ANALYSIS OF GROUNDWATER RESOURCES VULNERABILITY FROM AGRICULRAL ACTIVITIES IN A LARGE IRRIGATION DISTRICT ALONG THE YELLOW RIVER

Bin HE*, Taikan OKI*, Shinjiro KANAE*,
Benjamin RUNKLE**, Xu LIANG***,
Ayan ZENG****, Fanghua HAO****
Institute of Industrial Science, the University of Tokyo*
Department of Civil and Environmental Engineering, University of California-Berkeley **
Department of Civil and Environmental Engineering, University of Pittsburgh***
Institute of Environmental Sciences, Beijing Normal University****

***ABSTRACT*:** Groundwater forms an important source of water supply in arid and semi-arid region. Optimum conjunctive utilization of surface and groundwater resources has become extremely important to fill the gap between water demand and supply. Hetao Irrigation District (HID) is the largest irrigation district along the Yellow River and its groundwater table is shallow. The project of Water Saving Reconstruction (WSR) has been conducted for the purpose of keeping the Yellow River free from drying up. The water taken from the Yellow River is about 5.2 and 4.0 billion m^3/year before and after WSR, respectively. Thus, the gap between water demand and supply has increased manifolds due to increased agricultural activities and reduced irrigation water from the Yellow River. To satisfy the growing water demands, more groundwater has to be pumped since the water taken from the Yellow River is decreased. In this study, the hydrogeological condition and groundwater behavior will be analyzed based on long-term hydrogeological database. Then the causes of groundwater table drawdown will be discussed. Moreover, the vulnerability of groundwater in HID due to agricultural activities will be analyzed. Furthermore, the contribution of groundwater in meeting the crop water requirements varied with the water-table depth will be discussed. Finally, the importance of community management of groundwater and other attempts to regulate its use on checking over-extraction of groundwater will be discussed as solutions for sustainable development and management of groundwater resources in this arid region.

KEYWORDS: groundwater vulnerability, agriculture activities, irrigation district

1. INTRODUCTION

A clear challenge to future development and management of water resources is abating tension between human and ecosystem requirements for fresh water. Semi-arid and arid environments are particularly vulnerable to water related land-use practices and are currently threatened by rapid population and socio-economic changes. Irrigation in arid regions is always challenging because of many factors, such as low rainfall, high evapotranspiration, poor groundwater quality, poor soil condition and extreme weather condition. Irrigated agriculture faces the challenging of using less water to provide food and fiber for an expanding population. The Yellow River, the second largest river in China, is supplying water for 15% cultivation land and

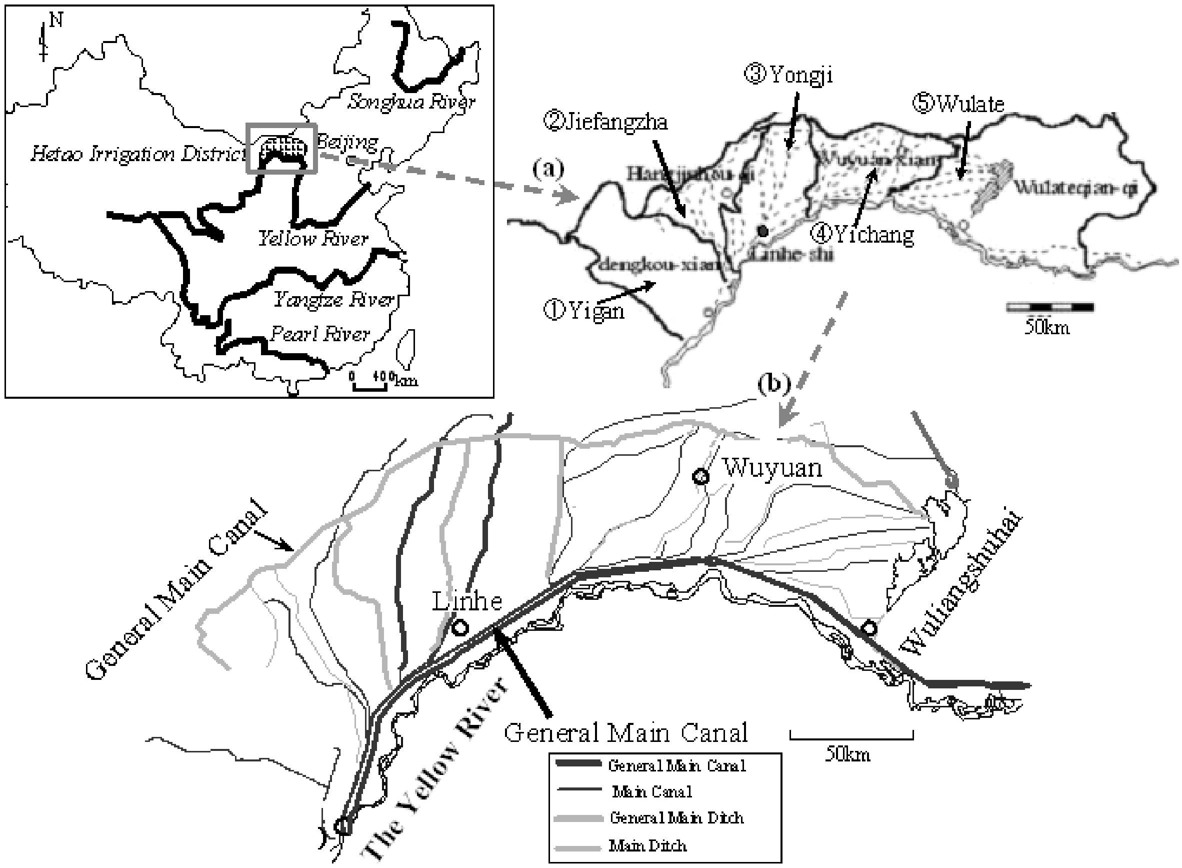

Fig. 1 Location of Hetao Irrigation District. (a) is the map of five sub-irrigation districts; (b) is the map of canal and ditch distribution.

feeding 12% population of the whole country. The Yellow River basin, which is located between 96º-119ºE and 32º- 42ºN, 1,900 km from west to east, 1,100 km from north to south and covers an area of 752,443 km^2, lies mostly in arid region. It is affected by human activities and unfavorable climate and is characterized with droughty and brittle ecological environment. Hetao Irrigation District (HID), located in the Yellow River basin (40°19′-41°18′N, 106°20′-109°19′E, 1.12 million ha with 0.57 million ha under irrigation of which 0.525 million ha are crop land, Inner Mongolia, North China), is the largest irrigation district along the Yellow River and one of the most important centers of agricultural production in China (**Fig. 1**). With the rapid regional development in the last decades, shortage of water resources has become a big concern affecting sustainable crop production (He et al., 2005, 2007).

The project of Water Saving Reconstruction (WSR) has been conducted for the purpose of keeping the Yellow River free from drying up. The water taken from the Yellow River is about 5.2 and 4.0 billion m^3/year before and after WSR, respectively (Wang, 2002). Thus, to satisfy the growing water demands, more groundwater has to be pumped since the water taken from the Yellow River is decreased. Groundwater plays an important role for agricultural, industrial, and urban water supply in the Yellow River basin, China (Chen et al., 2000; Jin, 1988; Shimada et al., 2002). Groundwater over-exploitation has caused large and continuous drawdown of groundwater levels and created serious environment problems in some cities of northern China. Some studies about safeguarding measures for groundwater resource protection have been undertaken (Yang et al., 2006; Zhang et al., 2000).

In this paper, the hydrogeological condition and groundwater behavior will be analyzed based on long-term hydrogeological database. Then the causes of groundwater table drawdown will be discussed. Moreover, the vulnerability of groundwater in HID due to agricultural activities will be analyzed. Furthermore, the contribution of groundwater in meeting the crop water requirements varied with the water-table depth will be discussed. Finally, the importance of community management of groundwater and other attempts to regulate its use on checking over-extraction of groundwater will be discussed as solutions for sustainable development and management of groundwater resources in this arid region.

2. Hydrogeological condition and groundwater behavior

2.1 Hydrogeological condition

The climate is semi-arid continent climate. The average sunshine hours are 3109.9; the lowest temperature in January is -35.1℃ while the highest temperature in July is 35.7℃. The average annual rainfall is 350.6mm and about 70% concentrated in the period of July to September. The average annual average evaporation is 1664.5mm .The average annual wind speed is 3.6m/s, annual highest wind speed is 18.6m/s. The frost-free period is 101 days. The water resources are consumed mainly for agriculture. The aquifer in the study area composed from confined and phreatic aquifer in term of the results of boring, geophysical prospecting and pumping test. The confined aquifer is underlain the phreatic aquifer. Phreatic aquifer water is used here and most pumping wells are penetrated to the bottom of phreatic aquifer. Recharges into groundwater are mainly natural replenishment from precipitation and irrigation. Discharges from aquifer are evaporation and pumping. Generally, flow through a porous medium domain is three-dimensional. However, since the geometry of aquifer is such that they are thin relative to their horizontal dimensions, the flow in the aquifer can be assumed to be everywhere essentially horizontal (aquifer-type flow) or that it may be approximated as such, neglecting vertical flow component.

2.2 Vulnerability of groundwater

In the HID, the shallow groundwater table continues declining gradually in the recent years so that more concerns are provoked on the reasonable groundwater utilization (**Fig. 2** shows an example in Jiefangzha sub-irrigatioin district (SID) in Hetao ID). In irrigation areas, hydrology-crop-pollution-erosion-controlling and water-saving are the key to improve the eco-environment in Yellow River Basin’s water saving. River flow is keeping decrease due to the increasing water demands. Increase in water intake makes increase in waste water discharge into the river, and degradation of water quality is becoming more and more serious. The leaching of nitrogen from farmland has become an important environmental issue because high nitrate concentrations in the groundwater can cause serious methemoglobinemia or blue baby syndrome. In rural area of the HID, most residents usually drink untreated groundwater. With the intensive agricultural production, the NO_3-N concentration in the groundwater can sometimes exceed 200 mg L-1. The increased incidence of nitrate contamination of the groundwater has been related to the increased use of N fertilizers and irrigation. Furthermore, in the HID, salinization is another serious problem and irrigation is essential for crop cultivation in order to increase the water availability in the soil and to leach a fraction of accumulated salts. In the irrigation area of HID, autumn flood irrigation system is being developed since 1980s to reduce salinity levels in the root zone and increase the water availability for the following spring crops (Feng et al., 2005; Meng and

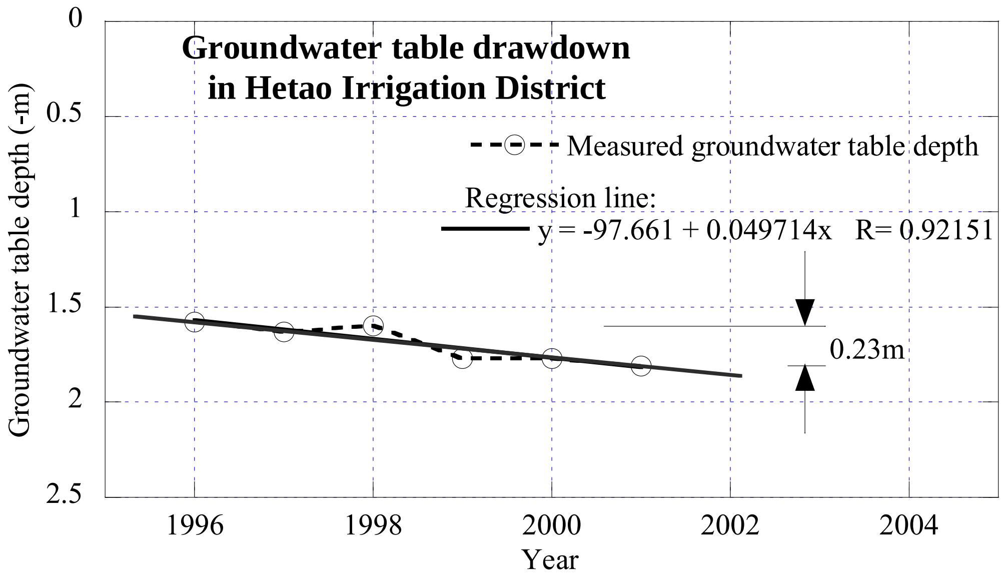

Fig. 2 Groundwater table drawdown in Jiefangzha SID of Hetao ID.

Yang, 2002; Zhang and Gao, 1987).

3. Modeling groundwater vulnerability

3.1 Method

In arid areas, the groundwater table is the most important and sensitive indicator of ecosystem response to environment flows. It is the constraining factor for riparian community restoration. All other ecological responses, such as soil water, plant growth and vegetation recovery, and any increase in biodiversity, will be based on the dynamics of the groundwater table. To understand the changes in the groundwater table is to understand the potential dynamics of the ecosystem. So assessing the changes in groundwater and using them to set management parameters become the vital issues for restoration strategies in arid regions.

Many researchers have studied about the groundwater table dynamics in the HID. Wang (2002) analyzed the changes of groundwater table before and after WSR in HID. His results showed that regional groundwater table drawdown of the HID will be 0.4 m after the WSR. However, Wang treated the whole HID as the object and the groundwater table drawdown in each SID was not considered. Meanwhile, the groundwater pumping after the WSR and supply amount from rainfall infiltration were not considered in his model. Yang (Yang et al., 2003) discussed some principles on groundwater utilization in the HID for the sustainable development of water resources in the irrigation district. It was recommended that 1100-1500 m^3/hm^2 of groundwater can be extracted annually on the basis of ‘three-recharge to sustain one-exploitation’. However, Yang did not consider the irrigation drainage volume after the WSR and the relation between groundwater table drawdown. Meanwhile, groundwater exploitation was not taken into account. Qu (Qu et al., 2003) applied a three and four-layer Artificial Neural Network (ANN) model based on long term regional groundwater, hydrological and climate data, for simulating dynamic movement of annual and monthly groundwater depth of the HID and forecasting the trend of change after reconstructing a WSR project. The average depth will decrease 0. 51m in 2010 compared with the present average depth. However, his results limited in one of the five SIDs in the HID. The trends of groundwater table changes in other SIDs are not discussed. Chen (Chen et al., 2005) analyzed the groundwater movement after the implementation of the WSR project by using the Finite Element Galerkin Method through analysis of the data in an experimental area (Shahao Canal irrigation area) on the basis of groundwater dynamics numeric simulation. Compared with the rapid calculation method by the ANN model in a larger area (Jiefang Sluice irrigation Sub-district), the result of the forecast was proved to be reliable and representative. His result showed that it can provide reference for the water environment evaluation and macro water management in the HID. However, the temporal-spatial hydro-geological database is not available or complete at some sites for the whole HID.

The schematic view of the irrigation district water cycle components is shown in **Fig. 3**. Q_{irr} is the supply amount from irrigation (m^3), Q_{dit} is the supply amount from ditch or cannel infiltration (m^3), Q_{lat} is the lateral supply amount from the area outside the HID (m^3), Q_{rain} is the supply amount from rainfall infiltration (m^3), Q_{pump} is the amount of groundwater pumping (m^3), Q_{drain} is the drainage amount (m^3), Q_{ep} is the phreatic evaporation amount (m^3). ΔH is the fluctuation of groundwater table (m).

3.2 Role of groundwater in vegetation water requirements

Vegetation may be wholly or partially dependent on groundwater. Even in riparian zones where sources of surface water are also available, the vegetation may have a high degree of groundwater dependency. The availability of groundwater may influence the type of plant growth (e.g. shrub or tree) as well as the species assemblage. Phreatophytes (plants that use groundwater) are sensitive to changes in the hydrogeological regime. This may be in the form of a water table declining at a rate faster than root growth or an alteration in the annual fluctuations of the water table. Groundwater abstraction by man or the regulation of effluent rivers may result in these changes. Vegetation affects aquifers by directly extracting groundwater from saturated strata and reducing the proportion of rainfall that is eventually recharged by interfering with the passage of precipitation from the atmosphere to the water table in recharge areas. The effects of fluctuating piezometric surfaces on vegetation communities have been studied and most work has been carried

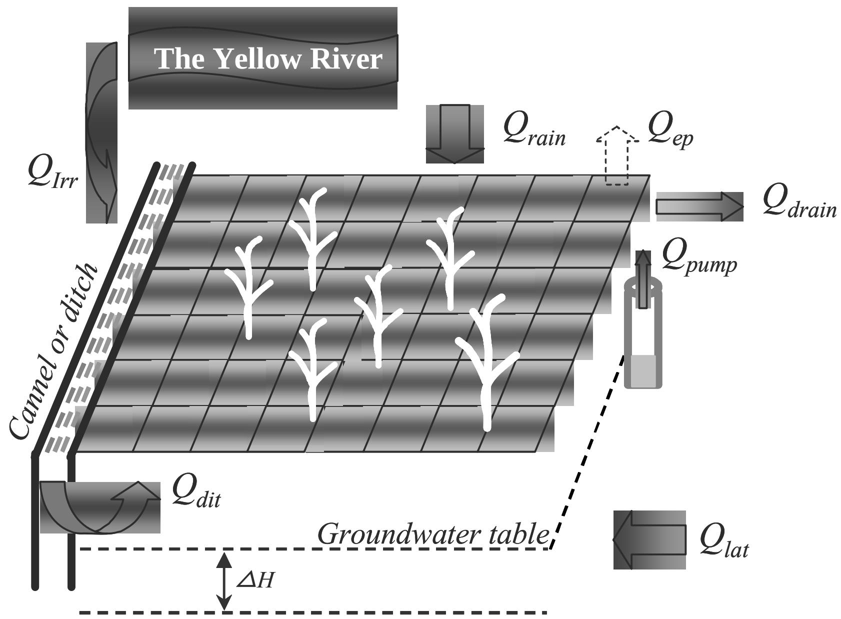

Fig. 3 Schematic view of the irrigation district water cycle components.

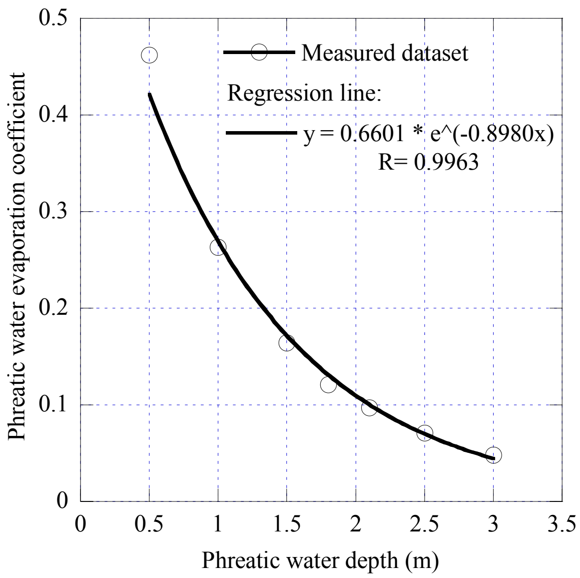

Fig. 4 Relation between phreatic water evaporation and water depth.

out in riparian zones, wetlands and areas of evaporative discharge. In Arizona, USA it was found that permanent lowering of the water table will cause a continual and quantifiable decline in height and structural complexity of Prosopis, mortality, and eventual replacement by desert scrub. In HID, groundwater has been changing extensively affected by human activities combined with desiccating climate conditions. Lower depth to groundwater table (DGT) may affect vegetation and vegetation adversely is influenced by DGT. The DGT dynamics in different stages of irrigation has been shown in Table 1. The critical DGT has been shown in Fig. 4.

3.3 Derivation of control indexes of DGT

If a soil containing excess moisture is allowed to drain without any gain or loss of moisture at the surface, it will ultimately reach a point where further drainage is reduced to negligible proportions. The moisture content profile corresponding to this state is called the field capacity profile. The critical height (h_0) can be regarded as the height above the water table within which the moisture content is influenced by the presence of the groundwater table. Crops whose roots penetrate into this zone can benefit from this moisture. The theoretical field capacity profile enables the effects of groundwater drawdown on available soil moisture to be anticipated. Pumping will cause the water table to fall, and as it does so the field capacity profile will effectively follow the phreatic surface down. The moisture content of the soil within the original critical height will decrease and, if the water table is close enough to the surface for roots to extend into this zone, the crops will experience a reduction in the available moisture (Fig. 2).

3.3.1 Capillary zone's thickness

Thickness of the capillary zone lies on water surface tension, gravity and soil physical property. Thousands upon thousands of pores in various shapes in soil are connected with each other and make up of the anfractuous capillary net system. Its thickness is mainly decided by the factors of soil porosity *e*, particle size *d*, soil sphericity *Kc*, water density *ρ*. Average thickness of the capillary zone, *h*, can be express by the following equation (Cui et al., 2005):

$$h_c = 6(1-e)\gamma_c K_c \cos\alpha / (ed\rho g) \qquad (1)$$

where γ_c is water tension coefficient, g is acceleration of gravity, α is the angle between water molecule and soil particle.

3.3.2 Thickness of the zone above capillary

Affected by molecule absorbability of soil particles and water surface tension, water above the phreatic surface is mainly in the forms of hygroscopic moisture, film moisture and suspended moisture. Moisture supporting forces are primarily absorbability between particles and water molecules, and affinity between water molecules. The thickness of the zone above capillary h_c can be expressed by the following equation (Cui et al., 2005):

Table 1 Requirement for regulating groundwater depth dynamic state in Hetao Irrigation District (Tan, 1981)

Stage of irrigation	Period	Groundwater depth (m)
Start of thawing	Early March to early April	2.0-2.4
Start of spring irrigation	End of April	2.1-2.3
End of first watering	First 10 days of May	1.2-1.5
End of Summer irrigation	Last 10 days of July	1.2-1.5
Start of winter irrigation	End of October	2.2-2.65
End of winter irrigation	Middle 10 days of November	1.3-1.5

$$h = \frac{2}{3}\beta^3 h_c \left(1/\theta_a^3 - 1/\beta^3 \right) \quad (2)$$

where β is field capacity, θ_a is the average surface soil moisture content.

3.3.3 Water table depth

The water table depth, *H*, equals to sum of the thickness of capillary and its above zone. Then, we can use the following equations to calculate the water table depth using the surface soil moisture content:

$$\begin{cases} H = \frac{2}{3}\beta^3 h_c \left(1/\theta_a^3 - 1/\beta^3 \right) + h_c & ,\theta_a < \beta \\ H = h_c \left(\frac{\beta}{\theta_a} \right)^2 & ,\theta_a \ge \beta \end{cases} \quad (3)$$

3.4 Critical DGT

Theoretically speaking, as long as the phreatic water exits, it must influence the surface soil moisture content. When the water table depth is very large, the influence of the phreatic water to the surface soil actually can be ignored. In fact, it means that the surface soil moisture content has declined to the wilting coefficient and the phreatic water has no effective meaning to the ecological water requirement, Thus, the critical DGT can be calculated by the following equation:

$$h_{\max} = \left[\frac{2}{3} \left(\frac{\beta}{\theta_{wp}} \right)^3 + \frac{1}{3} \right] \cdot h_c \quad (4)$$

where, θ_{wp} is soil wilting moisture content.

3.5 Groundwater table simulation

Fig. 3 shows a schematic view of the main components of the HID's water cycle. If detailed information is available, it is possible to describe the complete hydrological cycle using distributed hydrologic models which can simulate the spatial and temporal variation of the different components. However, these models require extensive computational resource for model set up and execution. Moreover, the topography in HID is almost horizontal flat and an almost homogeneous distribution of precipitation is observed (Wang, 2002). Furthermore, the groundwater flow is mainly the lateral water movement. Thus, it provides a possibility to analyze the water cycle in HID by using the lumped conceptual recharge (LCR) model. In this paper, we investigated a simplified method of estimating HID's water balance to quantify the components shown in **Fig. 3**.

The water balance at the HID can be described as,

$$\frac{dS}{dt} = \frac{1}{\mu}\left(Q_{irr} + Q_{dit} + Q_{lat} + Q_{rain} - Q_{pump} - Q_{drain} - Q_{ep}\right) \quad (1)$$

where, S is the water storage (m^3), dS/dt is the water storage change (m^3/year), μ is the specific yield coefficient of phreatic aquifer.

It is difficult to solve the Eq.(5) since the necessary database is not complete in the HID. Thus, the groundwater table is difficult to be solved from Eq.(5).

Let's describe $\left(Q_{irr}+Q_{dit}+Q_{lat}+Q_{rain}\right)$ as Q_{gw} which means the total groundwater recharge amount. Eq.(5) can be changed as,

$$\frac{dS}{dt}=\frac{1}{\mu}\left(Q_{gw}-Q_{pump}-Q_{drain}-Q_{ep}\right) \tag{6}$$

For a long term period (eg., one year), water storage change in the total irrigation district can be assumed as zero ($\frac{dS}{dt}=0$). In this paper, all variables are the annual average value of the HID.

$$Q_{gw}-Q_{pump}-Q_{drain}-Q_{ep}=0 \tag{7}$$

If we consider the conditions before and after WSR, Eq.(7) will be,

Before WSR,

$$Q_{gw}{}^{0}-Q_{pump}{}^{0}-Q_{drain}{}^{0}-Q_{ep}{}^{0}=0 \tag{8}$$

After WSR,

$$Q_{gw}{}^{1}-Q_{pump}{}^{1}-Q_{drain}{}^{1}-Q_{ep}{}^{1}=0 \tag{9}$$

(8) minus (9),

$$\begin{aligned}&(Q_{gw}{}^{0}-Q_{gw}{}^{1})-(Q_{pump}{}^{0}-Q_{pump}{}^{1})-\\&(Q_{drain}{}^{0}-Q_{drain}{}^{1})-(Q_{ep}{}^{0}-Q_{ep}{}^{1})=0\end{aligned} \tag{10}$$

We can define

$$\Delta Q_{gw}=(Q_{gw}{}^{0}-Q_{gw}{}^{1})$$

$$\Delta Q_{pump}=(Q_{pump}{}^{0}-Q_{pump}{}^{1})$$

$$\Delta Q_{drain}=(Q_{drain}{}^{0}-Q_{drain}{}^{1})$$

$$\Delta Q_{ep}=(Q_{ep}{}^{0}-Q_{ep}{}^{1})$$

Then,

$$\Delta Q_{gw}-\Delta Q_{pump}-\Delta Q_{drain}=\Delta Q_{ep} \tag{11}$$

If we define $\Delta Q=\Delta Q_{gw}-\Delta Q_{pump}-\Delta Q_{drain}$, then

$$\Delta Q=\Delta Q_{ep} \tag{12}$$

On the other hand, the phreatic evaporation amount can be described as the function of the open water evaporation and phreatic evaporation coefficient, which is shown as follows for both conditions before and after WSR, respectively,

$$Q_{ep}{}^{0}=E\cdot C\left(H_0\right)$$

$$Q_{ep}{}^{1}=E\cdot C\left(H_1\right)$$

where, H_0 and H_1 is the groundwater table (m) before and after WSR, respectively. E is the open water evaporation (m). $C\left(H_0\right)$ and $C\left(H_1\right)$ is the phreatic coefficient before and after WSR, respectively.

Then, Eq. (12) will be,

$$\Delta Q=E\cdot\left[C\left(H_0\right)-C\left(H_1\right)\right] \tag{13}$$

Eq. (13) can be changed its form as,

$$C\left(H_1\right)=C\left(H_0\right)-\frac{\Delta Q}{E} \tag{14}$$

From Eq. (14), it is obvious that H_1 can be solved in case ΔQ, E, and the relation between phreatic coefficient $C(H_1)$ and groundwater table is available. Meanwhile, H_1 is not limited to be defined as the groundwater table after WSR. It can be defined as the groundwater table in any period.

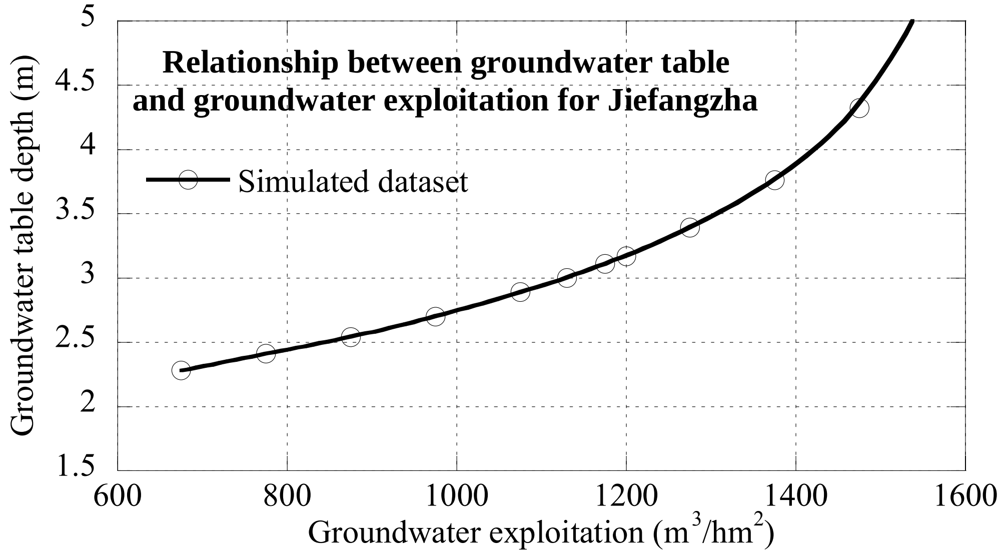

Fig. 5 Relation between groundwater exploitation and groundwater table depth in Jiefangzha SID

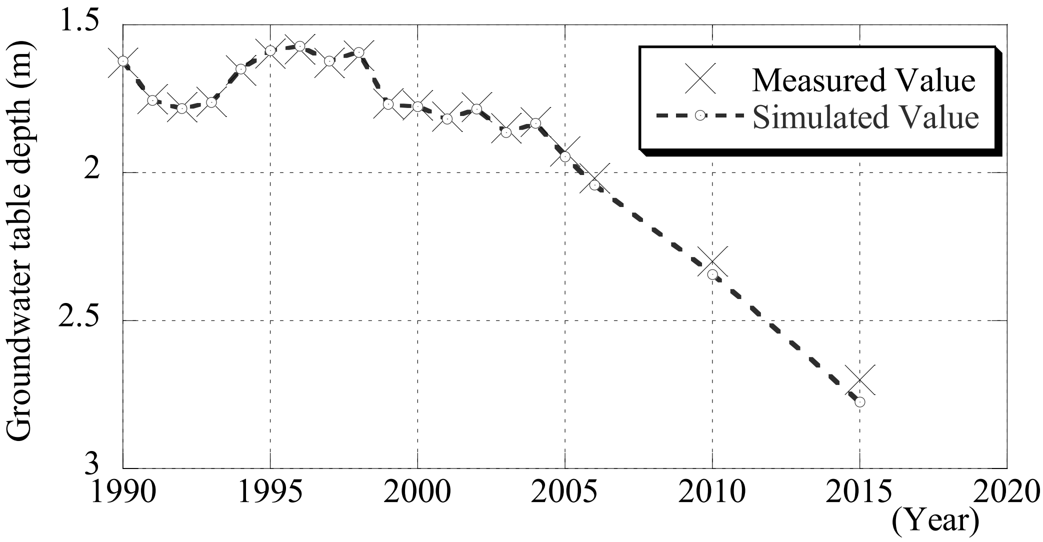

Fig. 6 Simulation of groundwater table depth from 1990 to 2001 (example in Jiefangzha SID)

In the HID, there are totally five SIDs, namely, Yigan, Jiefangzha, Yongji, Yichang, and Wulate (**Fig.1**). The relation between the groundwater exploitation and drawdown should be different for each SID since the hydro-geological condition is different from each other. By using the proposed LCR model, the relation between groundwater exploitation and groundwater drawdown is calculated for each SID as show in **Fig. 5** as an example.

By using the above results, it will be helpful to verify the groundwater table drawdown under different groundwater exploitation. Thus, the water management agency can refer it to decide water use plan in the future for each SID and also predict how much groundwater table drawdown will occur under their present groundwater exploitation policy. From **Fig. 6**, the simulated groundwater table drawdown by using the planned value of the local water resource management agency can be obtained and the deepest groundwater table will be not greater than 3.0 meter from the ground.

4 Simulated groundwater table drawdown

Furthermore, if the planned annual amount of water taken from the Yellow River and groundwater exploitation amount in the future is available, the groundwater table drawdown can be simulated by the proposed model. The average amount of water taken from the Yellow River before WSR is 5.199 billion m^3/year (Yang et al., 2003). The average measured groundwater table depth is 1.71, 1.70, 1.69, 1.66, and 1.65 meter for each SID, respectively (Wang, 2002). If we assume the amount of water taken from the Yellow River is 3.968 billion m^3/year after WSR and the groundwater pumping amount is 1200m^3/hm^2. By using the proposed LCR model, the groundwater table depth will be 2.81, 3.17, 2.83, 2.96, and 2.78 meter for each SID, respectively. This shows different groundwater exploitation should be applied in different SID. If the same groundwater exploitation amount is applied, the groundwater table may decrease a lot in some SID. Thus, it is necessary for us to decide different groundwater exploitation plan for each SID.

By using the proposed LCR model, the groundwater table depth was simulated from 1990 to 2001 based on the available database. **Fig. 6** showed the example in Jiefangzha SID with the simulated result. It shows the agreement between simulated and measured groundwater table depth. Thus, the long-term groundwater table drawdown can be simulated by the proposed LCR model. From **Fig. 6**, the groundwater table declined from the year of 1995 until 2001. According to the plan of the water management agency in HID, the water demand for HID will increase year by year. Thus more groundwater has to be exploited but the water taken from the Yellow River will be decrease to keep the Yellow River free from drying-up. Therefore, the shallow groundwater table in HID will continue decline gradually in the future. This is also the value of this study.

Furthermore, from the above mentioned **Fig. 4** in which the relation between groundwater table depth and phreatic evaporation coefficient is summarized, it is obvious that phreatic evaporation is very small when groundwater table depth is less than 3.0 meter. Thus, the groundwater table depth should be controlled to be less than 3.0 meter for satisfying the demands of vegetation growth.

5 Sustainable development and management of groundwater resources

Aiming at the sustainability of groundwater use, it is urgent that measures towards the rational exploitation of the aquifer as well as the utilization and application of its resources be adopted. A greater understanding of the groundwater requirements of plants will be required to enable a determination of the ecological reserve before water-use licences may be granted or renewed. Lowering of the water table can have a significant impact on terrestrial, riparian, wetland and evaporative discharge area communities. Raising the water table can be as harmful as lowering it and so can alterations of the seasonal and annual variations in flood frequencies and depths.

Control measures should be adopted and implemented to control the current rates of groundwater extraction and combat further deterioration. Water management measures should be taken to reduce water losses and to raise groundwater levels. It is useful for the local water resource management agency to develop an integrated planning and management to ensure that protection and use of groundwater takes places as part of an integrated management of fresh water resources. Groundwater on a long term basis should be managed together with surface water such as irrigation water taken from the Yellow River. Optimum decisions regarding management of groundwater and surface water system can be based on a clear understanding of the integrated systems dynamics and embodying full participation through consultant and education. Through the public common participation, benefits can be derived from current environmental research and can be transferred from the level at which policies are made down to the people affected by them. A management system to aid users , mainly farmers, as well as policy makers responsible for water management in decision making regarding water use should be developed.

The above goals can be achieved by using the geographical information system (GIS) tools to help users to obtain the maximum social and economic benefits in the application of the water policies designed at each moment to their farm. The strategies based on GIS contains spatial information that the scientific research generate and which incorporates a hydrogeological model of the aquifer. Moreover, the GIS can incorporate the assessment of water volumes extracted from the aquifer for irrigation by means of remote sensing techniques. A system which determines the irrigated area, the salinized soil map, the classification of the existing crops and the quanification of water volume used can be developed by means of multitemporal image analysis of the satellite Landsat (sensor TM). Data on water consumption by each crop can be obtained from field experiments. In this way, the evaluation of irrigation systems performance, assessment of crop water requirements and the estimation of efficiency of water use in rainfed area can be worked out. The weekly information to farmers about the volume of water to be used for the main crops can be provided.

6 Conclusions

The results of this study demonstrate the importance of the hydrophysical characteristics for the pattern of groundwater fluctuation. To ensure that groundwater is used in a sustainable way, groundwater dynamics was studied by a LCR model to simulate the groundwater table drawdown. The change of groundwater table in each SID under the present groundwater exploitation was calculated. The future groundwater table drawdown was also simulated by using the planned groundwater exploitation and water taken from the Yellow River. Results showed the proposed LCR model is available to simulate groundwater table drawdown by comparing with the measured ones. Results of examining annual data covering 10 years, combined with current water supply data, water use and geo-hydrological conditions, showed that the shallow groundwater table will continue declining gradually in the future.

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