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Groundwater Exploitation and Its Impact on the Environment in the North China Plain

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Abstract: *The North China Plain (NCP) is one of China's most important social, economic, and agricultural regions. Currently, the Plain has 17,950 thousand ha of cultivated land, 71.1 percent of which is irrigated, consuming more than 70 percent of the total water supply. Increasing water demands associated with rapid urban and industrial development and expansion of irrigated land have led to overexploitation of both surface and the ratio of groundwater resources, particularly north of the Yellow River. In 1993, the ratio of groundwater exploitation to recharge in many parts of the NCP exceeded 1.0; in some areas, the ratio exceeded 1.5. Consequently, about 1.06 million ha of water-short irrigated areas in the NCP also have poor water quality. Persistent groundwater overexploitation in the northern parts of the NCP has resulted in water-level declines in both shallow and deep aquifers. According to data from 600 shallow groundwater observation wells in the Hebei Plain, the average depth to water increased from 7.23 m in 1983 to 11.52 m in 1993, indicating an average water-table decline of 0.425 m/year. Water table declines are not uniformly distributed throughout the area. Depletion rates are generally greatest beneath cities and intensively groundwater-irrigated areas. Water-table declines have also varied over time. With the continued decline of groundwater levels, large depression cones have formed both in unconfined and confined aquifers beneath the Hebei Plain. Groundwater depletion in the NCP has severely impacted the environment. Large tracts of land that overlie cones of depression have subsided, seawater has intruded into previously freshwater aquifers in coastal plains, and groundwater quality has deteriorated due to salinization, seawater intrusion, and untreated urban and industrial wastewater discharge. In order to balance groundwater exploitation with recharge, the major remedial measures suggested are to strengthen groundwater management, to raise water use efficiency, to adjust the water-consumed structure, and to increase water supply.*
Keywords: *Groundwater exploitation, aquifer depletion, environmental impact, remedial measures.*

Introduction

The North China Plain (NCP), also known as the Huang-Huai-Hai Plain for the three major rivers that traverse it, is located in the eastern coastal region of China between 32° and 40° N latitude, and 100° and 120° E longitude. The 1998 population of the NCP was 213.9 million, 172.5 million of whom reside in agricultural areas and 41.4 million in urban areas including Beijing, Tianjin, Shijiazhuang, and Zhengzhou cities. Drainage is generally from west to east. The Plain has a continental monsoon climate. Annual precipitation, most of which occurs during the summer monsoon, ranges from about 800 mm in the south to 500 mm in the north.

One of China's most important social, economic, and agricultural regions, the NCP produces about one-fourth of the country's total grain yield. Its main grain crops are winter wheat and summer maize. The average annual water consumption of winter wheat is 450 mm, which is two to three times the average rainfall that occurs during its growth period. Summer maize consumes about 360 mm, or 70 pecent the total rainfall that occurs during its growth period, leaving insufficient soil moisture to produce a wheat crop the following winter. Therefore, irrigation is necessary to maintain high levels of grain production in the NCP. Currently, the Plain has 17,950 thousand ha of cultivated land, 71.1 percent of which is irrigated, consuming more than 70 percent of the total water supply. As the population has increased, so has the demand for industrial, domestic, and agricultural water. Because these water demands exceed the naturally renewable supply, water shortages have occurred in many urban and irrigated areas. The irrigation water shortage is estimated to be 1.6 billion m^3/year.

Irrigation water is supplied either by surface water or by groundwater, depending upon accessibility. Generally, surface water is used in areas located near rivers or reservoirs, and groundwater is used in areas that lack convenient surface-water supplies. As overexploitation causes the lower reaches of natural streams and rivers to dry up, groundwater has become the default supply source for an increasing number of irrigation systems. This is especially true in the northern part of the NCP, which has relied primarily on groundwater since the 1970s. In the northeastern coastal plain of the NCP, the density of pumped wells has reached more than 19 per km^2, leading to severe groundwater depletion of both unconfined and confined aquifers. Typically, deep, confined aquifers supply big cities and industries, while shallow, unconfined aquifers supply small cities and agriculture.

Persistent groundwater exploitation in excess of natural recharge has induced serious environmental problems. In this paper, we describe some environmental impacts of groundwater exploitation in the NCP and propose some strategies for regional sustainable agricultural water use.

Groundwater Exploitation

Pumping Rates

Increasing water demands associated with rapid urban development and expansion of irrigated land have led to overexploitation of both surface and groundwater resources, particularly north of the Yellow River. In areas where the surface-water supply is insufficient, irrigators have become increasingly dependent upon a steadily decreasing ground-water supply. In 1993, the groundwater exploitation rate (the ratio of groundwater withdrawals to groundwater recharge) in many parts of the NCP exceeded 150 percent, and in some areas, the ratio exceeded 150 percent (Figure 1).

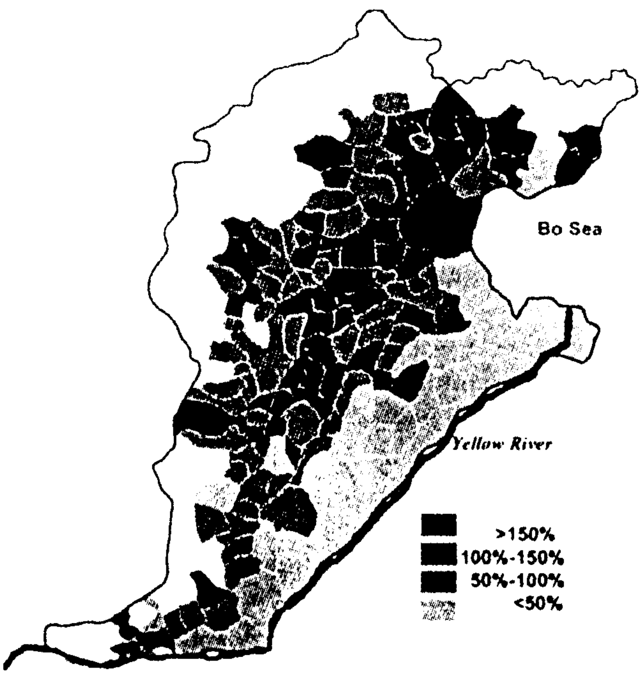

Figure 1. Groundwater exploitation rates in the NCP, 1993.

The Hebei Plain provides a typical example of groundwater exploitation in the NCP. The Hebei Plain covers an area of 73,100 km^2 in Hebei Province, which is in the northern part of the NCP. Prior to groundwater development, farmers relied upon moderate rainfall (500–600 mm) and runoff from the Taihang and Yan Mountains, west of the plain, to water their crops. During the 1950s to 1960s, the shallow groundwater table was 0-3 m beneath the land surface. The presence of flowing wells indicated that the potentiometric surface of the underlying artesian aquifer was, in places, above the land surface. Since the 1970s, however, a series of changes drastically altered the water situation. Rapid development of cities and industries, and the expansion of the irrigated area doubled the water demand.

In 1993, the average exploitation rates for seven urban areas in the NCP were 1.55 km^3 and 2.14 km^3 for shallow and deep groundwater, respectively (Table 1). The number of motor-pumped wells sharply increased from 1,800 in the 1960s to 353,800 in 1973, and reached 825,000 by the end of 1997. Of those wells, 700,000 pumped shallow groundwater primarily for agricultural use. Consequently, average annual withdrawals from shallow aquifers increased from 3,885 km^3 in the 1960s, to 7,913 km^3 in the 1970s, to an average rate of 10,579 km^3 between 1980 and 1997. Annual recharge to the shallow aquifer beneath the Hebei Plain is estimated to be about 7,701 km^3. Therefore, from 1980 to 1997, about 2,878 km^3 of shallow groundwater (with a mean overdraft module of 39,300 m^3) was over-extracted annually. More than 70 percent of groundwater use on the Hebei Plain is concentrated in intensive grain-production areas in the piedmont plains of the Taihang Mountains near Handan, Xingtai, Shijiazhuang and Baoding Cities, where annual overdrafts amount to 2,749 km^3.

Deep groundwater has been exploited since the 1970s in the low-lying flatlands of the middle and eastern parts of the Hebei Plain, where surface water is in short supply and shallow groundwater is saline. About 298 km^3 of deep groundwater was over-pumped from the Hebei Plain from 1980 to 1998, with a mean annual overdraft of 15.66 km^3.

Water-Level Declines

Persistent groundwater overexploitation in the northern parts of the NCP has resulted in water-level declines in both shallow and deep aquifers. According to data from 600 shallow groundwater observation wells in the Hebei Plain, the average depth to water increased from 7.23 m in 1983 to 11.52 m in 1993, indicating an average water-table decline of 0.429 m/year.

Water-table declines are not uniformly distributed throughout the area. Depletion rates are generally greatest beneath cities and intensively groundwater-irrigated areas. For example, along a west-to-east transect from the piedmont to the seashore, water tables have declined less near the seashore than beneath the piedmont (Figure 2) because less water is pumped from eastern than western

Table 1. Groundwater Withdrawals from Selected Urban Areas in the NCP, 1993

		Shallow Groundwater			*Deep Groundwater*		
Urban Area	*Area (km^2)*	*Number of Wells*	*Amount Pumped (10^4m^3)*	*Amount Recharged (10^4m^3)*	*Number of Wells*	*Amount Pumped (10^4m^3)*	*Amount Recharged (10^4m^3)*
Shijiazhuang	253	3,111	43,913	29,688	-	-	-
Baoding	125	2,038	19,274	8,647	45	530	407
Langfang	823	6,890	17,905	16,761	823	5,630	2,821
Cangzhou	195	3,316	4,808	2,420	372	3,728	915
Hengshui	448	216	2,972	1,086	851	3,415	2,065
Xingtai	138	1,274	16,117	12,206	-	-	-
Handan	94	518	11,079	3,888	-	-	-

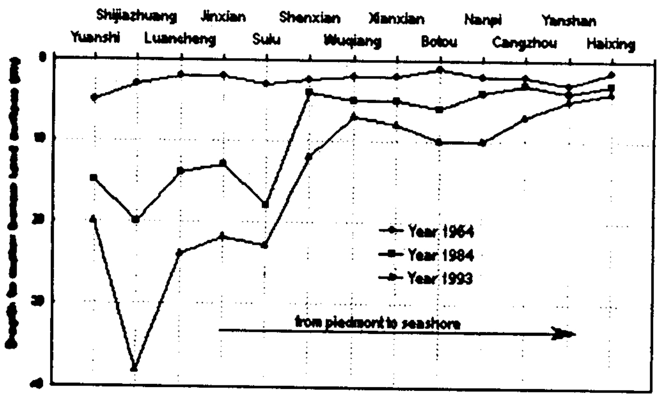

Figure 2. Depths to shallow groundwater in a west-to-east transect across the NCP, 1964, 1984, and 1993.

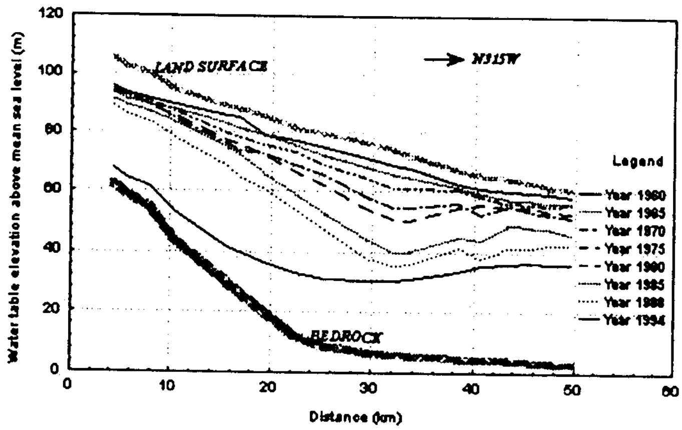

Figure 3. Elevation of the water table at the center of the Shijiazhuang depression cone beneath Shijiazhuang City, 1960–1994.

ern areas. The hydraulic characteristics of the aquifer are such that its natural ability to yield groundwater to wells decreases from west to east (Liu and Wei, 1989). Thus, less water is pumped in the east, and also the irrigation rate (the ratio of irrigated area to cultivated land) decreases from 97 percent to 26 percent from the piedmont to the seashore. Intensive exploitation has resulted in average water levels beneath the piedmont cities of Handan, Xingtai, Shijiazhuang and Baoding declining 0.54 m/year from 1980 to 1997.

Water-table declines have also varied over time. For example, the mean annual water-level decline beneath Shijiazhuang City increased from about 0.8 m between the 1970s and 1980s to 1.0-1.2 m in the 1990s (Figure 3). As another example, the water table beneath Luancheng Agro-ecological Systems Station, Chinese Ecological Research Network, Chinese Academy of Sciences, declined from a depth of about 3 m below the land surface in the 1950s to about 30 m in the 1990s (Figure 4). The annual water table drop beneath the Hebei Plain between 1984 and 1993 was about twice that during 1964 to 1984 (Table 2).

Deep aquifers, like the shallow ones, have become seriously depleted. For example, Cangzhou and Hengshui Prefectures in Hebei Province depend upon withdrawals from deep, confined aquifers. Although the quantity of

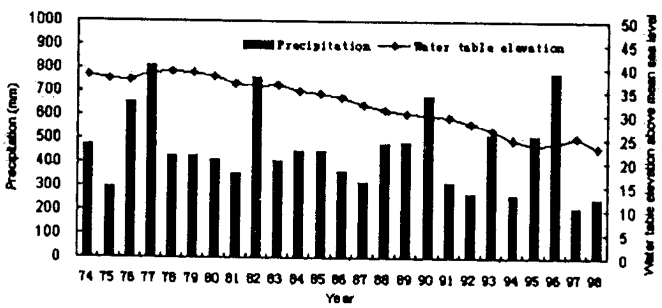

Figure 4. Annual precipitation and elevation of water table beneath Luancheng Station, Hebei Province, 1974–1998.

Table 2. Average Water-table Depths Beneath the Hebei Plain, 1964, 1984, and 1993

	Land area overlying water table of given depth							
	<4 m		*4-10 m*		*10-20 m*		*>20 m*	
Year	*10^4 km^2*	*%*	*10^4 km^2*	*%*	*10^4 km^2*	*%*	*10^4 km^2*	*%*
1964	7.18	98	0.13	2	0	0	0	0
1984	1.26	17	3.94	54	2.0	27	0.11	2
1993	1.33	18	3.32	45	1.75	24	0.91	13

Source: Tian et al., 1998.

available deep groundwater is severely limited, it has been mined extensively because the shallow groundwater is saline and surface-water supplies have dwindled since the 1970s. In the initial stages of exploitation, artesian water levels were near the land surface; some wells were even flowing. However, the persistently high rate of groundwater withdrawal led to a water-level decline of two to three meters annually by the 1980s, and to the formation of large cones of depression. Currently, the centers of the cones of depression are declining at a rate of about 1.0 to 1 m/year, and extend to depths of about 92 m and 76 m beneath Cangzhou and Hengshui Prefectures, respectively.

Thus, by the 1990s, both shallow and deep groundwater levels were declining at rates of more than 1 m/year beneath intensive exploitation areas of the Hebei Plain, and depths to groundwater in shallow and deep aquifers exceeded 40 m and 90 m below land surface, respectively, in some areas of the Hebei Plain (Figures 5a, 5b, 5c, and 5d).

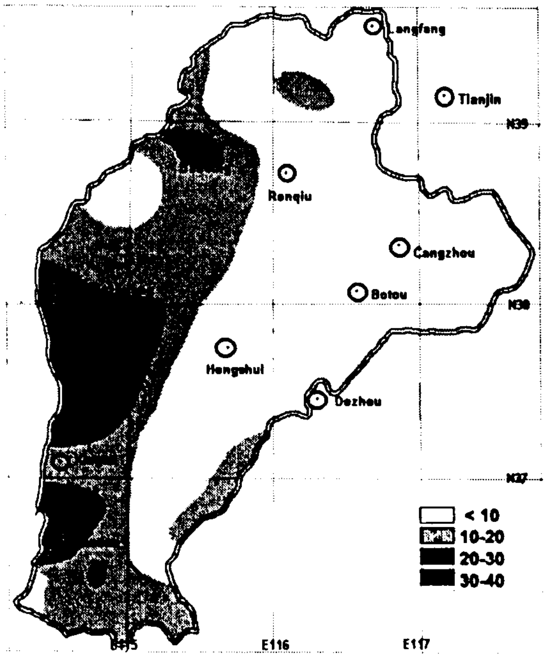

Figure 5a. Depth to water table (m below land surface) beneath the Hebei Plain, 1992.

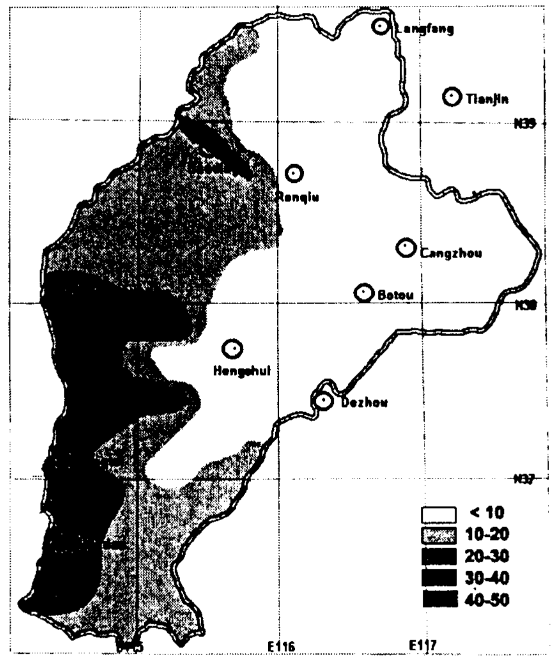

Figure 5b. Depth to water table (m below land surface) beneath the Hebei Plain, 1998.

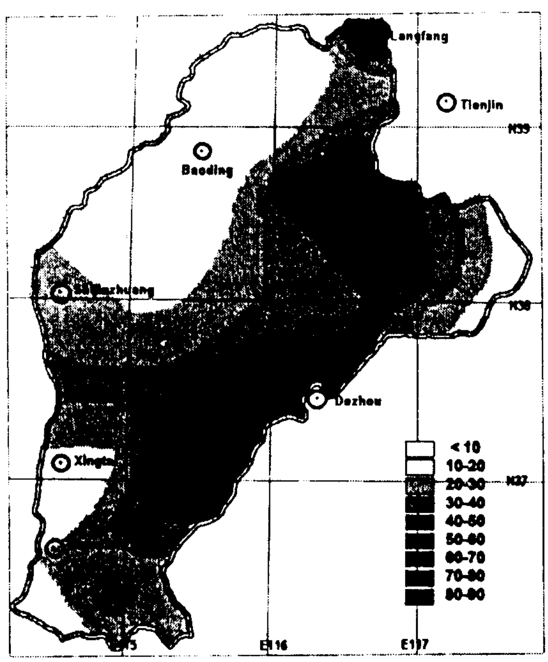

Figure 5c. Depth to water table to potentiometric surface (m below land surface) beneath the Hebei Plain, 1992.

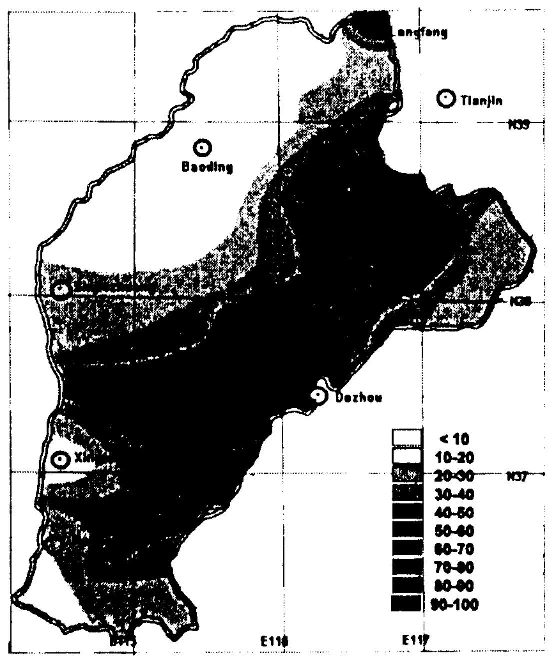

Figure 5d. Depth to water table to potentiometric surface (m below land surface) beneath the Hebei Plain, 1998.

With the continued decline of groundwater levels, large depression cones have formed and expanded both in unconfined and confined aquifers beneath the Hebei Plain (Figures 6 and.7). By the end of 1997, 11 cones of depression in the shallow aquifer extended beneath an 8,598-km² area. The Shijiazhuang depression cone, Baoding depression cone, Ning-Bai-Long depression cone, and Gao-Zhuo-Qing depression cone are among the well-known depression cones beneath the NCP. Beneath Shijiazhuang City, the depth to the center of the cone in 1994 was 42.53 m. Thus, 62 percent of the total original thickness of the 69 m aquifer had been depleted (Figure 3).

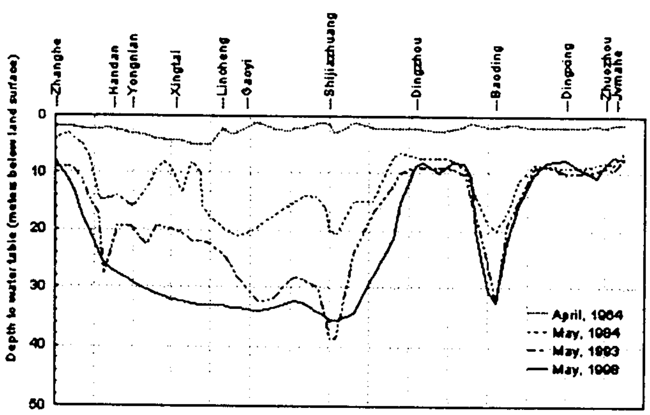

Figure 6. Depths to shallow groundwater in a south-to-north transect across the NCP, 1964, 1984, 1993, and 1998.

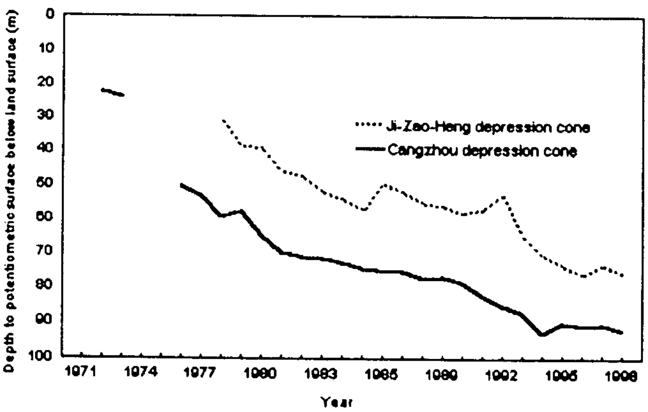

Figure 7. Depths to potentiometric surface at the centers of two typical cones of depression in the deep aquifer underlying the NCP.

Ten large cones of depression with a total area of 30,900 km² existed in deep aquifers beneath the eastern part of the Hebei Plain by the end of 1997. Two famous compound depression cones are the Ji-Zao-Heng depression cone and the Cangzhou depression cone. The Ji-Zao-Heng depression cone first formed beneath Hengshui City in the early 1970s, and by 1997 had expanded to an area of 11,051 km² and a depth of 75.68 m below land surface at its center (Figure 7). This increase represents an average expansion rate of 305 km²/year in area and 1.74 m/year in depth. The Cangzhou depression cone first formed beneath Cangzhou City in 1967, and by 1997 had expanded to an area of more than 10,000 km² and a depth of 92.42 m at its center (Figure 7). The water-level decline at the center of the cone averaged 3.8 m/year from 1971 to 1985 and 1.4 m/year from 1985 to 1997. Recently, cones of depression in the deep aquifer beneath the areas between and including Tianjin City and Dezhou City have merged together, creating a regional depression cone.

Impacts

Groundwater depletion in the NCP has severely impacted the environment. Large tracts of land that overlie cones of depression have subsided, seawater has intruded into previously freshwater aquifers in coastal plains, and groundwater quality has deteriorated due to salinization, seawater intrusion, and untreated urban and industrial wastewater discharge.

Land Subsidence

Loss of subsurface hydraulic pressure due to groundwater depletion has resulted in widespread land subsidence in the NCP, particularly in the Hebei Plain (Table 3). As of 1995, 17 land-subsidence areas had been identified, including about 40,000 km² of southern Haihe Basin that had subsided more than 200 mm (Table 4). Subsidence in Xushui County of Baoding City, Hebei Province, cracked the walls of more than 200 buildings by 1995.

Land subsidence in excess of 2 m has serious implications for China's third largest harbor, the Xingang area of Tianjin. As a result of land subsidence, the elevations of the harbor structures are now lower than the design criteria, which has weakened their capability to resist storm surges. In 1985, when attacked by two successive storms, the wharves in Xingang became flooded and most of the freight yards and storehouses were submerged.

In addition to land subsidence, land fissures first appeared in Handan City in the mid-1960s. Now, nearly 200 fissures have been identified in 65 towns of 35 cities in the Hebei Plain. Fissures of several to 500 m in length and as much as 2 m in width threatened urban construction, transportation facilities, river flood protection, and personal property.

Degradation of Water Quality

About 1.06 million ha of water-short irrigated areas in the NCP also have poor water quality. One reason is that groundwater depletion has affected the interaction between fresh and saline groundwater. In parts of the NCP, shallow, saline ground water overlies deeper fresh groundwater. However, pumping from the freshwater zone has lowered the fresh/saline interface, thus inducing saline water to flow downward into previously freshwater aquifers. For example, in Changxian and Fucheng Counties of the Heilonggang River basin, the fresh/saline interface dropped an average of 10 m and a maximum of 30 m.

Groundwater salinity is especially a problem in coastal

Table 3. Land Subsidence in the NCP

City or Province	*Land subsidence area (km²)*	*Number of Cases and Amounts and Rates of Subsidence*
Tianjin City	10,000	One case found in 1959. Maximum subsidence was 2.916 m, with a maximum subsidence rate of 80 mm/y.
Shandong Province	52.6	Three cases found in Heze City in 1978, Jining City in 1988, and Dezhou City in 1978. Maximum subsidence of 0.077 m, 0.063 m and 0.164 m, respectively.
Henan Province	59	Four cases found in Xichang City in 1985, and in Kaifeng City, Luoyang City, and Anyang City in 1979. Maximum subsidence of 0.208 m, unknown, 0.113m and 0.337m, respectively.
Hebei Province	36,000	Ten cases found in Changzhou, Heshui, Renqiu, Hejian, Bazhou, Yimuquan of Baoding, Dacheng, Nangong, Feixiang, and Handan in the mid 1950s. The most serious case is in Cangzhou with 1.823 m of subsidence by 1996.
Shanxi Province	200	Four cases found in Taiyuan in 1979, and in Datong, Yuci, and Jiexiu in 1988. Maximum subsidence of 1.967 m, 0.06 m, unknown, and 0.065 m, respectively.
Beijing City	313.93	One case found in late 1950's. Maximum subsidence of 0.597 m.

Source: Chen, 2000.

areas, where groundwater depletion has led to seawater intrusion into previously freshwater aquifers. For example, in Laizhou, the rate of lateral seawater intrusion has increased from 50 m per year during 1976 to 1979 to 404.5 m in 1988. The area affected by seawater intrusion increased from 11.4 km^2 in 1979 to 149.9 km^2 in 1985 (Yin, 1992). By 1993, approximately 429.1 km^2, or 44 percent of the total area of the coastal plain in Laizhou City, was affected. As a result, the overlying farmland area could no longer be irrigated and gradually became salinized, decreasing the area's agricultural production by 20 to 40 percent (Yu et al., 1999).

In addition, hydraulic gradients increased due to overexploitation, which induced untreated wastewater discharge from a variety of urban, industrial, and agricultural sources to flow into the underlying aquifer. However, the depleted aquifers have a reduced ability to dilute contamination. Consequently, groundwater contamination has been found in some areas. For example, the concentrations of Cr^{6+} in groundwater in Shijiazhuang City, NH_4-N in Xingtai City, and phenol and NH_3^- in Baoding City all exceed national drinking-water standards.

Remedial Measures

The renewability of groundwater resources is the foundation of water resources management and must be considered to achieve sustainable utilization of groundwater. The renewability of water resources is expressed as an exchange cycle:

$$d = s / \Delta s$$

in which *d* is the exchange cycle or period of groundwater renewal period (year); *s* is the aquifer storage capacity (cubic meters); and *delta s* is the annual change in groundwater storage (m^3/year). Using this formula, we estimate the *d* value of shallow groundwater in the NCP to be about eight to ten years. In contrast, confined groundwater below a depth of 30 meters has an isotopically (C^{14}) determined age of 6,000 to 7,000 years indicating that deep groundwater was recharged over historic and geologic time (Liu and You, 1994).

The following major remedial measures are suggested to achieve sustainable groundwater use and to reduce the environmental impacts of groundwater exploitation.

Strengthen Groundwater Management

Since deep groundwater was recharged thousands of years ago, it would be very slow to recover from overexploitation. Therefore, it is essential that laws be passed to stop mining deep aquifers in the areas where cones of depression have appeared. The quantity of groundwater withdrawals must be limited to the groundwater recharge capacity in order to prevent further depletion. The permitted withdrawal should be allocated to regions of the NCP according to groundwater availability to prevent overexploitation. The water pricing policy should be adjusted to strengthen water withdrawal controls according to the amount permitted. For instance, the price for water withdrawal should differ for different water withdrawal levels according to whether the actual water pumped exceeds the amount permitted. The water user must pay a penalty price which is two or three times higher than the normal price for withdrawals above the norm.

Raise Water Use Efficiency

In the North China Plain, irrigation is the major water consumer, however, irrigation water is wasted. About 55 percent of irrigation water in surface-water irrigated areas and 35 percent in groundwater-irrigated areas are lost

Table 4. Accumulated Land Subsidence in the Southern Haihe Basin, 1995

Accumulated subsidence (mm)	*>200 mm*	*>300 mm*	*>500 mm*	*>1,000 mm*
Area (km²)	40,000	15,224	4,009	504

to seepage from canals and evaporation from fields. Improvements in water use efficiency are essential for decreasing groundwater withdrawal in the water-short NCP. By analyzing annual rural water consumption rates on the piedmont plain, Chen (1999) determined that irrigation overdrafts consume 40–160 mm/year, or an average of about 100 mm/year. However, field experiments have shown that by mulching winter wheat with plastic membranes and mulching summer maize with wheat straw, this entire quantity of water can be saved without decreasing productivity (You and Wang, 1996). Further experiments demonstrated that by combining pipe delivery, mulching, irrigation control, and other water-saving measures, water efficiency (ratio of crop yield produced to water volume consumed) can be increased to 1.5 kg/m^3 and irrigation applications can be reduced by more than 100 mm. Therefore, shallow groundwater depletion can conceivably be effectively controlled through water-saving agronomic technologies in the piedmont plain. Industrial water use efficiency is also low in the NCP. The present industrial water reuse rate reaches 80 percent in only a few metropolises, while the rate is just 50 percent in most cities, and some town industries seldom or never reuse water (Wang et. al, 2000). Industrial output value per cubic meter is about 200 yuan (US$25/$m^3$). Therefore, by raising industrial water use efficiency, both the reuse rate and the output value per cubic meter will increase.

Adjust Structure of Water Use

Some adjustments in industrial and agricultural structure should be carried out in order to eliminate conflicts between water supply and demand. For example, large water-consuming factories should be moved away from serious aquifer depletion areas, and drought-tolerant crops should replace the high water-consuming ones. In the northern part of the NCP, spring corn, winter wheat, and summer maize in two-year rotations should replace winter wheat – summer maize in one-year rotations, because the former cropping sequence consumes less water than the latter one with almost the same annual yield (Yu, 1995).

Increase Water Supply

The economic development of the NCP is important to its position in the nation's economy. However, the local water resources are insufficient to improve the ruined environment while supporting environment-friendly economic development at the same time. Increasing the water supply is necessary because the water demand goes far beyond the capacity of water resources. The recommendations are: (1) develop and utilize inferior water including polluted drainage water, saline water and seawater; (2) increase rainfall infiltration by efficient conjunctive use of groundwater and surface water, or by artificially recharging groundwater with flood runoff; and (3) transfer water from the Yangtze River to the NCP.

Conclusions

Increasing water demands associated with rapid urban development and expansion of irrigated land have exceeded the naturally renewable water supply, resulting in overexploitation of water resources in the NCP, one of China's most important social, economic and agricultural regions. Groundwater overexploitation began in the 1970s and became serious after the 1980s in the areas with intensive groundwater withdrawals, especially in the northern part of the NCP. Consequently, water levels in both unconfined and confined aquifers are declining rapidly and groundwater depression cones have developed and expanded. Groundwater overexploitation has induced serious environmental problems such as land subsidence and groundwater quality degradation, which further reduces groundwater renewability. Thus, the gap between water supply and demand will intensify. The challenge is to balance water supply and demand with environment-friendly solutions. The planned transfer of water from the Yangtze River will certainly increase the water supply in the NCP eventually. In the meantime, we must exploit the potential of local water utilization. First, strengthen groundwater management by imposing laws and a water price policy to limit water withdrawals. Second, raise water use efficiency by applying suitable water-saving techniques. Third, adjust the present structure of use and allocation of water within industry and agriculture in order to adapt to the water availability. Fourth, increase the water supply by purifiying polluted surface water, and utilizing saline groundwater and seawater. The planned water transfer from the Yangtze River to the NCP is the most important option for increasing the water supply. The authors here only give some macro-level ideas for achieving sustainable water use in the NCP and more detail measures for specific places over NCP need to be studied further.

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