Bulletin of the Geological Survey of Japan, vol.60 (1/2), p.105-115, 2009

Article

Geological interpretation of groundwater level lowering in the North China Plain

Shiro Tamanyu[1], Hirofumi Muraoka[2] and Takemasa Ishii[2]

Shiro Tamanyu, Hirofumi Muraoka and Takemasa Ishii (2009) Geological interpretation of groundwater level lowering in the North China Plain. *Bull. Geol. Surv. Japan*, vol. 60 (1/2), p. 105-115, 9 figs, 1 table.

Abstract: Groundwater level lowering in the North China Plain (NCP) has been developing during past several decades by overuse in populated cities and industrial districts as well as by irrigation. To interpret groundwater level lowering in terms of aquifer-bearing beds having relatively high porosity, contour maps and cross sections of water level lowering based on monitoring data are compared with subsurface Quaternary geologic map. The comparison revealed that the extents of productive shallow and deep aquifers are generally restricted in specific regions where sand and gravel occur in lenticular form. The groundwater resources are regarded as fossil resource because groundwater of deep aquifer is dated as older than 10,000 years BP. Therefore, if overproduction of groundwater continues at the same rate as at present, it should result in depletion or severe lowering of water level and induce ground subsidence and water quality deterioration. To overcome the problems, effective use of irrigation and recycling of used water from industrial and domestic uses by water purification are essential.

Keywords: groundwater level lowering, North China Plain, deep aquifer, shallow aquifer, Quaternary geology, sand, gravel, water recycling

1. Introduction

The North China Plain (NCP) refers to the eastern China between latitudes 35˚00´N and 40˚30´N, and longitudes 113˚00´E and 119˚30´E. It is bounded by Taihang Shan Mountains to the west, Yan Shan Mountains to the north, the Bohai Sea to the east, and the Yellow River to the southeast (Fig. 1). Climate of NCP is characterized by cold dry winter and hot humid summer.

The Quaternary aquifer of NCP has provided enormous amount of groundwater for agricultural irrigation, industrial, and potable water. Both population and economic activity have grown markedly in the past 25 years in this area. However, the development encountered increasing difficulties in recent years primarily as a result of aquifer depletion (*e.g.*, Foster *et al*., 2004). The authors are interested in the relationship between groundwater level lowering of shallow and deep aquifers with Quaternary geology in terms of space and time. The data of groundwater level lowering in NCP are available from Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences.

2. Comparison of groundwater level lowering and geology

2.1 Groundwater level lowering on the cross-section from Beijing to Tianjin (shallow aquifer)

Shallow aquifer is tentatively defined as unconfined aquifer formed between ground surface to sea level in this paper.

Institute of Hydrogeology and Environmental Geology has been monitoring groundwater levels and summarized their changes along many cross-sections through major cities in NCP from 1960s to 2002. One of them is the cross-section from 1980 to 2002 along Beijing to Tianjin. Positions of summarized cross-sections are shown as lines 1-1’ and 2-2’ in Fig. 1 for shallow and deep aquifers, respectively. Quaternary geologic map and cross-section of Huang-Huai-Hai Plain in China were reported by Shao and Wang (1989a, b). The positions of the cross-sections of Quaternary geology are shown as lines I-I’ and II-II’ in Fig. 1. The former is for shallow part and the latter is for deep part of Quaternary geology. The positions of cross-sections for groundwater levels and geology were close to each other. In Fig. 2 are shown cross-section of water table level along Beijing to Tianjin for shallow aquifer in

[1]AIST, Geological Survey of Japan, Geological Museum

[2]AIST, Geological Survey of Japan, Institute for Geo-Resources and Environment

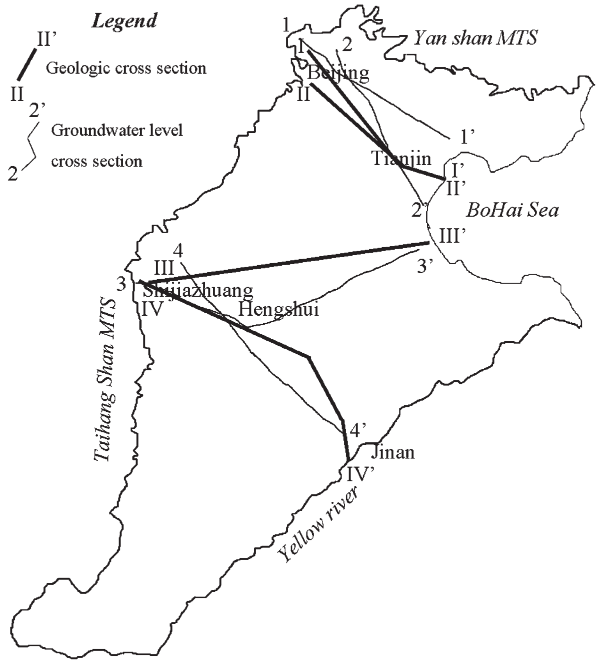

Fig. 1 Index map of the North China Plain and cross-sections for monitored groundwater levels and Quaternary geologic formations.

the upper diagram, and geology of shallow lithologic sequences in the lower diagram.

The upper diagram shows the fast lowering of groundwater levels in shallow aquifer from 1984 to 2001 around Beijing, but no change around Tianjin. This is because heavy groundwater production has been carried out around Beijing while Quaternary aquifer development has been prohibited to prevent ground subsidence in downtown Tianjin (pers. comm., Tianjin Geothermal Management Division). The severe lowering around Beijing is understood to be related to the lithologic features of gravel and sand in fan deposits. The excessive production of groundwater around Beijing has exhausted the water resources in shallow aquifer.

2.2 Groundwater level lowering on the cross-section from Beijing to Tianjin (deep aquifer)

Deep aquifer is tentatively defined as confined aquifer formed below sea level in this paper. Water table level along Beijing-Shijingshan to Tianjin for deep aquifer (cross-section along line 2-2') is shown as upper diagram, and geology as lower diagram in Fig. 3. The positions of the cross-sections for groundwater level and geology are close to each other.

The upper diagram shows lowering of groundwater level by 30 m in the deep aquifer from 1980 to 2002 around Tongxian (northeast of Beijing), 40 m in the west of Tianjin and 50 m in the west coastal plain of Dagong. This shows heavy groundwater production from deep aquifer during this period resulting in the regional lowering of water tables. Remarkable lowering around Beijing occurred in Pleistocene fluvial sand and gravel. There, more of the deep aquifer can not be expected because Quaternary beds are thin and underlain by impermeable pre-Quaternary bed rock. The production bed in the west of Tianjin is fluvial sand while that in the west of Dagong is fluvial sand and marine sediments. In the latter area, inland deep aquifer is heavily contaminated by seawater.

2.3 Lowering of groundwater level seen on the cross-section from Shijiazhung to Huanghua (shallow aquifer)

The positions of overall cross-sections from Shijiazhung to Huanghua or Qihe are shown as lines 3-3' and 4-4' in Fig. 1 for shallow and deep aquifers, respectively, in which water table level for shallow aquifer (3-3') is shown as the upper diagram, and geology as the lower diagram in Fig. 4. The positions of the cross-sections of Quaternary geology are shown as lines III-III' and IV-IV' in Fig. 1. The former is for shallow part and the latter is for deep part of Quaternary geology. The positions of the cross-sections for groundwater and geology are not so apart from each other.

The upper diagram shows fast lowering of groundwater level in shallow aquifer from 1960s to 2001 from Shijiazhung to Hengshui, but no change from Hengshui (about midpoint of cross-section) to Huanghua. This means that heavy groundwater production had occurred from Shijiazhung to Hengshui, where groundwater producing bed was Pleistocene fluvial gravel and sand. In contrast shallow aquifer from Hengshui to Huanghua was poor because groundwater producing bed for this area consisted of fluvial fine-grained material (clay) and could not have been utilized.

2.4 Groundwater level lowering on the cross-section from Shijiazhung to Huanghua (deep aquifer)

Deep aquifer is defined as before. The cross-section of water table level along Shijiazhung to Qihe for deep aquifer (4-4') is shown as the upper diagram, and geology as the lower diagram in Fig. 5. The positions of cross-sections for groundwater levels and geology are not so apart from each other.

The upper diagram shows 20 to 70 m lowering of groundwater level in the deep aquifer from 1980 to 2002 suggesting heavy groundwater production from deep aquifer in all the places in this period. The 20-30 m lowering at both ends of the cross section are correlated to Pleistocene fluvial gravel and sand. In those areas, more of the deep aquifer can not be expected because Quaternary bed is thin and underlain

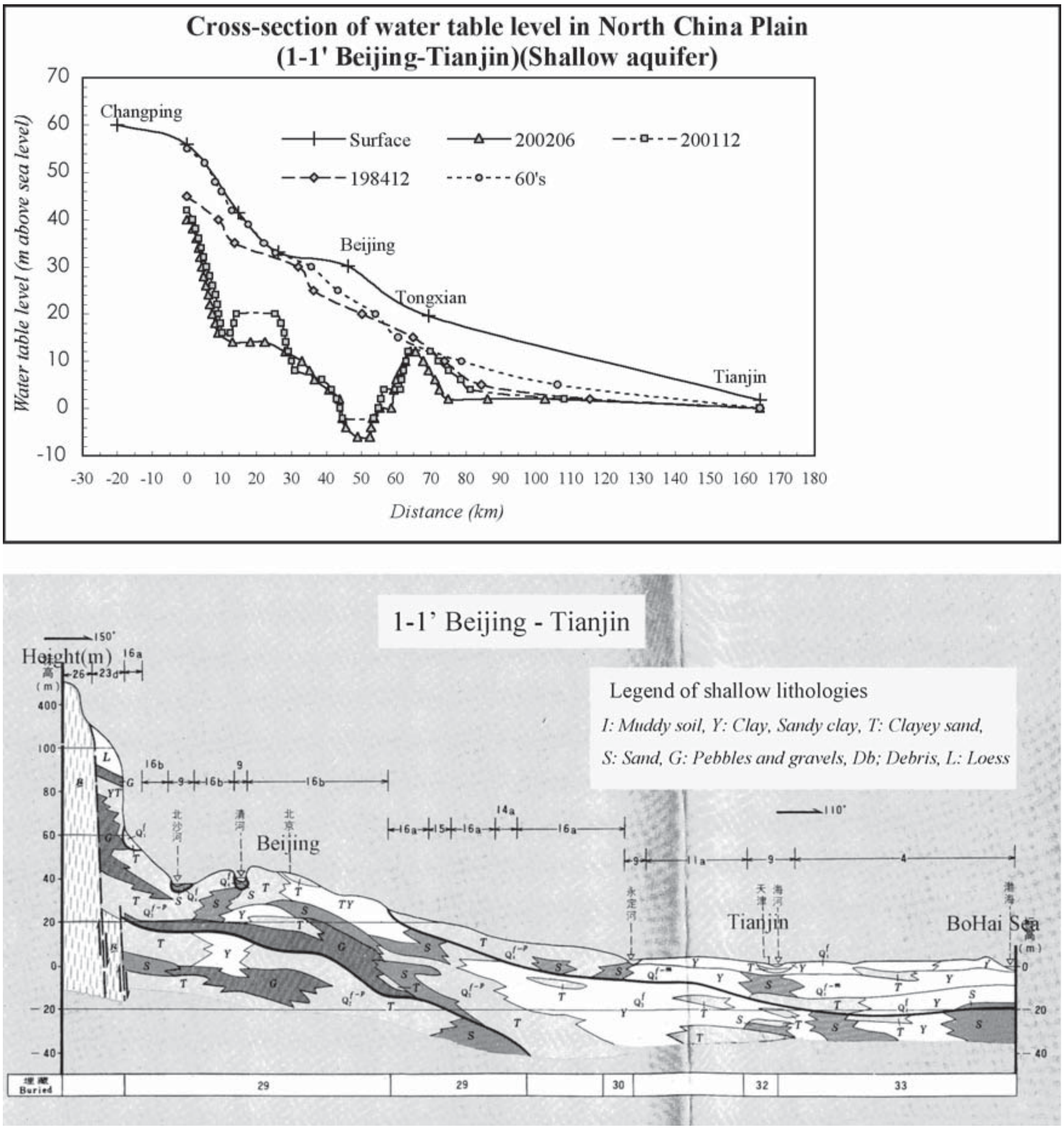

Fig. 2 Comparison between groundwater lowering and Quaternary formations for shallow aquifer along Beijing to Tianjin. Upper diagram shows groundwater lowering with monitored ages. Lower diagram shows shallow lithofacies of Quaternary formations.

by impermeable pre-Quaternary bed rock. The 40-70 m lowering of groundwater in the middle of cross-section is correlated to the fluvial sand deposited by old Yellow River in Late Pleistocene.

3. Comparison of extents of groundwater level lowering and thickness of Quaternary formations

3.1 Shallow aquifer

Contour lines of shallow aquifer water levels for 1984 and 2001 are compared in Fig. 6. It indicates that the 10 m contour line of shallow aquifer extends toward the south in the east of Shijiazhung and to the west around Beijing indicating overproduction of shallow aquifer resulting in severe water table drop at these densely populated cities. The 30 m contour line of shallow aquifer extends toward the south in the west of Jinan. This depletion was caused by heavy water production for irrigation.

Most shallow aquifers have been already depleted in populated areas.

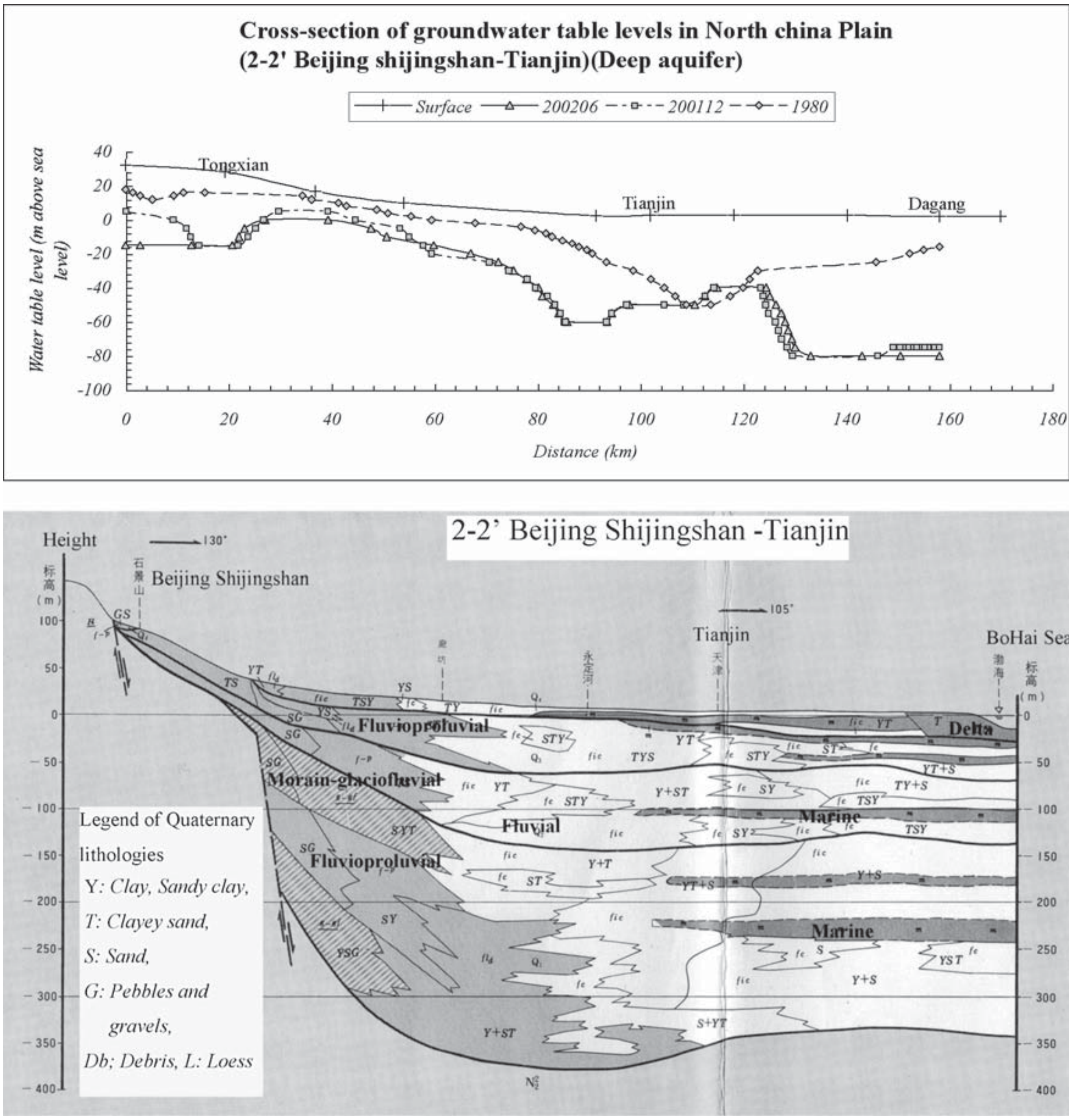

Fig. 3 Comparison between groundwater lowering and Quaternary formations for deep aquifer along Beijing Shijingshan to Tianjin. Upper diagram shows groundwater lowering with monitored ages. Lower diagram shows deep lithofacies of Quaternary formations.

3.2 Deep aquifer

Contour lines of deep aquifer water levels for 1980 and 2001 are compared in Fig. 7. It shows that the -10 m contour line of 2001 is found almost at the same position of 10 m contour line of 1980. Within the -10 m contour line of 2001, there are remarkable funnel-shaped depressions around east of Tianjin, Canzhou, and Dezhou. It is caused by overproduction by industrial use.

4. Characteristics of spatial aquifers

Foster *et al*. (2004) classified hydrogeologic area of NCP from western mountain area to eastern coastal area into the following three distinct zones: piedmont, flood plain and coastal strip (Fig. 8). Hydraulic conductivity (permeability) and specific yield (storativity) decrease from west to east, and the subsurface infiltration capacity and natural recharge rates (from excess rainfall and river flow) also tend to decrease in the same direction.

Chen *et al*. (2004) related groundwater flow system and geochemical characteristics as follows. The flow systems are mainly controlled by tectonics, geomorphology, and lithology. The groundwater in the NCP has a two-layer structure, with boundary at depths

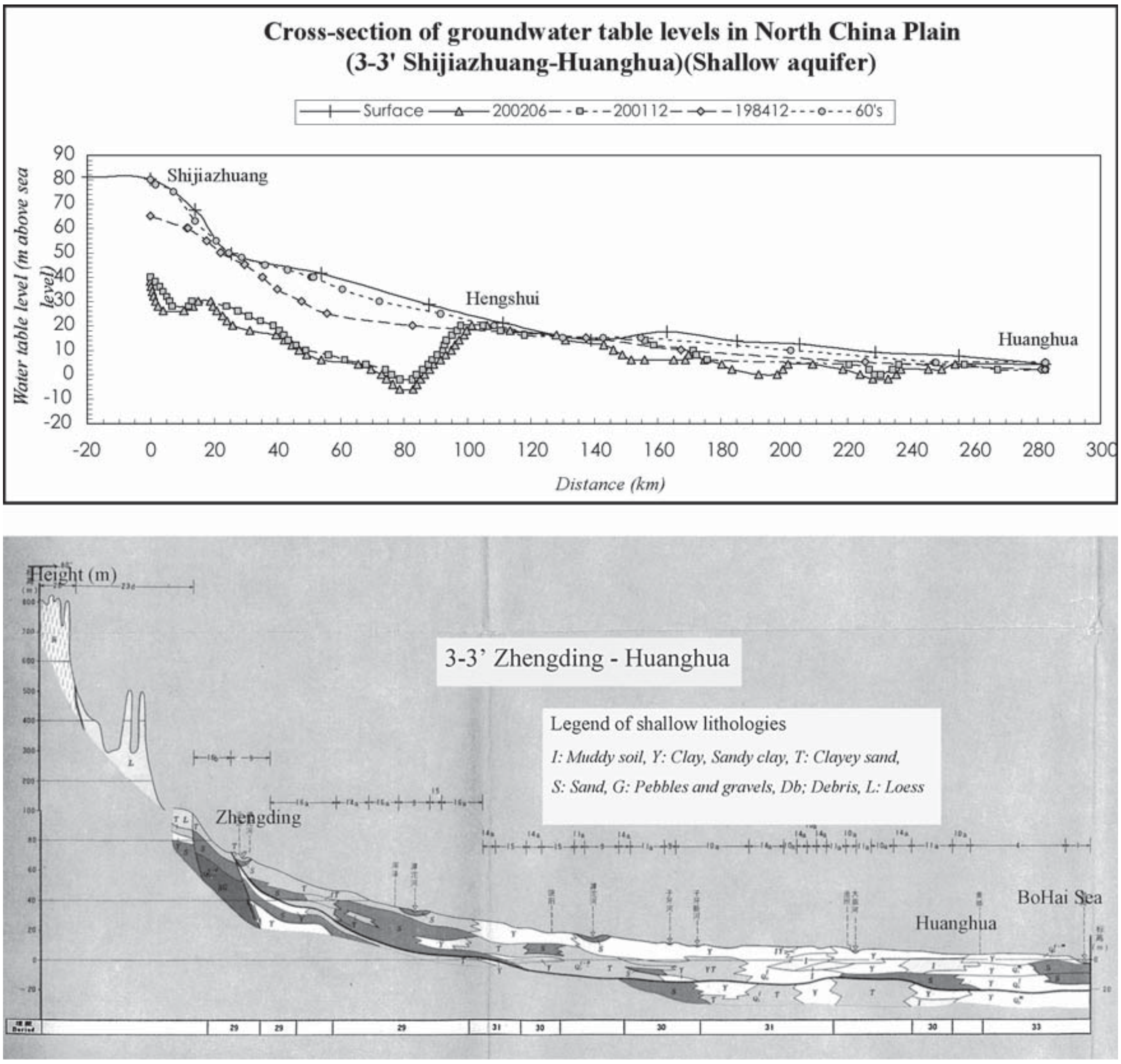

Fig. 4 Comparison between groundwater lowering and Quaternary formations for shallow aquifer along Shijiazhuang to Huanghua. Upper diagram shows groundwater lowering with monitored ages. Lower diagram shows shallow lithofacies of Quaternary formations.

of about 100-150 m. Chemical compositions of water in the upper layer showed a wider range and higher variability than those in the lower layer, indicating impact of human activity. Three hydrogeological zones are identified: recharge zone, intermediate zone and discharge zone. Each zone corresponds to mountains and piedmont plain; alluvial fan plain and part of flood plain; and coastal plain and part of flood plain, respectively.

With reference to above mentioned papers, NCP is hydrogeologically divided into three zones: western recharge zone in mountains and piedmont plain, middle intermediate zone in alluvial fan plain and part of the flood plain, and eastern discharge zone in coastal plain and part of the flood plain. The shallow aquifers in the western part of NCP are almost depleted at populated cities, and the water table of deep aquifer is quickly dropping. The deep aquifers in the western zone can not be expected to last long because the thickness and extents of coarse-grained sediments are spatially limited. While the deep aquifers in the middle and eastern coastal plain occur in relatively fine grained-sand, the water contents are low compared to western zone, even though the thickness of aquifers are thicker than those of western zone. The deep aquifers in eastern zone are extensively invaded by seawater, and the use of the salty water for irrigation is not suitable.

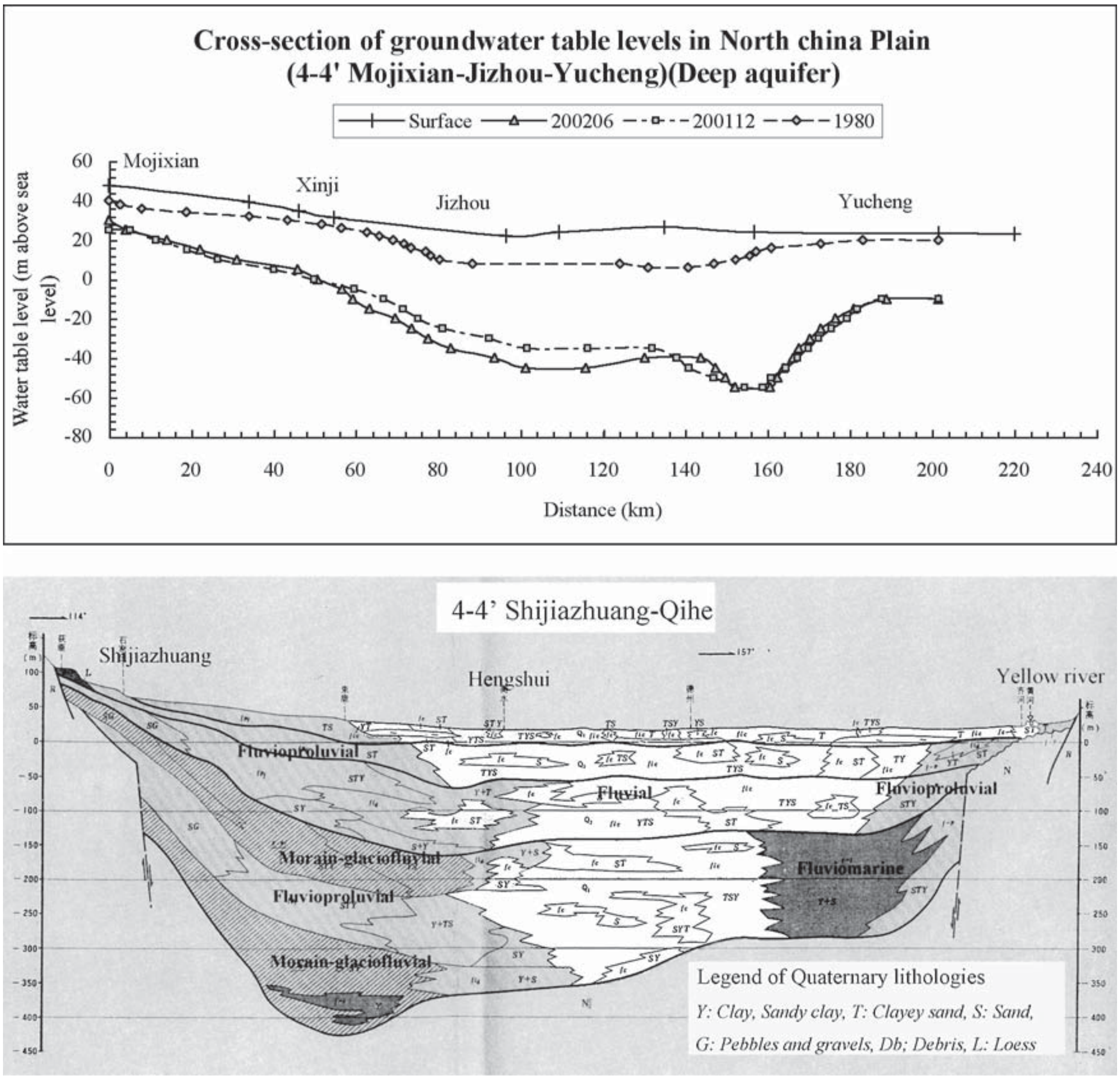

Fig. 5 Comparison between groundwater lowering and Quaternary formations for deep aquifer along Shijiazhung to Yellow River (close to Jinan). Upper diagram shows groundwater lowering with monitored ages from Mojixian to Yucheng through Jizhou). Lower diagram shows deep lithofacies of Quaternary formations from Shijiazhung to Qihe close to Yellow River through Hengshui.

5. Ages of groundwater

Chen *et al*. (2004) reported that the groundwater age, using ^{36}Cl, from wells of 150-250 m and 341-456 m depths in the Cangzhou area were estimated to be 250,000 yr BP and 300,000 yr BP, respectively referring to Zhou *et al*. (2001). However, the upper layer is likely to be much younger than those reported by Zhou *et al*. (2001) using ^{14}C and stable isotopes by Zhang *et al*. (2000) and Chen (2003).

Zongyu *et al*. (2005) analyzed hydrogen and oxygen isotopes and also dated groundwater using ^{14}C. These isotopic data suggest that most groundwater in the central and littoral portions of NCP is 10,000 to 25,000 years old (Fig. 9). The $\delta^{18}O$ (δD) values of this groundwater are 1.7 ‰ (11 ‰) less than those in the piedmont plain groundwater possibly reflecting recharged water during a cooler climate of the last glaciation. The isotopic data indicate that groundwater in the central and littoral part of NCP is being pumped under non-steady state condition.

From the results of studies in the above papers, the ages of deep aquifers in middle and eastern zones were understood to be fossilized water older than 10,000 to 25,000 years old and not renewable.

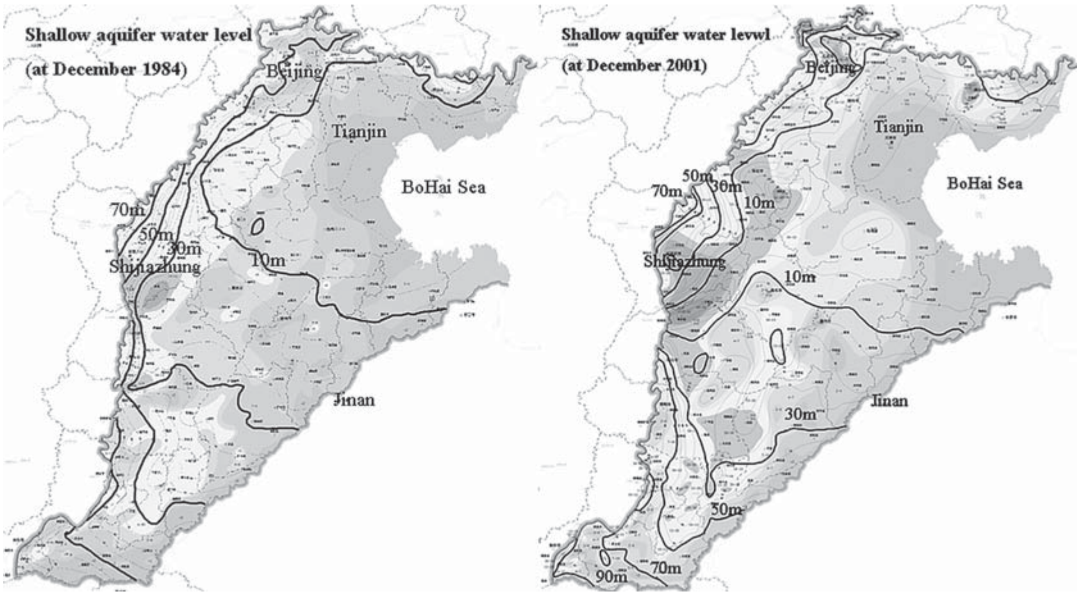

Fig. 6 Contour map of shallow aquifer water levels at 1984 and 2001 in NCP.

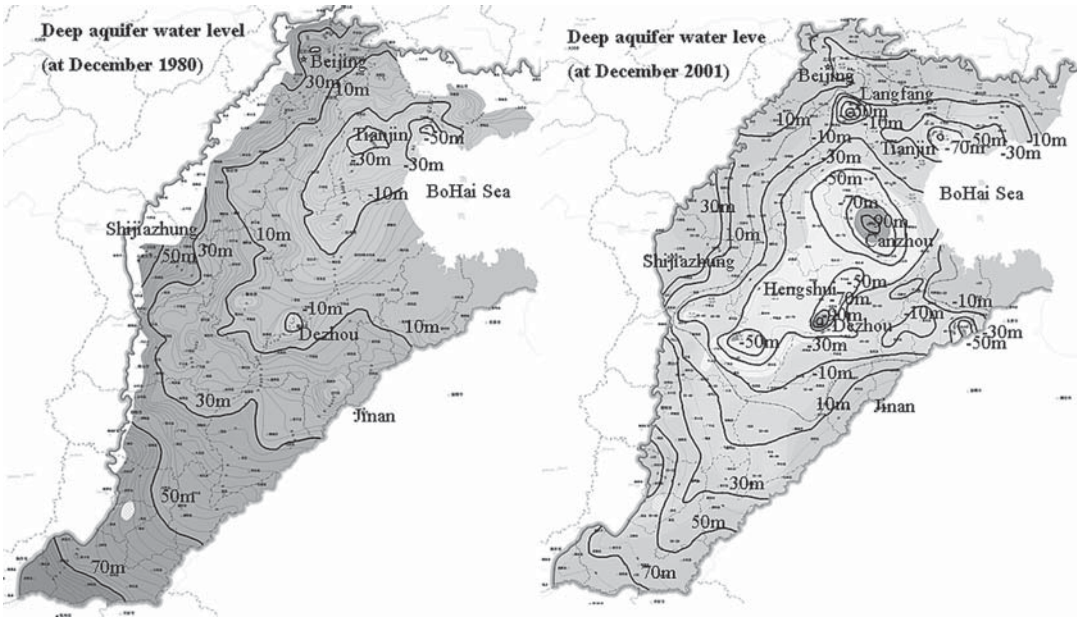

Fig. 7 Contour map of deep aquifer water levels at 1980 and 2001 in NCP.

6. The ratio between surface water and groundwater

Japan Bank for International Cooperation (2004) summarized the situation in a report entitled "Issues and challenges for water resources in North China – case of the Yellow River Basin-". The report on basin-by-basin comparison of water resources was presented in Table 1 referring to China Water Resource Gazette (2000). The authors read the data representing ratios of groundwater to total available water. Despite the fact that the method of calculation of double-count of surface water and groundwater was not clearly defined in the original reference, Hai River drainage area (almost

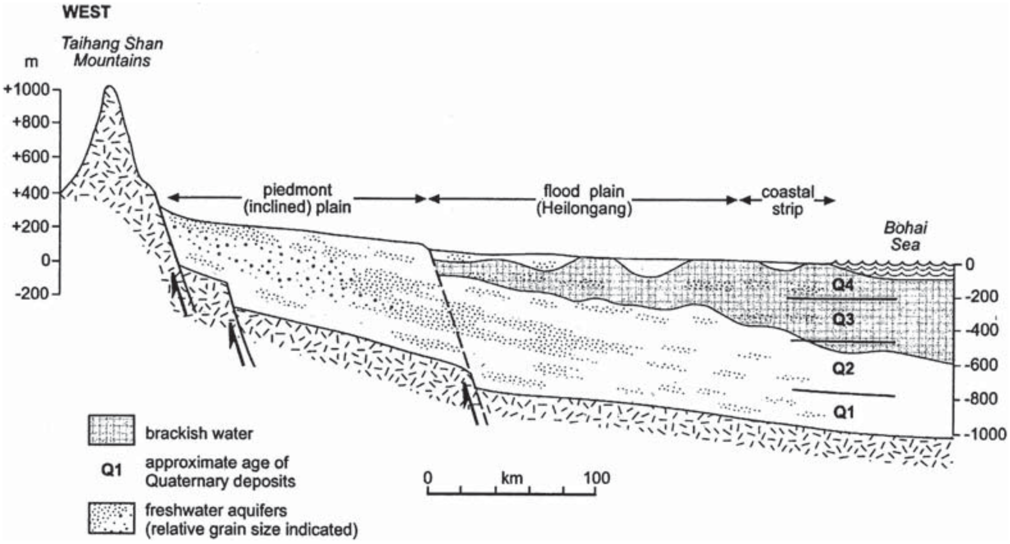

Fig. 8 East to west cross section of the North China Plain showing the general hydrogeological structure (Foster *et al*., 2004)

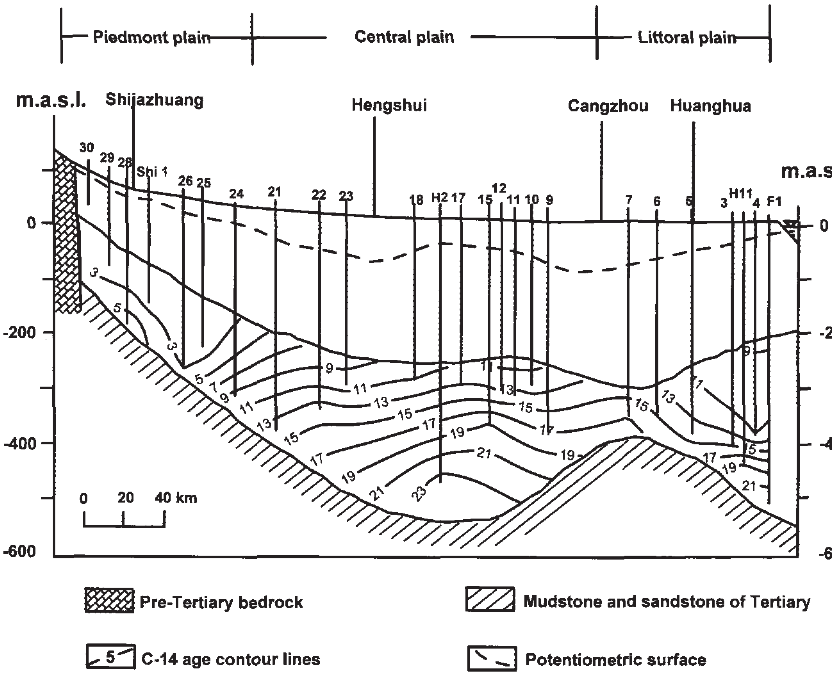

Fig. 9 Cross section showing ^{14}C age of ground water in the deep confined aquifer (Zongyu *et al*., 2005). Unit of ^{14}C age is in thousand years

Table 1 Basin-by-basin comparison of water resources (Original data from China Water Resource Gazette, 2000, refer to Japan Bank for International Cooperation, 2004)

Unit: 100Mtons

River Basin	Precipitation	Surface Water	Ground Water	Double-count	Water Resource Volume
Sonhua and Liao Rivers	5,415.68	1,122.74	577.78	305.47	1,395.05
Haihe	1,559.36	125.18	221.95	77.57	269.56
Huaihe	3,062.29	877.09	498.77	142.99	1,232.87
Yellow River	3,043.46	456.07	351.56	241.78	565.85
Changjiang	19,561.45	9,924.09	2,516.30	2,407.97	10,032.42
Pearl River	8,548.94	4,401.16	1,110.60	1,082.37	4,429.40
Southeast rivers	3,723.67	2,117.04	546.80	534.92	2,128.92
Southwest rivers	9,517.54	6,122.46	1,690.54	1,689.75	6,123.25
Inner rivers	5,659.95	1,416.11	987.56	880.17	1,523.50
Total	60,092.34	26,561.94	8,501.86	7,362.99	27,700.82

equivalent to NCP) was shown to have the highest ratio (about 80 %) of groundwater to the total amount. It was suspected, however, that some of the water (up to 30 %) was identified as both groundwater and surface water. In any case, the groundwater must be the major water source rather than surface water in NCP. It should be kept in mind, however, that large part of surface and groundwater are transitional to each other because of high permeability of Upper Quaternary formations.

Recently I noticed the definition of double-count of surface water and groundwater must be related to river base flow which is explained as follows by Jackson *ed*.(1997): “that part of stream discharge that is not attributed to direct runoff from precipitation or melting snow. It is sustained by ground water discharge.” In general, base flow is closely related to the water level of shallow groundwater aquifer except deep gorge where deep groundwater as well as shallow aquifer can seep through the wall. Judging from shallow valley floors for most rivers in NCP, base flows are strongly related to the water levels of shallow aquifers. The high ratio (about 80 %) of groundwater to the total amount of water seems to be caused by the high density of river channels in NCP where is composed of many alluvial fan and fluvial deposits.

7. Future estimation

If water production continues at the present rate, the deep aquifers would continue to go down and would finally be depleted when it reaches to the bottom of Quaternary formations several hundred meters below sea level. However, the deep aquifers cost so much to pump up and it is not renewable, so pumping would cease well before that.

8. Conclusion

Groundwater level lowering in NCP has occurred extensively at densely populated industrial cities and agricultural districts during past several decades. Available data are summarized as contour maps and cross sections based on the monitoring data along with subsurface Quaternary geologic maps. The comparison of these data revealed that the extents of productive shallow and deep aquifers are generally restricted only in specific regions where Quaternary sand and gravel occur in thick lenticular form. The groundwater resources are regarded as the fossil resource because deep aquifers in middle and eastern regions were dated to be 10,000 to 25,000 years old. Hai River which is the major drainage system of NCP has the highest ratio (about 80 %) in the amounts of groundwater to the total water in China, although surface and groundwater are up to 30 % transitional to each other due to high permeability of Upper Quaternary formations. It is clear that the groundwater is the major water source than surface water in NCP. The high ratio (about 80 %) of groundwater to the total amount of water seems to be caused by the high density of river channels in NCP where is composed of many alluvial fan and fluvial deposits.

Therefore, if overproduction of groundwater continues at the same rate as at present, it should result in depletion or more lowering of water level, and may induce ground subsidence and water quality deterioration. To overcome these problems, it is essential to use water more effectively for irrigation and recycle used water from industrial and domestic sources.

Acknowledgments: The authors are grateful to the

Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences, China Geological Survey, the Ministry of Land and Resources, and China Institute of Geo-Environmental Monitoring for their cooperation on the information gathering of subsurface geology and water table lowering.

References

Chen, J.Y. (2003) Study on nitrate pollution in groundwater in the North China Plain from the viewpoint of groundwater flow system and land-use change based on chemistry and isotopes. PhD Thesis, Chiba University, Japan.

Chen, J., Tang, C., Sakura, Y., Kondoh, A., Yu, J., Shimada, J. and Tanaka, T. (2004) Spatial geochemical and isotopic characteristics associated with groundwater flow in the North China Plain. *Hydrological Processes*, **18**, 3133-3146.

Foster, S., Garduno, H., Evans, R., Olson, D., Yuan T., Weizhen Z. and Zaisheng H. (2004) Quaternary aquifer of the North China Plain - assessing and achieving groundwater resources sustainability. *Hydrogeology Journal*, **12**, 81-93.

Jackson, J. A. *ed.* (1997) Glossary of Geology, fourth edition, Ameriacan Geological Institute, USA. 769p.

Japan Bank for International Cooperation (2004) Issues and challenges for water resources in North China –case of the Yellow River Basin-. JBICI Research Paper No. 28, 55p. with 7p. appendices.

Shao, Shixiong and Wang, Mingde (1989a, chief compilers) Quaternary Map of Huang-Huai-Hai Plain in China (1:1,000,000), Quaternary Lithofacies and Paleogeographical Map of Huang-Huai-Hai Plain in China (1:2,000,000), Quaternary Profile of Huang-Huai-Hai Plain in China (1:1,000,000) and Explanatory Notes to the Quaternary Map and Quaternary Lithofacies and Paleogeographical Map of Huang-Huai-Hai Plain in China, Geology Publishing House.

Shao, Shixiong and Wang, Mingde (1989b, chief compilers) Geomorphologic Map of Huang-Huai-Hai Plain in China 1:1,000,000 and Geomorphologic profiles of Huang-Huai-Hai Plain in China 1:1,000,000 Explanatory Notes of Geomorphologic Map of Huang-Huai-Hai Plain in China, Geology Publishing House (in Chinese).

Zhang, G. H., Chen, Z. Y., and Fei, Y. H. (2000) Relationship between the formation of groundwater and the evolution of regional hydrologic cycle in North China Plain. *Advanced Water Science*, **11(4)**, 415-420. (in Chinese).

Zongyu, C., Zhenlong, N., Zhaoji, Z., Jixiang, Q. and Yunju, N.(2005) Isotopes and sustainability of ground water resources, North China Plain. *Ground Water*, **43(4)**, 485-493.

Zhou, L., Liu, C. F., Jiang, S. and Gao, S. (2001) A study of ^{36}Cl age in Quaternary groundwater of Hebei Plain. Sci. China (Series E) 44. (suppl.), 11-15. (in Chinese).

Received December, 15, 2008
Accepted December, 19, 2008

華北平野の地下水水位低下に関する地質学的解釈

玉生志郎・村岡洋文・石井武政

要　旨

華北平野の地下水は過去数十年にわたり顕著な水位低下を起こしている．その原因は農地への大量の灌漑と都市部での多量の地下水汲み上げである．本報告では，帯水層の観点から地下水位低下を解釈するために，地下水位モニタリング記録と第四系岩相との比較対照を行った．この結果，地下水が豊富に含まれる箇所は，砂礫層がレンズ状に発達している地域に限定されることが判明した．一方，深層地下水の年代が10,000年以上古いと測定されている事から，地下水資源は化石資源と考えざるを得ないことが判明している．従って，現在と同じ速度で地下水の過剰生産を継続すると，地下水の消滅や顕著な水位低下による地盤沈下，水質悪化などの問題が生ずる．この問題を回避するためには，灌漑用水の効率的な使用と工業用水・家庭用水の浄化による再利用が不可欠である．