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Original Research Paper

Effect of Precipitation Variation on Groundwater Buried Depth in Well-irrigated Areas

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ABSTRACT

Precipitation variation affects the groundwater system in well-irrigated areas. First, it directly affects groundwater recharge and buried depth. Second, it affects crop irrigation, and consequently, also affects buried depth. The direct and indirect effects of precipitation on groundwater buried depth must be elucidated to achieve stable production and promote the rational use and protection of groundwater resources. In this study, Shijiazhuang Plain is selected as the subject. Variations in groundwater buried depth and exploitation are first analysed. Then, the relationship between groundwater buried depth and precipitation, as well as that between precipitation and groundwater irrigation intensity per area, are investigated. Finally, the effect of precipitation on groundwater buried depth is revealed. Results show that the annual mean groundwater buried depth does not change with increasing or decreasing precipitation. As an important source of groundwater recharge, precipitation directly affects groundwater buried depth during a year and affects groundwater buried depth differently during wet, normal, and dry years. Precipitation is an important supplier of crop water requirements. Thus, increased precipitation reduces irrigation intensity requirement per cultivation area. By contrast, irrigation intensity increases with decreasing precipitation. That is, precipitation can affect groundwater buried depth by affecting irrigation intensity per cultivation area, and this effect can be obviously observed from the varying characteristics of irrigation intensity both in different decades as well as in wet, normal, and dry years.

INTRODUCTION

Agriculture consumes a huge amount of water. In well-irrigated areas, precipitation, soil water, and irrigation are major sources of water for agricultural requirements (Jat 2009). Precipitation has significantly changed since the 1950s. On one hand, it affects groundwater buried depth as a major source of groundwater; therefore, precipitation variation directly influences groundwater buried depth (Packialakshmi et al. 2011, Li et al. 2012). On the other hand, as a main water source for agricultural water requirements, precipitation indirectly affects groundwater buried depth. In general, as precipitation increases, the effective precipitation that crops can use also increases, and consequently, the need for human-assisted irrigation decreases. Conversely, as precipitation is reduced, the need to use groundwater sources increases to satisfy agricultural water requirements. That is, precipitation can affect groundwater buried depth by influencing the use of groundwater for irrigation in agriculture.

Therefore, understanding the effects of precipitation variation, on groundwater buried depth is crucial (Zhang et al. 1999, Jia & Liu 2002). Precipitation can support the development of food production security programs. It can also be used as an index to determine the trends in groundwater evolution. Moreover, it can improve sustainable development between groundwater resources and agriculture (Javi et al. 2014).

Shijiazhuang Plain is an important grain production area in Hebei Province and even in China. Irrigation has developed early in this area, and the level of agricultural production is currently high. Grain production in Shijiazhuang Plain has already risen to national ranks, particularly those of wheat and maize (Zhang et al. 2009). As surface water resources continue to decrease sharply, groundwater has become the principal source of irrigation water for agriculture. Agricultural irrigation accounts for over 80% of total ground water exploitation. Therefore, this research determines the effect of precipitation variation on groundwater buried depth in grain cultivation areas by conducting a case study on Shijiazhuang Plain.

MATERIALS AND METHODS

Study area: Shijiazhuang Plain is located at longitude 114°17’-115°22’, latitude 37°02’-38°03’ (Fig. 1). It belongs to a piedmont alluvial plain and is part of the Hutuo River drainage basin, with Taihang Mountain in the west and central Hebei Plain in the east. Shijiazhuang Plain comprises

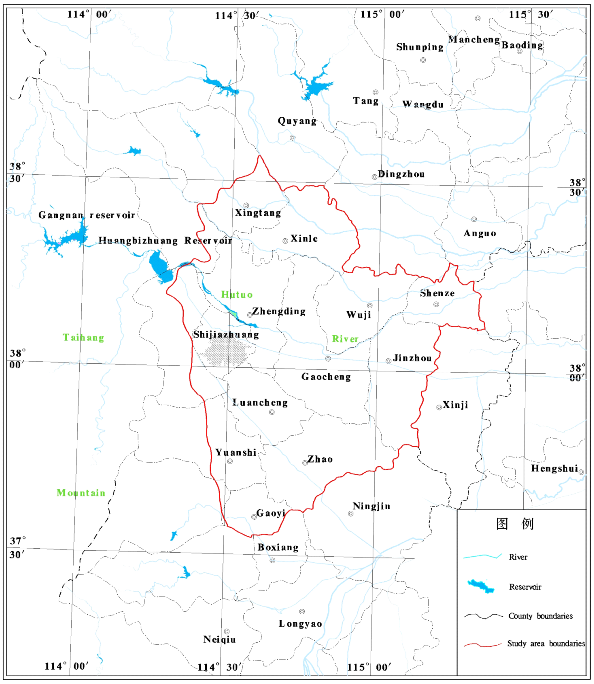

Fig. 1. Location of the study site.

one city (Shijiazhuang City) and eleven counties (Zhengding, Luancheng, Xingtang, Gaoyi, Shenze, Wuji, Yuanshi, Zhao, Gaocheng, Jinzhou, and Xinle). The area measures 6,673 km^2 and its population is 4,787,000, of which, the agricultural population is 3,852,000.

Shijiazhuang Plain has a continental monsoon climate, with an annual average temperature of 12.8°C and an annual average precipitation of 496.6 mm. The precipitation in the area is unevenly distributed and is concentrated between June and September. Precipitation during this period accounts for 70%-80% of the total precipitation in the area. Evaporation from water surface is strong, and average evaporation reaches 1,992 mm (Li & Xu 1986).

The plain is located in the piedmont alluvial zone of Taihang Mountain; thus, the main type of groundwater is phreatic, which is confined locally (Zhang et al. 2006). The main source of groundwater recharge is the infiltration of precipitation and surface water bodies. However, the runoff in the lower reaches of Hutuo River has been significantly reduced with the completion of Gangnan Reservoir and Huangbizhuang Reservoir in the upper reaches of this river. Since 1980, the river is dry nearly all year round. Consequently, groundwater recharge from the infiltration of surface water sharply decreased, and precipitation became the most important groundwater recharge source (Liu et al. 2004). Artificial exploitation and evaporation constitute a main groundwater discharge. However, the groundwater buried depth has continuously increased as a result of excessive ground water exploitation. Meanwhile, evaporation consumption has been reduced, and exploitation has become the major drainage cause.

DATA SOURCES AND METHODS

Data on precipitation were provided by the Hebei Province Meteorological Bureau. Data on groundwater exploitation and buried depth were obtained from the Water Resources Bulletin in Hebei Province and the Groundwater Dynamics Yearbook in Hebei Province. Data on wheat and maize cultivation areas were procured from the Shijiazhuang Rural Statistical Yearbook.

To analyse the relationship between groundwater exploitation and agricultural cultivation areas, effective precipitation should be calculated. This study mainly used the following empirical formula to calculate effective precipitation (Dastane 1974, Kowalczyk 2008).

$$P_e = \alpha * P \quad ...(1)$$

Where, P_e is the effective precipitation (mm), P is the quantity of precipitation (mm), and α is the coefficient of effective precipitation used (Table 1).

Four types of water supply can satisfy crop water consumption: precipitation (the part that crops can use), soil water content, artificial water supply (irrigation), and capillary water (Zhang et al. 2006, Wang et al. 2015).

Groundwater capillary water supply can be disregarded because of the large groundwater buried depth in Shijiazhuang Plain. Consequently, precipitation, soil water content, and irrigation become the major sources of crop water requirements. In general, increased precipitation means a high amount of water available for use by crops and high soil water content. Thus, irrigation requirement is small. Besides its direct effect on groundwater buried depth as a major groundwater recharge supply, precipitation can also indirectly affect groundwater buried depth by influencing groundwater exploitation for agricultural irrigation. That is, precipitation has an indirect effect on groundwater.

Over the past 50 years, cultivation areas of high-water-

Table 1. Precipitation and the corresponding coefficient of effective precipitation used for crops.

Precipitation (mm)	< 5	5-30	30-50	50-100	100-150	> 150
Coefficient of effective utilization	0	0.85	0.80	0.70	0.58	0.48

consumption crops, mainly wheat and maize, have continuously changed. Such change has influenced groundwater exploitation for agriculture. To study the influence of effective precipitation variation on groundwater buried depth, we must distinguish between the functions of variation in wheat and maize cultivation areas on groundwater exploitation. Therefore, groundwater exploitation intensity is used in this research.

Groundwater exploitation intensity is the ratio of groundwater exploitation for agriculture to the total wheat and maize cultivation areas, and its unit is million m^3 per hectare. This ratio is calculated by using the following formula:

$$I = E / S \qquad ...(2)$$

Where I is the groundwater exploitation intensity (in 10^4 m^3/ha); E is the groundwater exploitation from agriculture (in 10^8 m^3); and S is the cultivation area of high-consumption crops, mainly wheat and maize in Shijiazhuang Plain (in 10^4 ha).

RESULTS AND DISCUSSION

Variation in precipitation, groundwater exploitation and buried depth: The average precipitation in Shijiazhuang Plain is 496.6 mm. In the 1950s and 1960s, the average precipitation was 552.0 mm and 525.1 mm, respectively. Mean precipitation was lowest in the 1980s, i.e., approximately 440.4 mm. It increased in the 1990s, i.e., 496.1 mm, and from 2000 to 2008, i.e., 503.6 mm. Therefore, average precipitation decreased before the 1980s and then subsequently increased afterward. However, precipitation was still smaller than that in the 1950s and 1960s.

Groundwater buried depth was between 2 m and 6 m from 1953 to 1969. Groundwater level increased or decreased (Fig. 2). The average groundwater exploitation was 9.88×10^8 m^3, but it increased from 3.59×10^8 m^3 in 1954 to 17.60×10^8 m^3 in 1969. Accordingly, groundwater buried depth increased from 2.27 m to 5.56 m, and groundwater level dropped by an average of 0.15 m per year.

Groundwater buried depth was between 5 m and 9 m from 1970 to 1979. In wet years (i.e., 1976 and 1977), groundwater level still increased. Groundwater exploitation continuously increased from 23.81×10^8 m^3 in 1978 to 28.83×10^8 m^3 in 1979, with an average exploitation of 22.62×10^8 m^3. Groundwater level decreased by an average of 0.37 m per year.

Groundwater buried depth was between 10 m and 30 m after 1980, but it increased more obviously, i.e., approximately 0.83 m per year on average. Groundwater level rose except in special wet years (i.e., 1990 and 1996). In other

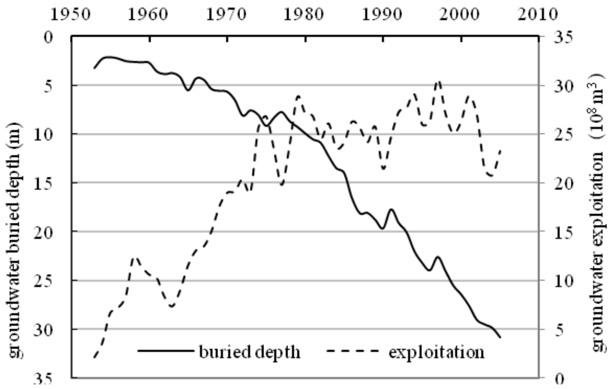

Fig. 2: Dynamic curve of groundwater exploitation and buried depth.

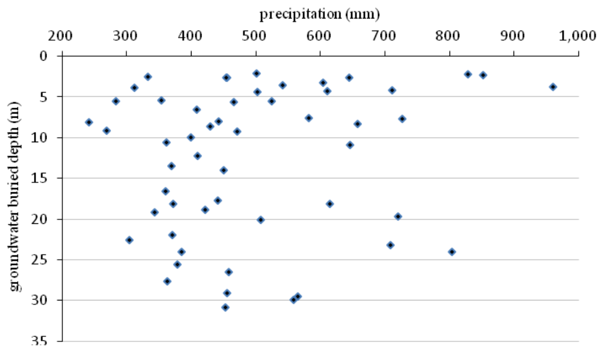

Fig. 3: Distribution of precipitation and groundwater buried depth.

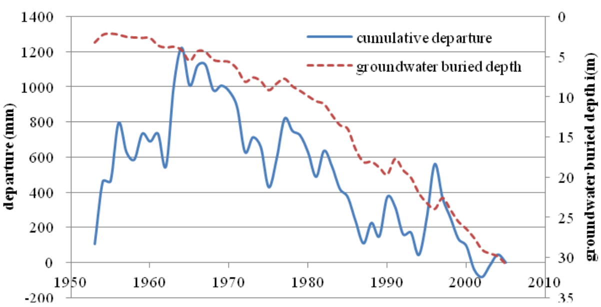

Fig. 4. Cumulative departures from mean annual rainfall and groundwater buried depth.

wet years (i.e., 1992 and 1995), groundwater level continued to decline, although the decrease was more gradual. Between 2000 and 2005, groundwater exploitation was reduced. Mean exploitation was recorded at 24.66×10^8 m^3, which was smaller than 26.57×10^8 m^3 in the 1990s. However, groundwater level still obviously dropped at a rate of 0.74 m per year.

Annual direct effect of precipitation variation on groundwater buried depth: The relationship between precipitation and groundwater buried depth is shown in Fig. 3.

Table 2: Variation condition of groundwater table in wet and dry years.

Wet years	1954	1966	1976	1977	1991	1997
Variation in groundwater table this year (m)	+ 0.95	+ 1.2	+ 0.82	+ 0.6	+ 1.95	+ 1.37
Dry years	1957	1965	1968	1972	1975	1986/1987
Variation in groundwater table this year (m)	- 0.27	- 1.34	- 0.96	- 1.59	- 1.12	- 2.57/- 1.56
Variation in the preceding year (m)	- 0.13	- 0.42	- 0.11	- 0.86	- 0.47	- 0.48
Variation in the succeeding year (m)	- 0.08	+ 1.2	- 0.18	+ 0.53	+ 0.82	+ 0.03

"+" indicates groundwater level rising. "-"indicates groundwater level declining.

Table 3: Variation in effective precipitation and agricultural exploitation intensity in different periods.

Different periods	1956 - 1959	1960 - 1969	1970 - 1979	1980 - 1989	1990 - 1999	2000 - 2005
Effective precipitation (mm)	285.54	272.65	250.63	257.35	277.36	284.76
Variation range (%)	-	- 4.51	- 8.08	+ 2.68	+ 7.78	+ 2.67
Groundwater exploitation intensity (104 m^3/hm^2)	0.43	0.51	0.60	0.53	0.50	0.53
Variation range (%)	-	+ 19.27	+ 18.05	- 11.34	- 5.04	+ 4.25

"+" indicates increasing variation. "-" indicates decreasing variation.

Table 4: Variation in agricultural groundwater exploitation intensity in wet and dry years (unit: 10^4 m^3/hm^2).

Wet years	1963/1964	1976/1977	1982	1988	1990	1995/1996
Exploitation intensity this year	0.43	0.48	0.55	0.46	0.38	0.50
Exploitation intensity in the preceding year	0.51	0.56	0.60	0.49	0.48	0.57
Exploitation intensity in the succeeding year	0.57	0.73	0.59	0.48	0.46	0.59
Dry years	1972	1986/1987	1992	1994	1997	2001
Exploitation intensity this year	0.63	0.51	0.53	0.57	0.59	0.63
Exploitation intensity in the preceding year	0.56	0.51	0.46	0.53	0.51	0.54
Exploitation intensity in the succeeding year	0.51	0.49	0.53	0.50	0.50	0.60

In general, groundwater buried depth did not change with precipitation. However, there is a close relationship between cumulative rainfall departure and groundwater buried depth (Fig. 4).

Groundwater levels have been generally decreasing with some fluctuation since 1954, following a similar pattern to the cumulative precipitation departure curve, especially from middle of 1960s to 2005. Groundwater level slowly decreased from 1957 to 1960, and sharply dropped down from 1961 with some fluctuation. Groundwater levels show an upturn within one to two years. The groundwater levels from the middle of 1960 to 2005 continue to reflect changes in cumulative precipitation, but remained more level than the cumulative precipitation departure. This may be due to the pumping increase in the plain with agriculture, population and economy developments.

It is also possible that the recent history of water levels is related to a decline in recharge. This would mean that the timing of precipitation and some other combination of climate factors influenced recharge quantity, independent of total precipitation.

In addition, precipitation did obviously affect ground water level in wet and dry years. In wet years, groundwater level increased or decreased more slowly than in normal years. By contrast, groundwater decreased more rapidly in dry years (Table 2). For example, in two consecutive wet years (1976 and 1977), groundwater level increased by 0.82 m and 0.60 m, respectively. In the dry year of 1975, groundwater level declined by 1.12 m, whereas it declined by 0.47 m in 1974 and rose by 0.86 m in 1976. Obviously, the rate of groundwater decrease was higher in the dry year than in the preceding and succeeding years.

Direct effect of precipitation variation on groundwater buried depth during a year: The trend in groundwater change is the same every year in Shijiazhuang Plain. The highest water level is recorded in March, but it obviously

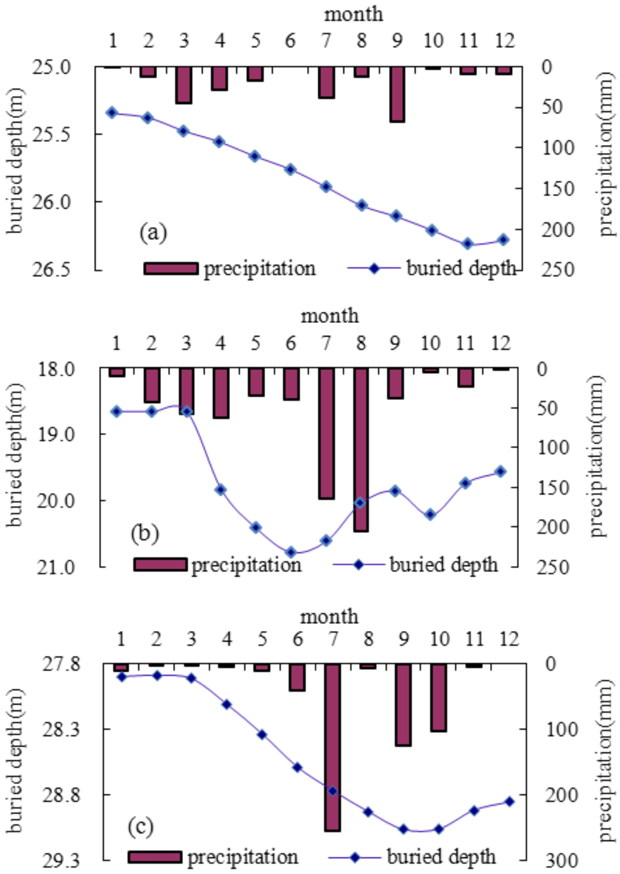

Fig. 5: Monthly variation in groundwater buried depth in wet, normal, and dry years.

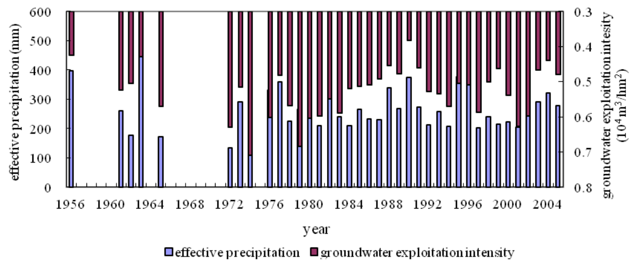

Fig. 6: Variation in effective precipitation and groundwater exploitation intensity.

declines afterward. The lowest water level is recorded in July, and then it increases afterward. The changes in groundwater level over a year in wet, normal, and dry years are shown in Fig. 5.

The manner by which groundwater level changes over a year in wet, normal, and dry years varies. Precipitation is more in wet years than in other years. When the rainy season in Shijiazhuang Plain begins in June during a wet year, precipitation increases, and groundwater can be recharged; consequently, the groundwater level obviously increases. Groundwater level increases after June, which is sooner than that in other years. In normal years, groundwater is recharged less from precipitation infiltration than in wet years. Thus, the range of groundwater level increase is relatively small. In addition, groundwater level increases at a later period. Groundwater recharge from precipitation infiltration is smallest in dry years. Groundwater buried depth is too large, such that a small precipitation may make groundwater unable to recharge. Therefore, groundwater level increases very late or do not increase at all.

Indirect effect of precipitation variation on groundwater buried depth in different decades: The relationship between effective precipitation and groundwater exploitation intensity is shown in Fig. 6. In general, when effective precipitation is large, groundwater exploitation intensity is small. By contrast, when effective precipitation decreases, groundwater exploitation intensity correspondingly increases.

The relationship between effective precipitation and groundwater exploitation intensity is shown in Fig. 6. In general, when effective precipitation is large, groundwater exploitation intensity is small. By contrast, when effective precipitation decreases, groundwater exploitation intensity correspondingly increases.

Table 3 gives the variation in effective precipitation and groundwater exploitation intensity in different periods. The smallest effective precipitation and largest groundwater exploitation intensity were recorded in the 1970s. Effective precipitation in the 1960s was 14% less than that in the 1950s, and groundwater exploitation intensity increased by 19.27%. In the 1970s, effective precipitation was 250.63 mm, which was 8.08% lower than that in the 1960s. Correspondingly, agricultural groundwater exploitation intensity increased by 18.05% from the 1960s to the 1970s, with 0.51 million m^3 per hectare and 0.60 million m^3 per hectare in the 1960s and the 1970s, respectively. Effective precipitation was 2.68% higher than that in the 1970s, and agricultural groundwater exploitation intensity was reduced by 11.34%. In the 1990s, effective precipitation was 277.36 mm, which was 7.78% higher than that in the 1980s. Meanwhile, agricultural groundwater exploitation intensity decreased from 0.53 million m^3 per hectare in the 1990s to 0.50 million m^3 per hectare in the 1980s, i.e., a decrease of approximately 5.04%. After 2000, both effective precipitation and agricultural groundwater exploitation intensity were more than those in the 1990s. This result may be related to the increasing degree of human intervention. For example, vegetable and fruit cultivation areas significantly increased after 2000 and consumed more groundwater resources than before. However, we cannot separate this portion from groundwater exploitation for agriculture, which makes groundwater exploitation intensity larger after 2000 than that in the 1990s.

Indirect effect of precipitation variation on groundwater buried depth in wet, normal, and dry years: A close relationship exists between precipitation and groundwater exploitation intensity for agriculture. In wet and dry years, groundwater exploitation intensity obviously changes with precipitation (Table 4). Intensity is smaller in wet years than those in the preceding and succeeding years. By contrast, it is bigger in dry years than those in the preceding and succeeding years. This finding indicates that when precipitation is large, groundwater exploitation intensity for agriculture is small, and vice versa. For example, in two consecutive wet years (1963 and 1964), groundwater exploitation intensity was 0.43 million m^3 per hectare. This value was smaller than those in 1962 and 1965, which were 0.51 million m^3 per hectare and 0.57 million m^3 per hectare, respectively. In 1994 (a dry year), groundwater exploitation intensity was 0.57 million m^3 per hectare, which was larger than the 0.53 million m^3 per hectare in the preceding year and the 0.50 million m^3 per hectare in the succeeding year.

SUMMARY AND CONCLUSIONS

Precipitation directly affects the groundwater system, but annual groundwater buried depth does not generally change with precipitation variation.

The direct effect of precipitation on groundwater buried depth is significant during a year as well as in wet, normal, and dry years. After the rainy season, groundwater level begins to rise. The time and value of groundwater level increase are determined by precipitation quantity. In wet years, groundwater level rises or declines more slowly than in normal years. In dry years, groundwater level declines more rapidly than in normal years.

Precipitation is a major water source for crop water requirements. It can affect groundwater dynamic variation by influencing groundwater exploitation intensity. When effective precipitation for crop use increases, groundwater exploitation intensity decreases, and vice versa.

In wet and dry years, groundwater exploitation intensity significantly changes with precipitation. Groundwater exploitation intensity is smaller in wet years than those of the preceding and succeeding years. By contrast, it is bigger in dry years than those of the preceding and succeeding years.

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