (m^3/d)
2	7.7	0.07	1078
4	5.25	0.26	735
6	4.44	0.46	621.6
8	4.03	0.69	564.2

10	3.79	0.94	530.6
12	3.62	1.21	506.8
13	3.55	1.35	497

The amount of leakage at this stage is:

$$Q_1 = \sum_{i=1}^{7} (d + D) lv_i t_i = 4282.14m^3 , \tag{1}$$

where D is the thickness of the filter material, and d is the pipe diameter.

3.2.1.2.Stable free leakage stage

The first duration of unstable free leakage was 1.35 d, and the water levels relative to pipe bottom were calculated in the remaining 5.65d during the diversion period. If the calculated values exceeded 13m, then the rising values of water levels at the same time were calculated at different distances from the pipeline. If the average rising values of the water level exceeded 13m at some points, the jacking leakage stage had been reached, otherwise it was still in the stable free leakage stage.

According to the formula of stable free leakage stage and the theoretical formula of channel free leakage calculation[7], it can be calculated that this stage lasted for 4.86d. Then the leakage at this stage is $Q_2 = qlt = 9875.52m^3$.

3.2.1.3.Jacking leakage stage

When the unstable free leakage lasts for 1.35 days and the stable free leakage lasts for 4.86 days, the remaining 0.79 days is the stage of jacking leakage. Within the study area with a radius of 200 m, the boundary water table rises 1.84m at the end of stable free leakage stage, and the third stage leakage is calculated based on the groundwater dynamic formula:

$$q = K\frac{h_1^2 - h_2^2}{2l} \tag{2}$$

During the entire leakage process, the leakage of a pipe is the superposition of the three leakage stages that is

$$Q_{pipe} = Q_1 + Q_2 + Q_3 = 17436.94m^3 . \tag{3}$$

3.2.2. Leakage of river

Similarly, the leakage of the river section was divided into three stages, and the calculation methods are the same as above. It can be seen that the total amount of leakage in the river during the diversion period is

$$Q_{river} = Q_1 + Q_2 + Q_3 = 3753.78 + 35789.6 + 28180 = 67723.38\mathrm{m}^3 . \tag{4}$$

From the above calculation results, it can be seen that the total leakage of the three pipelines is 52310.82 m^3. The river leakage on the side of the buried pipe is 33861.69 m^3, which is half of the river leakage. During the 7 day water diversion processes, the total groundwater recharge was 86172.51 m^3, increasing the groundwater recharge and accounting for 60.7% of the total groundwater recharge.

3.3. Verification of engineering design plan

The scheme and parameters obtained by theoretical calculations were verified by field recharge tests and tracer tests.

3.3.1. Field recharge test

The Yellow River diversion and recharging experiments in the study area were run for 7 days. The electromagnetic flowmeter installed through the pre-filtration device showed that the infiltration capacity of one filter pipe was 21975 m^3 and the total infiltration capacity was 65925 m^3, which was basically consistent with the infiltration capacity of the superposition of the calculation results. Due to the possible clog of the filter pipe in the actual operation processes, there was a certain deviation between the two infiltration capacities.

3.3.2. Field tracer test

In this tracer test, the tracer (Rhodamine B) was placed in the pre-filtration device of the recharge project and the receiving point was in the shaft. The concentration change curve in the shaft is shown in Figure 2.

The peak velocity was used to characterize the average velocity of water flow in underground perforated pipes. The length of the underground perforated pipe is 200 m and the tracer concentration at the receiving point reaches the peak value for 80 minutes. Therefore, it can be calculated that the average flow velocity of the water flow in the underground perforated pipe is 150 m/h, which is close to 169.2 m/h of the blind ditch water delivery capacity calculated by Manning formula. Through the verification of the above two field tests, it can be seen that this recharge project plays an important role in replenishing groundwater and alleviating the development of drawdown cone.

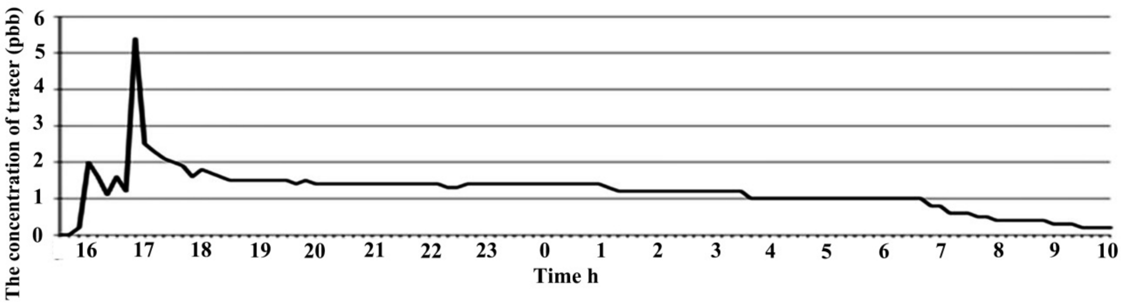

Figure 2. The curve of tracer concentration.

4. Conclusion

Aiming at the problems of groundwater over-exploitation in the Yellow River flood plain area and the spread of drawdown cone, an Open channel-Underground perforated pipe-shaft recharge system is proposed. The construction parameters of the recharge system are preliminarily designed through theoretical calculations. The recharge control area is 5.4 hm^2; the bottom area of the filter tank is 4 m^2; the distance between the three underground perforated pipes is 90 m; the pipe length is 200m; the inner diameter is 30cm; the pipe slope is 1/500 and the shaft depth is 10 m. The recharge capacity was calculated quantitatively. The total leakage of the three pipelines is 52310.82 m^3, accounting for 60.7% of the total groundwater recharge. The results of field recharge test and field tracer test show that the theoretical calculation results are accurate. This system increases the groundwater recharge amount through the leakage of underground perforated pipes and expands the scope of groundwater recharge. The use of three anti-clogging measures of filter tank, underground perforated pipe and shaft can prevent physical blockage of suspended solids and ensure the service life of the recharge project. It is of great significance to replenish groundwater and alleviate the development of drawdown cone. This engineering design has a great promotion value in the plain funnel area.

Acknowledgement

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