Changes in Water Resources Systems: Methodologies to Maintain Water Security and Ensure Integrated Management (Proceedings of Symposium HS3006 at IUGG2007, Perugia, July 2007). IAHS Publ. 315, 2007.

Groundwater and its association with sustainability of agriculture in the North China Plain

JIANYAO CHEN[1], YOSHIHIRO FUKUSHIMA[2] & MAKOTO TANIGUCHI[2]

1 *School of Geographical Science and Planning, Zhongshan (Sun Yat-sen) University, 135 Xingang Xi Road, Guangzhou 510275, China*
chenjyao@mail.sysu.edu.cn or chenjianyao@hotmail.com

2 *Research Institute for Humanity and Nature, Motoyama Kamigamo, Kita-ku, Kyoto 603-8047, Japan*

Abstract During 1981–2000 annual precipitation decreased in the North China Plain (NCP), based on monthly data from 20 meteorological stations. Groundwater tables in the lower reach remained relatively stable, with a seasonal fluctuation of approximately ±2 m, while it decreased roughly 1 m year^{-1} in the piedmont of the plain, mainly due to overpumping of groundwater and reducing precipitation. Diversions from the Yellow River contributed to this spatial disparity, and three different temporal patterns of groundwater table change were identified in the lower reach. Groundwater resources play an important role in water supply for irrigation and domestic water use, especially in extreme years of drought, and it is thus a major factor, affecting the sustainability of agriculture in the NCP.

Key words agriculture; groundwater; North China Plain; sustainability; Yellow River

INTRODUCTION

The North China Plain primarily includes the Hebei Plain, basically covering the Haihe River basin, and the lower reach, which is defined as a range between Huayuankou and Lijin of the Yellow River (Fig. 1). Both of these areas are main agricultural production areas in China. Water shortage in the last 20–30 years due to the decline of precipitation and the increase of water demand has caused many environmental problems, e.g. continuous drop-down of the groundwater table in the piedmont of the Hebei Plain, and no flow in the lower reach of the Yellow River (Chen *et al.*, 2003, 2004). Many reports or papers relevant to groundwater resources and groundwater flow were published, focusing on a specific area in either the Hebei Plain or the lower reach, which includes Shandong and Henan Provinces, but few documents cover the whole study area. The study area should be considered collectively because of the similar climate, geomorphology, water resources development and utilization, crop system, and the history of the shifts of the Yellow River (Yu, 2002).

Water supply for irrigation, domestic and industrial water use in the NCP depends heavily on groundwater resource development, and groundwater resources play a key role in maintaining the sustainability of agriculture in the Hebei Plain, especially in the past 25 years (Foster *et al.*, 2004). On the other hand, irrigation water in the lower reach of the Yellow River comes from either the diversion canal or pumping groundwater, which is then recharged by the diverted water. The irrigation area in the lower reach (Fig. 1) was estimated to be 2.32×10^6 ha in 2000 (Chen *et al.*, 2005). The main objective of this paper is to identify the role of the groundwater resource in maintaining the sustainability of agriculture in NCP by focusing on its change in spatial and temporal pattern. This role becomes more important under the situation of augmentation of water demand and climate change.

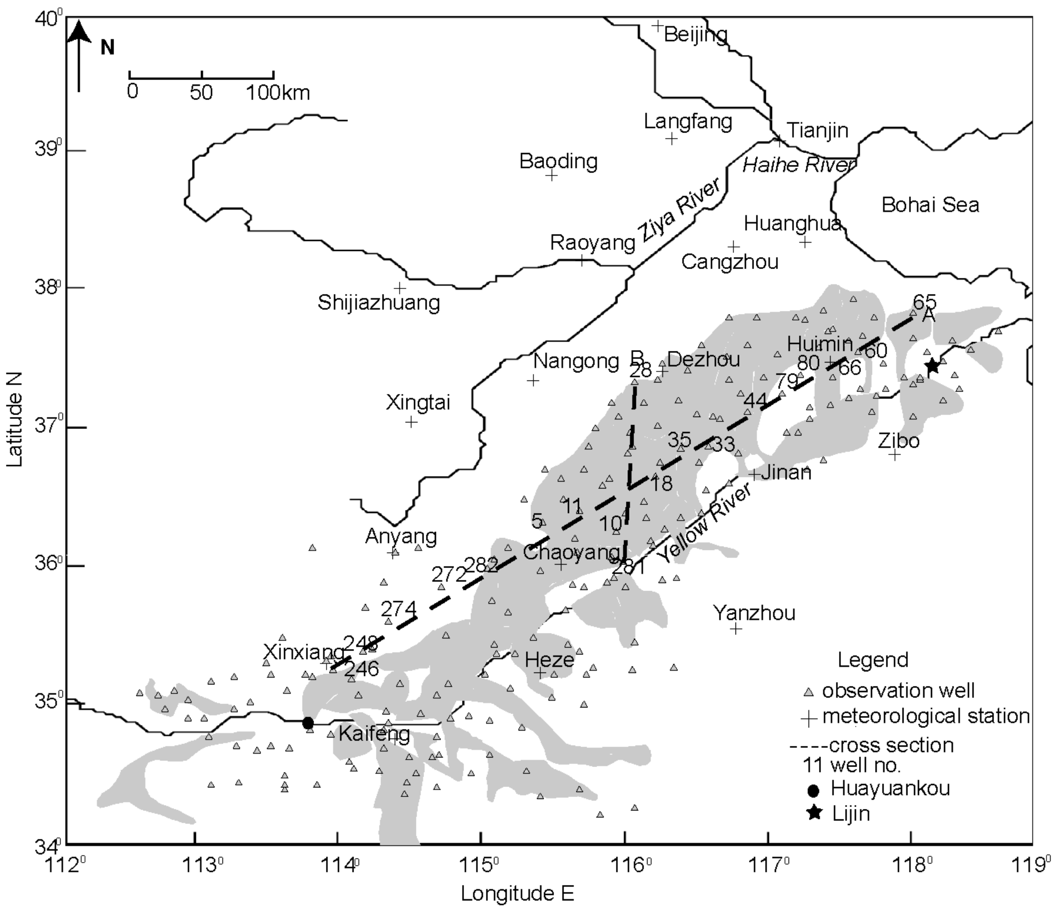

Fig. 1 Map of the study area in the North China Plain. The irrigation area (shaded) in the lower reach is adapted from CDCID (2002).

MATERIAL AND METHODOLOGY

Lots of documents relevant to hydrogeological condition, groundwater development, use of the Yellow River water for irrigation, etc. were collected. Monthly groundwater table series of 1981–2000 were collected, except 1997 and 1998, with water table measurements every 5 days, for 284 observation wells in the lower reach. The contours of the water table were created by the Kriging method, then joined and compiled with the contours of the water table in Hebei Plain. Monthly precipitation data was collected from 1951 to 2000 for 20 meteorological stations. Monthly discharge data at Lijin was collected from the documents published by the Yellow River Conservancy Commission.

A simple statistical method was adopted for analysing the change in precipitation and groundwater table.

RESULTS AND DISCUSSIONS

Generally, precipitation is the primary source of recharge for the aquifer in the NCP, and its change causes seasonal and annual fluctuations of the groundwater table. Annual average precipitation of 20 meteorological stations shows a decreasing trend after the 1980s (Fig. 2). Decadal average precipitation was 620, 611, 589, 539 and 568 mm in the 1950s, 1960s, 1970s, 1980s and 1990s, respectively. Standardized difference from the average precipitation (*AP*) was calculated as:

$$SDP = (Xi - AP)/AP$$

where *Xi* is the original precipitation, and *SDP* was summated cumulatively, showing increasing, relatively stable and decreasing trends, for the periods 1951–1964, 1975–1978, and 1978–2001, respectively (Fig. 2).

In the piedmont of the NCP, a north–south transect from Baoding, Shijiazhuang to Handan shows a significant drawdown of water table (Fig. 3(b)) mainly due to over pumping of groundwater for irrigation. Water tables of observation wells at Luancheng station of Chinese Academy of Sciences near Shijiazhuang have fallen at a rate of approximately 1 m year^{-1}, which is equivalent to over pumping of approximately 150 mm year^{-1} water for irrigation and other uses (Chen *et al.*, 2003). However, the water table in the lower reach, where most of the arable land is irrigated by the diverted water from the Yellow River, remains relatively stable (Fig. 3(a)). The water table at wells nos 272 and 282, located in an area where Yellow River water is not available for irrigation, decreased considerably at a rate of 0.7 and 0.6 m year^{-1}, respectively. This rate is comparable to that at Luancheng station.

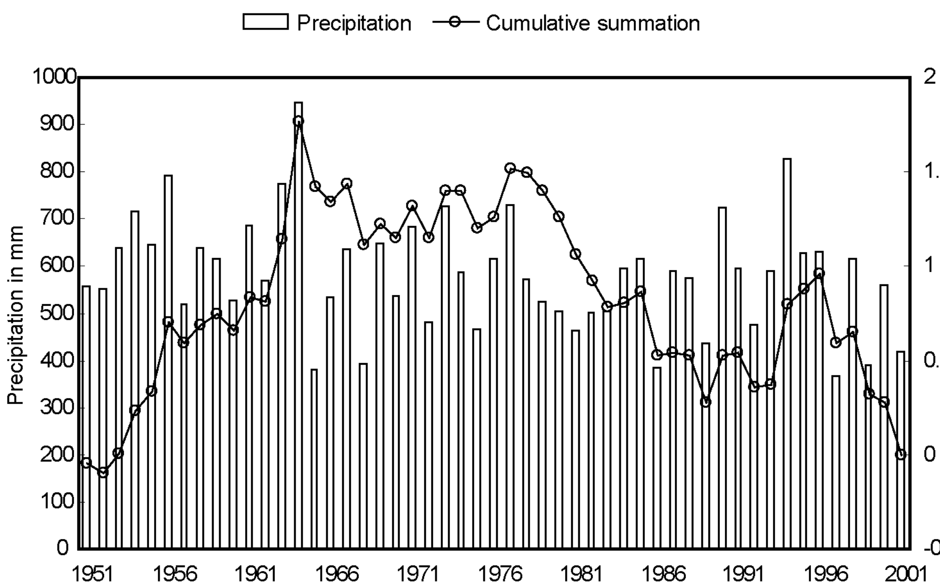

Fig. 2 Change of annual average precipitation in the NCP in the last 50 years.

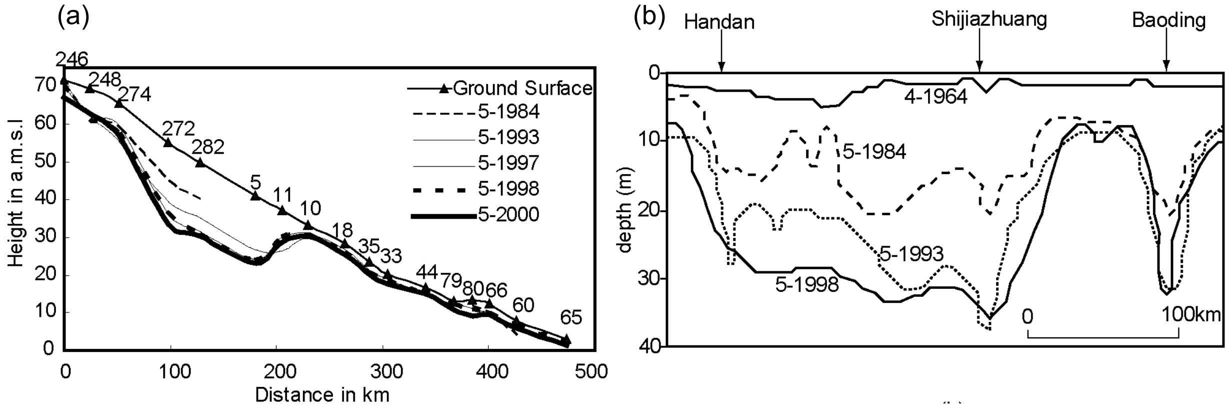

Fig. 3 Change of water table along a west-east transect A (Fig. 1) in the lower reach (a), and a north–south transect in the piedmont of NCP (b), adapted from Foster *et al.* (2004)

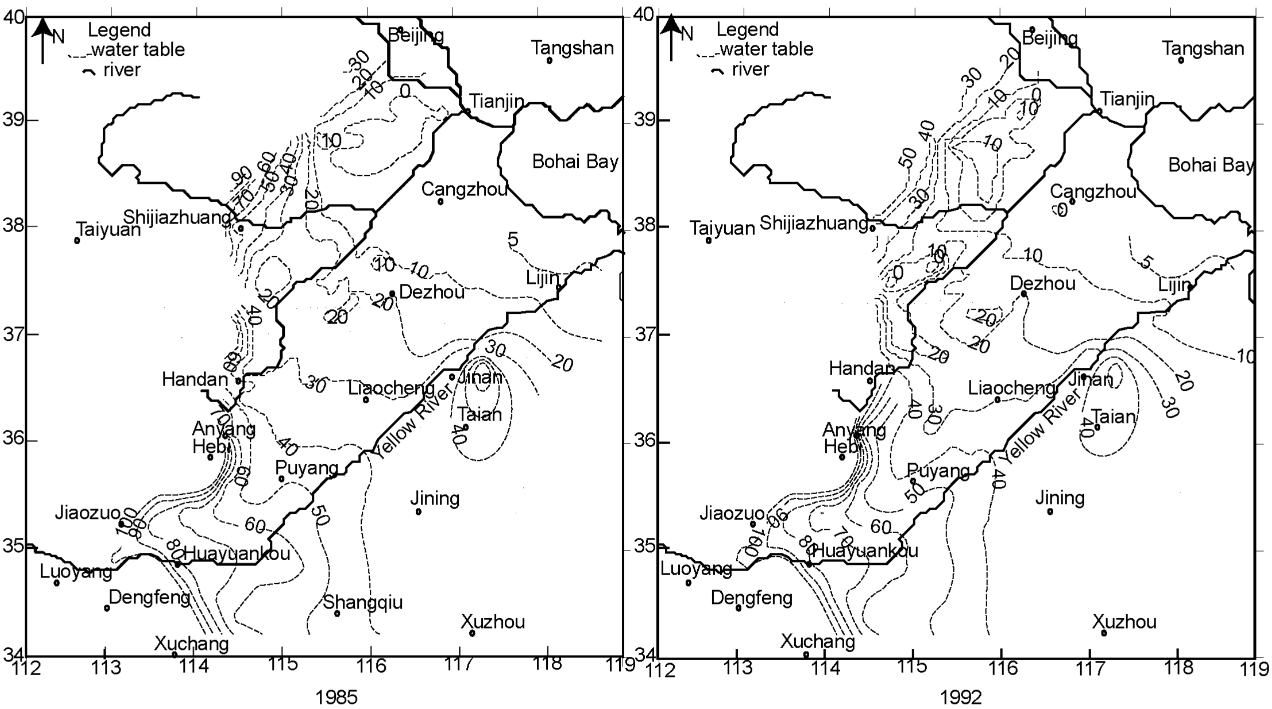

Fig. 4 Contour of water table of the shallow aquifer in 1985 and 1992 in the NCP. Contour of Hebei Plain was adapted from Zhang *et al.* (2000).

Although climate and the crop system are rather homogeneous within the NCP, water diversion from the Yellow River considerably affects the recharge of the aquifer and therefore the groundwater flow but only in the lower reach. As less water is recharged to the aquifer in the Hebei Plain than that in the lower reach, the water table drops continually in the Hebei Plain. The spatial pattern in terms of water table contour and its shape is different in these two areas. Water table in the Hebei Plain extends longitudinally with groundwater flows eastward, while it extends northward or latitudinally with aquifer in the vicinity recharged by the Yellow River in the north part of the lower reach (Fig. 4). The flow from the river collides with the general flow in the north–east direction, e.g. from Puyang to Liaocheng, in a line near transect A (Fig. 1), resulting in an "impact zone" between the Yellow River and the line A. Figure 4 also shows several meters of draw-down during the period of 1985–1992 in the piedmont near Shijiazhuang.

The hydraulic gradient of the shallow aquifer in the piedmont near Shijiazhuang was estimated to be 7.8×10^{-4}, 7.8×10^{-4}, 1.19×10^{-3}, and 8.9×10^{-4} in 1959, 1975, 1985 and 1992, respectively, based on the document by Zhang *et al*. (2000). Groundwater has been developed since the 1970s, and the gradient reached its highest in 1985, indicating a relatively high inflow from the west side, Taihang Mountain. Inflow decreased afterwards and thus enhanced the continuous draw down of the water table. The gradient along the cross-sections B and A is estimated to be 1.27×10^{-4} and 1.44×10^{-4}, respectively (Fig. 1). Though these two gradients are in the same order of magnitude, they are uneven spatially, with high gradients in the western part, e.g. the gradient perpendicular from the Yellow River to the well no. 271 is approximately 4.35×10^{-4}. Given a hydraulic conductivity of 10 m day^{-1} and an aquifer thickness of 50 m (Zhang, 1988; Chen *et al*., 2002), groundwater flow flux to the North China Plain in the lower reach of approximately 780 km length is calculated to be $0.18–0.62 \times 10^8$ m^3 $year^{-1}$. Groundwater flow flux in the piedmont of Hebei Plain is several times the flow rate of that in the lower reach, given a similar hydraulic conductivity.

Seasonal variation of water tables along transect A (Fig. 1) in the lower reach clearly indicates three temporal patterns given as group I, II and III in Fig. 5. Group I has the highest water table in August, earlier than the other two groups, corresponding well to the Monsoon climate, with precipitation occurring in June–September. Group II recovers from the lowest water table in June and July and reaches the highest level in January and February, similar to Group III. The water table of Group III in response to the recharge is the latest, and decreases annually as shown in Fig. 3(a). Group I shows a second peak of water table change in April and May, when the Yellow River is diverted for the irrigation of winter wheat in the lower reach. Thus, groundwater depth, Monsoon climate and irrigation are regarded as main factors affecting the water table change. A change of water table of 1–2 m could provide approximately 100–200 mm water for irrigation, given a specific yield of 0.1, and account for 39–78% of the water deficit of 257 mm (Chen *et al*., 2005). Since agricultural water use accounts for around 80% of total water use, and the water loss, e.g. evaporation from the water table, outflow from the aquifer to other regions, is not significant, it is reasonable to suggest that 1/3 of the water deficit should be provided by using the temporary aquifer storage.

Serious dry-up in the lower reach has occurred since 1972, and has definitely affected the aquifer recharge. Annual average maximum variation (AAMV) of the water table was defined as the difference of the highest and the lowest water table for a specific year, and its relationship with annual discharge (AD) at Lijin during the period of 1981–2000, and is given in Fig. 6. AAMV increases exponentially as annual discharge decreases:

$$AAMV = 3761.2 * e^{-1.8354 * AD} \quad (R^2 = 0.46)$$

The highest AAMV of 2.41 m was found in 1997, when the most serious dry-up occurred in the lower reach. The high variation in groundwater table responds generally to the low flow, while the low flow, on the other hand, does not respond

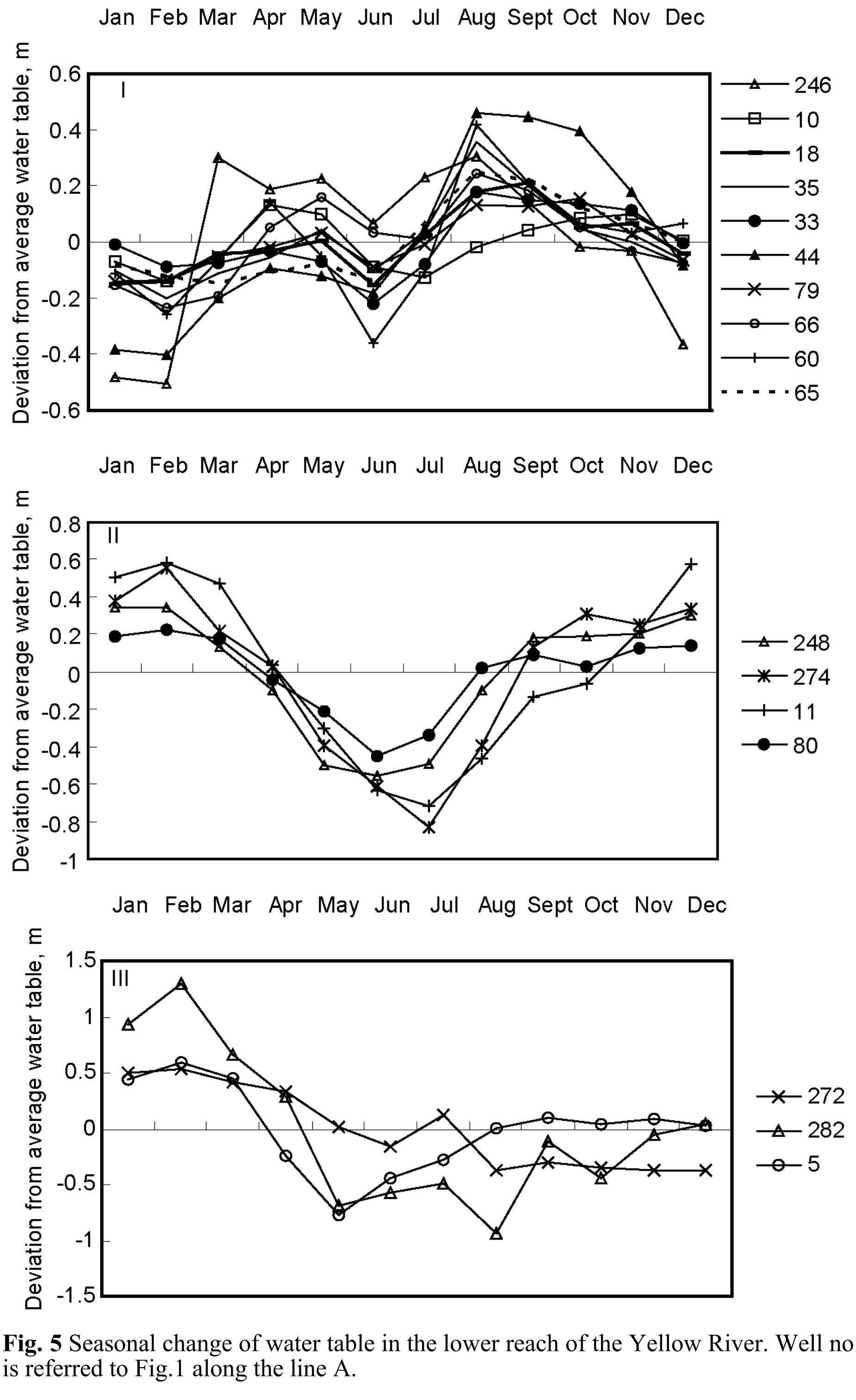

Fig. 5 Seasonal change of water table in the lower reach of the Yellow River. Well no. is referred to Fig.1 along the line A.

necessarily to the high variation in groundwater table. For example, the low flow in 1999 responded to a variation of 1.55 m in groundwater table, smaller than that in 1984, when the high flow occurred. Because the water amount from this storage change could balance the water deficit as mentioned, agricultural production was little

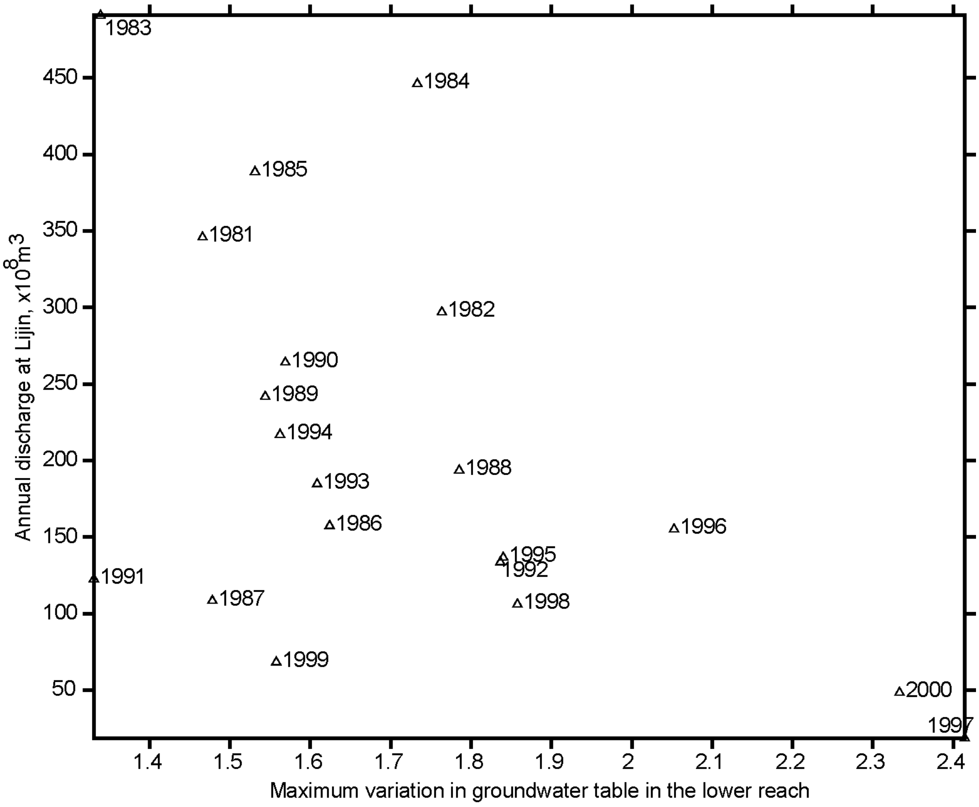

Fig. 6 Relationship between annual maximum variation of groundwater table in the lower reach and annual discharge at Lijin during the period of 1981–2000.

affected in this year. The shallow aquifer is at least 50 m in thickness (Zhang, 1988), demonstrating an ability to provide water for irrigation in a few years, even without flow in the lower reach.

CONCLUSIONS

Precipitation was found to have decreased in the North China Plain during the period of 1951–2000. The groundwater table fell continually at a rate of approximately 1 m/y in the piedmont of the NCP, but it remains constant due to the diverted water in the lower reach with a seasonal fluctuation of 1–2 m. Groundwater depth, irrigation and Monsoon climate are the main factors affecting the recharge of aquifer in the lower reach, which shows three noticeable temporal patterns. Annual maximum variation of water table increases as discharge in the Yellow River decreases, and the highest variation of 2.41 m was found in 1997, A low flow is a necessary but not a sufficient condition for the large variation in the groundwater table. Seasonal change in aquifer storage could provide 100–200 mm of water for irrigation, accounting for at least one-third of the water deficit, and it may provide water to cover the total deficit in the extreme drought condition. This is the reason that agriculture was sustainable in the lower reach even in the dry-up condition. The sustainability of agriculture in the piedmont of NCP remains a problem since continuous draw-down of the aquifer could not provide sufficient water for irrigation.

Acknowledgements This study is supported by the National Natural Science Foundation of China (no. 40571027), "985 Project" of GIS and remote sensing for geosciences from the Ministry of Education of PR China, and Monbusho of Japan for the Human-Nature-Earth Revolution Research Project in "Prediction Mission in Water Cycle Change—Development of Water Resource Prediction Model—Surface Water Research Program in the Yellow River".

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