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Groundwater resources and hydro-environmental problems in China

Groundwater supplies have played a key role in economic progress in China. However, the irrational development of water resources may lead to a variety of environmental problems including the expansion of desertification in arid areas, groundwater pollution, saline intrusion and land subsidence. Ways are being investigated to alleviate the consequences of past practice and to develop methods for the prediction of potential problems.

Introduction

An enormous amount of investigation and research work, including regional hydrogeological surveys and specific prospecting work, has been undertaken during the past 40 years to facilitate water supply to many cities, industrial bases, and agricultural areas. Consequently, groundwater has become an important water source and has played an important role in developing industry, agriculture, and municipal construction, particularly in north China. Unfortunately, many environmental problems have occurred here and there as a direct result of groundwater development. Effective measures are needed to prevent such man-made disasters.

The regional characteristics of groundwater

China has a total land area around 9.6 million km². To date, more than two thirds of the territory has been covered by regional hydrogeological surveying. During the investigation, an assessment of the regional groundwater resource, chiefly calculated by the method of water balance, has also been made. According to preliminary results, the total amount of annual precipitation is about 6×10^{12} m³ for the whole country, while the total natural groundwater resource is around 8716×10^8 m³/year (Chen, 1987).

As for regional distribution, 70% of pore water occurs in north China, and only 30% in south China; while fissure water in the south is three times that of the north, and more than 90% of karst water is in the south (Table 1). It is clear that pore water in the north and karst water in the south are playing important roles as resources.

Table 1 Distribution of groundwater resources in north and south China (10^8 m³/year).

Area	Pore water	%	Fissure water	%	Karst water	%	Total	%
North China	1773.17	70	1139.55	27	192.64	9	3105.36	35.6
South China	730.37	30	3034.08	73	1847.03	91	5611.48	64.4
Total	2503.54		4173.63		2039.67		8716.84	

Table 2 Amounts of groundwater extracted in north and south China (10^8 m³/year).

Area	Pore water	Fissure water	Karst water	Total
North China	540.35 (72.41%)	5.51 (0.74%)	94.63 (12.68%)	640.49 (85.83%)
South China	26.36 (3.53%)	12.27 (1.64%)	67.15 (9.00%)	105.78 (14.17%)
Total	566.71 (75.94%)	17.78 (2.38%)	161.78 (21.68%)	746.27 (100%)

According to statistics, the total annual amount of groundwater exploited throughout the country is about 746×10^8 m³, which is 11.6% of the groundwater resource; 76% of the groundwater exploited annually is from plain areas and 24% from hilly land. With regard to distribution, 86% of the annual extraction is in the north and 14% in the south (Table 2). In the plain areas of north China, the extraction of groundwater is about 72% of the total, compared to only 3.5% in south China. The exploitation of groundwater in the plain areas of north China is chiefly for agricultural use and forms the major part of consumption.

Problems in semi-arid and arid regions

Comprehensive treatment in semi-arid areas

The Huang-Huai-Hai plain of north China is in a typical semiarid area. It has an average annual precipitation from 400 to 800 mm, and potential evaporation reaches 1100 to 1700 mm. It is one of the most important cereal production areas of our country but in the central part of this wide plain, there is a combination of natural hazards such as drought, waterlogging and salinisation. They are inherently linked to each other and closely related to hydrogeological conditions. The water table is shallow and mostly about 1–2 m but shows periodical variations, chiefly controlled by precipitation and evaporation as well as exploitation. According to data from an experimental station in Shangqiu district, both the infiltration of precipitation-groundwater depth relation curve and the evaporation-groundwater depth relation curve reach the maximum and minimum values respectively at 3–4 m (Figures 1–3). This makes it possible to determine an optimum groundwater level to maximise infiltration of rainfall and to minimise evaporation by well-pumping (Chen and Xu, 1986).

A successful experiment known as the 'Shangqiu experience' was carried out in Shangqiu district for the comprehensive control of drought, waterlogging and salinisation. The water table was maintained by pumping at a depth of 3–5 m, which not only increases the infiltration of precipitation to recharge but also reduces evaporation of shallow water to a minimum. In this way, more than 40×10^8 m³ per year of groundwater, previously lost to evaporation, becomes usable. In addition, the aeration zone has a larger storage capacity which can be used as a subsurface regulated reservoir in the long term. According to calculations, the exploitable water resource has increased from 7.45×10^8 m³ to 12.89×10^8 m³.

Figure 1 α -H relation curves (precipitation 70 mm over one hour interval).

Figure 2 α -H relation curves of the Yellow River alluvial plain, Shandong Province.

Figure 3 E-H relation curve at a balance experiment site at Dawuzhuang, Shangqiu, 1984. The aeration zone is composed of clayey sand.

By way of long-term comprehensive harnessing and controlling, more than 400 000 wells have been drilled in the area with an annual pumping rate of $50 \times 10^8 \text{ m}^3$ from a shallow aquifer. Over 80% of the area, the water table was kept at regular depths of 2–4 m and 4–6 m depending on the season. As a result, the area under irrigation was rapidly expanded; the area of saline land was reduced from 210 000 to 66 700 ha, while waterlogging is well controlled. The ecological environment has been greatly improved, and agricultural production has increased.

Ecological effects in arid areas

Enormous inland basins in north-west China fall in the Gobi desert area. The annual precipitation is extremely low, but streams which originate from the melting snow and rainfall in high mountains such as the Tianshan and Qilian mountains, carry large volumes of surface runoff onto the piedmont plain. Almost 60% to 80% of the runoff penetrates the ground via gravel beds in the Gobi area to emerge in spring clusters on the frontal part of the alluvial fan. It then flows into the so called Oasis to become the chief water source for irrigation. The Hexi Corridor is a typical example. Infiltration of streams and canal seepage loss, accounts for nearly 90% of the total groundwater recharge while infiltration of local rainfall is only around 6%. The outflow of spring clusters reaches 45% of the total discharge (Chen, 1990).

During the past 30 years, many reservoirs and cemented channels have been built for the development of water resources. These have resulted in the reduction of groundwater recharge, a drastic decline in groundwater levels and a depletion of spring outflows. On the other hand, the high consumption of water resources in the upper reaches have caused rapid decreases of the inflow into the lower basin, even the interruption of the streams. These tremendous changes in the water environment by human activity have seriously affected the ecologic system of the whole region. The extensive fall in groundwater levels in the lower reaches has caused the decay of vegetation, degeneration of the pasture, deterioration of water quality and the disappearance or reduction of terminal lakes. The final result is the expansion of desertification. For example, the so-called 'green corridor' with a length of more than 300 km on the lower reaches of the Tarim river, the biggest river in Xinjiang, has almost disappeared and is threatened by desertification. The most pressing hydro-environmental problem in arid areas is how to prevent the harmful ecologic effects of such irrational water development.

Problems in urban areas

According to incomplete statistics, among the 181 large and medium cities throughout the country, 61 rely chiefly on groundwater for water supply, and 40 use groundwater and surface water conjunctively. The different grades of exploitation of groundwater in 27 major cities in north China, enables the cities to be classified into four types depending on the characteristics of the groundwater exploitation regimes. Among these 27 cities, 16 belong to depletion and over-exploitation types and the rest belong to balanced and stable types.

The main problems in groundwater resources development in urban areas are water pollution and negative environmental effects of groundwater over-exploitation, such as land subsidence and sea-water intrusion. Based on the data of groundwater quality monitoring for many years, and using methods such as regression analysis, trend extrapolation, probability statistics, and hydrodynamic dispersion, the trends of the polluted substances such as total hardness, mineralisation, nitrates, COD, chlorides in groundwater in urban areas for the above-mentioned 27 cities up to the year 2000 have been predicted. For each polluted substance a grade T_i is given according to the C_i/C_{0i} value. Using the formula:

$$T = \sum_{i=1}^n T_i$$

a comprehensive index of trends T is obtained for each city. The trends are evaluated and classified into five classes as shown in Table 3 (Li, 1988). This shows that the groundwater quality will be very rapidly or rapidly deteriorated in 12 cities (44.4%), rather rapidly and slowly deteriorated in 11 cities (40.8%), and remains stable in four cities (14.8%).

To mitigate land subsidence in Shanghai, a series of counter-measures have been taken since 1966. Consequently, the annual rate of subsidence has gradually decreased from 110 mm/year in 1961 to 2.5 mm/year in 1992, which means that land subsidence in the urban area of Shanghai has been almost brought under control.

A project for the prevention of land subsidence was carried out in Tianjin in 1985, and has already obtained effective results. The

Table 3 Comprehensive evaluation of the trends of groundwater pollution in urban areas up to 2000.

Classes of trends	Trend	Number of cities	%
Very rapid deterioration	20	4	14.8
Rapid deterioration	10–19	8	29.6
Rather rapid deterioration	5–9	4	14.8
Slow deterioration	1–4	7	26.0
Stable	0	4	14.8

Table 4 Changes in the annual rate of subsidence in Tianjin.

	1985	1986	1987	1988	1989	1990	1991
Amount of abstraction ($10^4 \text{ m}^3/\text{year}$)	9696	9662	8015	6645	5274	5182	4918
Artificial recharge ($10^4 \text{ m}^3/\text{year}$)	87	72	77.6	81.6	134	157.5	163.8
Rate of subsidence (mm/year)	86	62	43	24	18	15	17

measures chiefly included the closure of 630 production wells, with $4778 \times 10^4 \text{ m}^3$ of abstraction being curtailed. Meanwhile the amount of artificial recharge increased to $773.5 \times 10^4 \text{ m}^3$ (Table 4). As a result, the rate of annual subsidence decreased from 86 mm in 1985 to 17 mm in 1991 (Chen, 1994).

The process and prediction of seawater intrusion have been studied in some coastal urban areas of China. In Dalian, a correlation analysis has shown that the relationship between the concentration of chloride ions, (Cl), the drawdown (s) and the yield (Q) is as follows: $\text{Cl}=21.6 \text{ s}-1.4$; $\text{Q}=4.07 \text{ s}-2.14$. Taking 250 mg/l as the permissible concentration of chloride ions, one can determine that the permissible drawdown is 12.56 m and the permissible yield is $48.98 \times 10^4 \text{ m}^3/\text{month}$. In Laizhou-Longkou, a prediction of seawater intrusion has been made by establishing a three-dimensional model of seawater intrusion, considering density-related flow. To mitigate seawater intrusion, a subsurface physical barrier was constructed at the mouth of the Huangshui river in Longkou, which formed a subsurface reservoir. In Beihai, Guangxi Autonomous Region, the border of the artesian aquifers at the bottom of the sea was determined graphically to calculate the permissible yield.

Conclusion

To solve these problems, extensive research work on mathematical and management models has been undertaken. However, most of the models have not been fully utilised in practice due to insufficient understanding of hydrogeology and a non-holistic approach. Not only designers and engineers, but also administrative officials should have a correct and comprehensive understanding of the rational development and utilisation of groundwater resources. Only then can a correct strategy and policy be adopted.

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