Availability, Status of Development, and Constraints for Sustainable Exploitation of Groundwater in China

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Abstract

China is one of the 13 most water-deficient countries in the world and water shortage is limiting the development of its economy. The authors present an overview of the availability, status of development, and constraints for sustainable exploitation of groundwater in China. Groundwater is the most important or exclusive water source in arid or semi-arid regions of north and northwest China. Average groundwater recharge in China is estimated to be 883.6 billion m^3/yr, approximating 31 percent of the nation's total water resources. Estimated allowable yield of fresh groundwater resource is 352.8 billion m^3/yr, or 40 percent of total available amount. Groundwater pollution occurs in many areas of the country, and especially in urban areas. Main pollution sources are industrial and domestic pollution. Current groundwater use approximates 20 percent of total water use of China. Groundwater in the North China Plains (NCP) is over-exploited, being 52 percent of its total water supply for all purposes. Total annual groundwater abstraction in China increased from 57.2 billion m^3/yr in the 1970's to 111.5 billion m^3/yr in 1999. Groundwater in south China has great potential for development. To accommodate new water resource management concepts and challenges, China has promulgated many laws and rules in the 1980s and the 1990s and still drafts complementarities and modifies previous ones. The policy shifted several years ago; the primary emphasis from structural engineering interventions to water supply and control problems, and to recognition of the need for a more comprehensive and diffused notion of water as a resource to be developed and managed in response to changing market criteria. Sustainable use of groundwater requires comprehensive efforts from scientists, decision makers and all individual water users. The most important things are: to enhance public awareness and knowledge of groundwater; and to create work environments for better communication among water managers, planners, decision-makers, scientists, water users, etc. and reduce the gaps among different parties.

Introduction

China is a country with relatively limited and uneven distributed water resources, yet it has to meet the challenge of supplying usable water to its 1.3

billion citizens. China is the third-largest country in the world, with land ranging from plains to mountains having some of the highest peaks in the world. Mountainous regions comprise 33 percent of the country, plateaus 26 percent, basins 18.8 percent, plains 12 percent and hills 9.9 percent.

China has the third-largest river in the world, the Yangtze River, stretching over 6,300 km. Other major rivers include the Yellow River (stretching 5,464 km), the second largest in China, and the Huai River, which is one of the most polluted. Aside from natural waters, China possesses the longest man-made river in the world, the Grand Canal in the eastern coastal area, reaching 1,801 km in length, from Hangzhou in the south, via Nanjing, Shandong, Tianjin to Beijing in the north (See Fig 1 for detail).

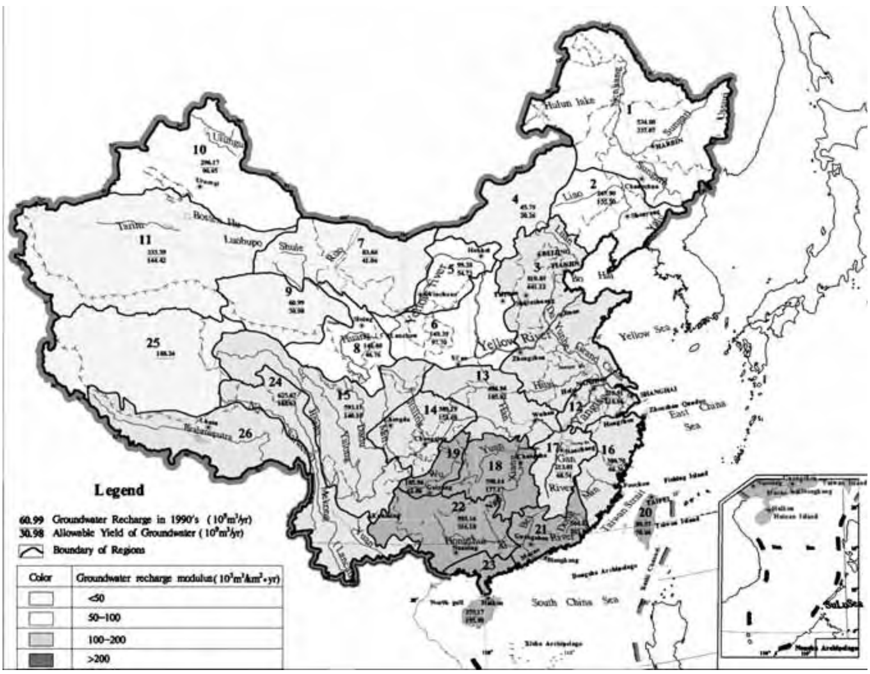

Figure 1. Distribution of groundwater resources in China

1.Hei-Song catchments; 2.Liao river catchments; 3.Huang-huai-hai region; 4.North Inner Mongolia plateau; 5.Ordos plateau and Yinchuan plain; 6.Loess plateau; 7.Hexi Corridor; 8.Upper reaches of Yellow River; 9.Saidam basin; 10.Dzungaria basin; 11.Tarim basin; 12.Lower reaches of Yangtze; 13.Middle reaches of Yangtze; 14.Sichuan basin; 15.Jinsha river catchments; 16.Min-zhe hilly land areas; 17.Boyanghu water systems; 18.Dongting water systems; 19.Wujiang catchments; 20.Taiwan; 21.Pearl river and Hanjiang; 22.Xijiang; 23.Lei-qiong areas; 24.Salween, Lancang catchments; 25.North Tibet plateau; 26.Brahmaputra

China is the most populous country in the world, and it is listed as one of the 13 most water-deficient countries in the world, having more than half of its cities suffering from a water deficit. The average total amount of water resources in China is 2812 billion m^3/yr (Chen, 1998), but the per capita water resource is only about 2200 m^3, which is only 31 percent of the world average. Table 1 shows the distribution of water resources in China. Water shortage and increasing levels of pollution are limiting development of the local economy, especially in agriculture and industry in many regions. Agricultural, industrial and urban entities all vie for limited precious water resources.

Influenced by monsoon climate, the distribution of water resources in China is extremely uneven in time and space. There is abundant water in the south but little land that can be used for agriculture due to the mountainous regions, while less water but more land is available in the north. Dryland makes up the majority of China's farmland (about 70 percent) and is affected greatly by water shortage, in the sense of unpredictable and unreliable rainfall. Most dryland is located in the north of China with arid or semi-arid conditions, of very low precipitation and a very high evaporation rate. Since agriculture is dependent upon water, the lack thereof can lead to poverty. Discrepancy between water availability and demand is becoming more and more serious, especially in the North and Northwest. The fundamental problem is that demand increases with increasing population, standard of living, urbanization and industrialization.

Table 1. Water resources in China in 2002[1]

Catchments/Regions	Rainfall (10^9 m^3)	Surface water (10^9 m^3)	Ground water (10^9 m^3)	Water deducted[2] (10^9 m^3)	Total water resources (10^9 m^3)	Per capita water res. (m^3)
Song-liao river	570.986	107.603	57.642	29.695	137.298	1157
Hai-river Basin	127.381	6.408	14.609	9.491	15.899	121
Huai-river Basin	237.591	44.536	34.366	25.647	70.183	343
Yellow River	322.487	35.766	33.401	11.574	47.340	428
Yangtze River Basin	2102.393	1078.831	270.493	10.248	1089.079	2521
Pearl River	987.692	522.721	124.435	2.392	525.113	3328
Southeastern	387.188	230.062	62.873	1.274	231.436	3233
Southwestern	888.702	563.983	172.506	0.068	564.051	26844
Inland Basins	636.609	134.419	99.393	11.312	145.731	5263
Total	6261.029	2724.329	869.718	101.701	2826.130	2200

Note: (1) Data from the annual report of 2002 by the Ministry of Water Resources PR China. Water resources in Taiwan, Hong Kong and Macao are not included in the table. (2) The water deducted is the water volume that has to be subtracted from the sum of surface and groundwater due to the interrelation between surface water and groundwater.

Total water use in China has increased in the past 5 decades (Table 2). It has been about 550 billion m^3 in recent years, being 5 times more than that in 1949 (103 billion m^3). Yet, the percentage of water use in agriculture has decreased from 97 percent in 1949 to 68 percent in 2002, which is because domestic and industrial use has substantially increased.

Availability of Groundwater Resources in China

Regional Hydrogeology of China

Groundwater resources comprise an important part of water sources in China. Especially in semi-arid and arid regions of north and northwest China, groundwater is the most important or exclusive water source.

Table 2. Total annual water use in China (10^9 m^3)

Year	Total water use	Industry	Agriculture	Domestic
1949	103.1	2.4 (2.33%)	100.1 (97.09%)	0.6 (0.58%)
1957	204.8	9.6 (4.69%)	193.8 (94.63%)	1.4 (0.68%)
1965	274.4	18.1 (6.60%)	254.5 (92.75%)	1.8 (0.66%)
1979	476.7	52.3 (10.97%)	419.5 (88.00%)	4.9 (1.03%)
1980	440.3	41.8 (9.5%)	370.7 (84.2%)	27.4 (6.3%)
1997	556.6	112.1 (20.1%)	391.7 (70.4%)	52.5 (9.4%)
1999	559.1	115.9 (20.7%)	386.9 (69.2%)	56.3 (10.1%)
2000	549.8	113.9 (20.7%)	378.4 (68.8%)	57.5 (10.5%)
2002	549.7	114.3 (20.8%)	373.8 (68.0%)	61.6 (11.2%)

Note: Data from annual reports by the Ministry of Water Resources and Liu and Chen (2001).

Physiographic and hydrogeological conditions of China vary greatly in different regions. From the 1950s, regional hydrogeological mapping, primarily on the scale of 1:200,000, has been carried out under the Ministry of Geology. Regional surveying has covered most areas of the territory.

Based on regional hydrogeological mapping, China is characterized by a great complexity of its regional hydrogeological conditions and may be divided into the following six main hydrogeological regions (Fig 2, Chen and Cai, 2000):

- The Songliao Plain and Huang-Huai-Hai Plain, with enormously thick unconsolidated sediments forming multiple aquifers recharged principally by vertical infiltration of rainfall.
- Inner Mongolian Plateau and Loess Plateau, an intermediate zone between the semi-humid zone in the east and the dry desert zone in the west.
- The Western Inland Basins, consisting mainly of the Hexi Corridor, Dzungaria Basin, Tarim Basin and Saidam Basin, typical arid desert land, usually with plenty of groundwater in broad piedmont plains.
- The Southeast and Central-south Hilly Land, characterized by different kind of rocks widely exposed, fissure water dominates in this area.
- The Southwest Karst Hilly Land, characterized by wide distribution of carbonate rocks, where karst water and subterranean drainage are well developed.
- The Tibet Plateau, with an average elevation of around 4000m. The aquifers are mainly of the permafrost or glacial genetic type and groundwater is entirely under the control of vertical zoning.

According to medium of aquifers, groundwater in China can mainly be classified as pore water, karst water and fissure water. Pore water is most prevalent and used most intensively. Karst water takes second place and fissure water last.

Available Groundwater Resources and the Distribution

Based on regional groundwater investigations and observation data mainly in the 1990s, it is estimated that total groundwater recharge (renewable fresh groundwater resources) in China amounts to 883.6 x 10^9 m^3/yr, approximating 31 percent of total water resources. Allowable yield of fresh groundwater resource is 352.8 x 10^9 m^3/yr, or 40 percent of total available amount (Ministry of Land and Resources, 2003). Allowable yield of brackish water (1-3 g/L in TDS) is 13 x 10^9 m^3/yr.

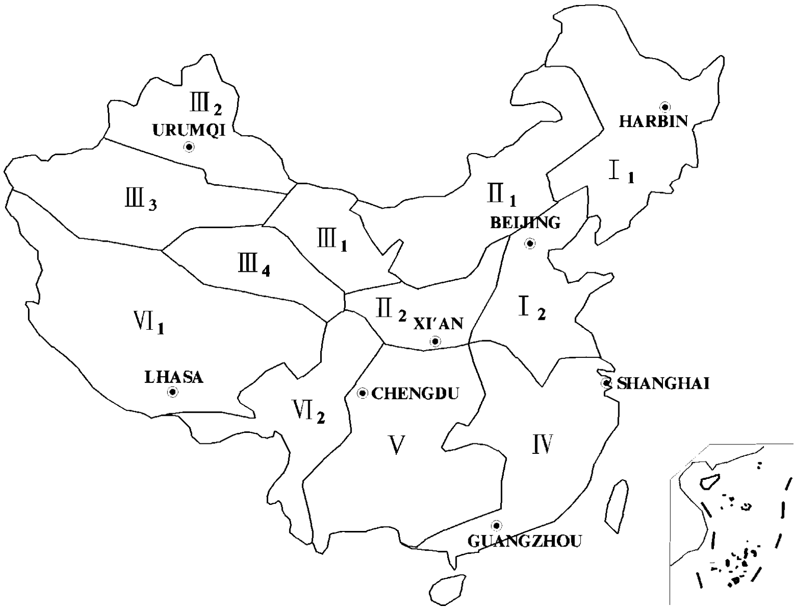

Figure 2. Hydrogeological regions in China (Insert: South China Sea)(Chen and Cai, 2000)
I_1. The Songliao Plain; I_2. Huang-Huai-Hai Plain; II_1. Inner Mongolian Plateau; II_2 Loess Plateau; III. The Western Inland basins; IV. The Southeast and Central-south Hilly Land; V. The Southwest Karst Hilly Land; VI. The Tibet Plateau

In the Standard for Hydrogeological Investigation of Water Supply (GAQSIQ and MOC, 2001), the allowable yield of groundwater resources is defined as: the water amount that can be sustainably abstracted from a groundwater system or a hydrogeological region by a certain rational pumping technique and scheme, resulting in a drawdown and variation of water quality that are within allowable ranges without any permanent damage to the geo-environments.

Distribution of regional groundwater in China has been estimated in 26 regions based on hydrogeological conditions (see Figure 1 and Table 3). Recharge modules for Pearl River Catchments is 322.4 x 10^3 $m^3/km^2 \cdot yr$; Yangtze River Catchments 148.2 x 10^3 $m^3/km^2 \cdot yr$; Yellow River Catchments is 61.1 x 10^3 $m^3/km^2 \cdot yr$; and Northwest area is less than 50 x 10^3 $m^3/km^2 \cdot yr$.

Groundwater in southern China is abundant, accounting for 71 percent of total national groundwater resources, while groundwater in northern China covering 60 percent of the land accounts for 29 percent only, and northwest regions covering one third of the land accounts for only 13 percent.

Besides, affected by population, farmland, and economy development, there exists great differences in groundwater availability per person and per ha farmland throughout the country. Water availability per person and per ha farmland is the lowest in the North China (Hai-river, Huai-river and Yellow River Basin), and the highest in southwest regions (Table 1). Groundwater per person in southeast and south-central regions is higher than north and northeast region of China. Groundwater per person in southwest is two times higher than the average of the country (Chen and Ma, 2002).

Table 3. Available groundwater resources in China[1]

Regions[2]		Average groundwater recharge in the 1990s		Allowable yield of groundwater	
		(10^9 m^3/yr)	(10^3 m^3/km^2·yr)	(10^9 m^3/yr)	(10^3 m^3/km^2·yr)
Yellow River Catchments	1. Hei-Song catchments	52.051	58.6	32.834	36.6
	2. Liao river catchments	24.647	86.3	15.474	109.1
	3. Huang-huai-hai region	63.533	114.6	51.210	101.8
	12. Lower reaches of Yellow River[3]	4.045	162.2	4.053	162.1
	6. Loess plateau	13.054	54.2	9.375	64.0
	5. Ordos plateau and Yinchuan plain	7.285	56.1	3.958	31.4
	8. Upper reaches of Yellow River	14.144	62.5	4.378	20.9
	Sum	38.528	61.1	21.764	43.0
Inland basins	4. North Inner Mongolia plateau	4.008	16.4	1.721	16.7
	7. Hexi Corridor	6.323	20.4	3.206	11.7
	9. Saidam basin	6.099	29.6	3.098	17.1
	10. Dzungaria basin	29.617	72.4	9.045	48.7
	11. Tarim basin	33.339	31.7	14.442	30.2
	25. North Tibet plateau	10.520	27.0	-	-
	Sum	89.906	34.5	31.512	25.8
Yangtze river catchments	12. Lower reaches of Yangtze	18.082	163.1	9.814	88.6
	13. Middle reaches of Yangtze	49.486	173.1	18.582	67.8
	14. Sichuan basin	38.919	196.4	15.369	77.6
	15. Jinsha river catchments	59.244	86.1	14.210	30.1
	17. Boyanghu water systems	21.300	133.8	6.854	44.1
	18. Dongting water systems	59.014	231.2	17.717	69.4
	19. Wujiang catchments	18.596	209.6	6.286	70.8
	Sum	264.641	148.2	88.832	57.2
Pearl river catchments	21. Pearl river and Hanjiang	56.181	382.0	20.086	222.8
	22. Xijiang	98.516	296.0	31.618	101.1
	25. Sum	154.697	322.4	51.704	128.3
	16. Min-zhe hilly land areas	38.578	189.7	6.797	57.2
	20. Taiwan	9.056	251.6	5.686	157.9
	23. Lei-qiong areas	37.233	415.3	19.406	216.5
	24. Nujiang(Salween), Lancang catchments	62.122	152.8	15.865	44.1
	26. Brahmaputra (Yaluzangbu)	52.701	136.7	15.747	40.8
	National total	883.648	106.1	352.778	57.0

Note:: (1) Data from Ministry of Land and Resources, China, 2003; (2) Location see Fig. 1.; (3)The number of Huang-Huai-Hai region includes 4.045 billion m^3/yr of the lower reaches of Yellow River.

Status of Groundwater Development in China

General Status

Groundwater abstractions in China in the past three decades are shown in Table 4. From the table we can see that total annual groundwater abstraction increased from 57.2 billion m^3/yr in the 1970s to 111.6 billion m^3/yr in 1999.

Current groundwater abstraction accounts for 20 percent of total water use in China.

The area with the highest intensity of groundwater exploitation is north China plains (NCP) where groundwater plays a very important role to water supply and approximately provides 52 percent of total water use. For urban ,domestic and industrial use, groundwater contributed 80~90 percent in 1999. For agricultural use, groundwater contributed approximately 38 percent on the average in the NCP. In Hebei province, groundwater occupies 75 percent of total water supply and beyond 50 percent in Shanxi and Henan province (MLD, 2003).

Influenced by the distribution of water resources and population and economic development and groundwater exploitation conditions, the imbalance of groundwater supply and demand is very serious in cities of north China. So far, there are almost 400 cities whose main water sources are groundwater. More than 300 cities suffer from water stress and scarcity, which are mainly located in the north China.

Furthermore, groundwater pollution in urban areas is rather serious. An uncompleted statistics showed that there are 136 large and medium cities where groundwater has been contaminated to varying degrees. Main pollution sources are industrial and domestic pollution. Groundwater has been polluted also in some agricultural regions, mainly near suburbs. There were over 1.33 M ha farmland irrigated with industrial wastewater in 2000, directly polluting groundwater there. Groundwater is polluted by pesticides and fertilizers in some areas (Chen and Cai, 2000). There are observation networks of groundwater throughout China; some wells are monitored thrice a year and some once a year.

Over-exploitation of Groundwater in Northern China

Groundwater in northern China (especially Hebei, Beijing and Tianjin provinces) has been intensively exploited. In most areas of northern China, especially large and medium sized cities, groundwater has been seriously overexploited (CIGEM, 2003).

For example, actual groundwater abstraction in Hebei province in 1999 was 14.946 billion m^3 (including 2.196 billion brackish groundwater of TDS 1-5g/L), but its recharge of fresh groundwater is estimated at 13.160 billion m^3 and the allowable yield of fresh groundwater is only 9.954 billion m^3/yr. This means that about 1.8 billion m^3 of fresh groundwater is overexploited every year. The overexploitation has resulted in serious environmental problems.

Because of the monsoon influence, the rainfall and runoff in the semi-arid Hebei are highly variable over the year, with, 60-70 percent of the annual precipitation (500-600mm) and runoff being concentrated between June and August. This water resource seasonality thus produces a spectrum of natural disasters such as spring droughts, autumn floods, soil salinization and alkalization, saline groundwater, which limit the expansion of agriculture in the area. In addition, with the development of agriculture since the 1980s, long-term groundwater over-extraction has led to a reduction in volume of fresh unconfined groundwater and continued lowering of groundwater levels for deep fresh confined water. This has resulted in serious environmental problems such as seawater intrusion, saline connate water invasion into fresh groundwater, land subsidence, etc. Consequently, the conflicts between socio-economic development and environmental protection become increasingly critical (Jin et al., 1999b).

Table 4. Groundwater abstractions in China in last three decades ($10^9 m^3$/yr.)

Provinces, autonomous regions or Municipalities	Mean annual abstraction in 1970s	Mean annual abstraction in 1980s	Mean annual abstraction in 1999	Change in abstraction 1980s-1970s	Change in abstraction 1999-1980s
Beijing	2.562	2.733	2.715	0.171	-0.018
Tianjin	0.714	0.809	0.633	0.095	-0.176
Hebei	11.403	13.900	14.946	2.497	1.046
Shanxi	2.628	3.030	4.199	0.402	1.169
Inner Mongolia	-	-	5.987	-	-
Liaoning	2.675	4.688	6.869	2.013	2.181
Jilin	0.935	1.300	2.992	0.365	1.692
Heilongjiang	2.809	5.821	6.500	3.012	0.679
Shanghai	0.078	0.112	0.104	0.034	-0.008
Jiangsu	0.195	0.655	1.834	0.460	1.179
Zhejiang	0.090	0.409	0.608	0.319	0.199
Anhui	0.920	1.071	1.848	0.151	0.777
Fujian	0.379	0.559	0.607	0.180	0.048
Jiangxi	0.524	0.828	1.251	0.304	0.423
Shandong	9.014	10.270	12.299	1.256	2.029
Henan	7.730	8.700	12.972	0.970	4.272
Hubei	0.051	0.923	1.397	0.872	0.474
Hunan	-	0.184	2.587	0.184	2.403
Guangdong	-	-	2.200	-	-
Guangxi	0.226	1.024	1.304	0.798	0.280
Hainan	0.290	-	0.492	-0.290	0.492
Chongqing	0.120	0.352	0.857	0.232	0.505
Sichuan	1.729	2.083	2.816	0.354	0.733
Guizhou	2.223	2.668	3.333	0.445	0.665
Yunnan	-	0.067	0.628	0.067	0.561
Tibet(Xizang)	-	-	0.166		-
Shaanxi	2.645	2.368	3.419	-0.277	1.051
Gansu	1.818	2.006	2.622	0.188	0.616
Qinghai	0.095	0.263	0.540	0.168	0.277
Ningxia	0.221	0.456	0.555	0.235	0.099
Xinjiang	1.500	3.750	5.135	2.250	1.385
Taiwan	3.631	3.801	7.139	0.170	3.338
National total	57.205	74.830	111.554	17.625	36.724

Note: data from the Ministry of Land and Water Resources, 2003.

Groundwater level depth for the deep freshwater in NCP was in the order of 20-100 m in 2001, but it was near surface, even artesian in the 1960s. Rates of groundwater level declines for the deep fresh aquifers in depression cones are 1-2 m/yr. Cangzhou, a coast city in eastern Hebei plain, is one of the cities with most serious water level decline of deep confined aquifers, 100 m decline since the 1960s. The water head declines have resulted in land subsidence, degradation of water quality, and harmful ions being released during consolidation of the aquitards, besides increased costs of pumping.

The water table depth of the shallow groundwater in 90 percent of the areas of NCP was larger than 2 m, 50 percent being larger than 10m in 2001. The lowering of water table has resulted in some disadvantages to ecology and environment, but one positive result is that soil salinization is decreasing in most areas of the plain.

In some areas or cities of China, although groundwater exploitation is smaller than allowable yield on the whole catchments, local overexploitation has happened because of over-concentrated exploitation with high intensity in certain areas (Wu et al., 2004). This also resulted in groundwater table decline, land subsidence and water quality degradation.

Great Potential of Groundwater Exploitation in Southern China

Since rainfall and surface water in southern China is relatively abundant, large and medium sized cities in southern China mostly utilize surface water as main sources for water supply. Currently, the contribution of groundwater to water supply in most areas of southern China is low, and groundwater development has great potential.

However, many areas in southern China have shifted to use good quality groundwater for water supply because surface water has been contaminated with the development of economy. The proportion of domestic water use from groundwater is increasing year by year, e.g., Guangzhou, Guangdong Province, and Fuzhou, Fujian province in southern China. Groundwater abstraction in Gaungzhou city accounts for 96 Mm^3 in 1997, of which 52 Mm^3 was for domestic use, 18 Mm^3 for industry and 26 Mm^3 for agriculture; its groundwater abstraction is planned to be 206 Mm^3 in 2005. Allowable yield of groundwater in Guangzhou is estimated at 403.85 Mm^3/yr (Wu et al., 2004).

Strategies for Sustainable Use of Groundwater

Problems and Constraints for Sustainable Exploitation of Groundwater

Main problems of unsustainable exploitation of groundwater in China are irrational abstraction or over-exploitation of groundwater in northern and northwest China and its associated problems and groundwater pollution in many areas. These certainly threaten sustainable development of the local economy. In addition, there are 41.08 M people (12.66 M in northwest) from 569 counties in West China being short of drinking water, usually areas associated with poverty (CIGEM, 2003).

Besides uneven distribution of water resources and the natural conditions of drought, the water shortage situation is aggravated by irrational development and utilization of groundwater, poor management of water resources and poor studies of groundwater (in some areas). While water shortage occurs widely, a large amount of water is wasted. While over-irrigation has resulted in soil salinization and water-logging in some areas, over-use of surface water and over-exploitation of groundwater has resulted in soil desertification and environmental deterioration in other areas of the same river basin. For example, in the Sangong river catchments, North of Xinjiang Autonomous Uygur Region (XAUR), Northwest China, groundwater has been intensively abstracted in the diluvium/alluvium fans, and then conducted to reservoirs in the alluvium plain for irrigation in the last three decades. Observations show that the water table is significantly declining in the alluvium fans, but rising in the alluvium plain from irrigation and the plain reservoirs. This water table rising has resulted in serious soil salinization in the arid area.

In the Hebei plain (main part of NCP) deep fresh water is extracted, whereas the shallow brackish groundwater is not used much. Management options for water problems in the plains include water demand management on the basis of water resource conditions, like: limiting water intensive industries, restricted pumping of deep fresh water; use of brackish water for irrigation; extension of water-saving irrigation; reuse of wastewater and so on (Zhang et al., 1994; Jin et al., 1999a). The use of shallow brackish water will make recharge of rainfall to shallow groundwater more effective (Jin et al., 1998; 1999a). Many field experiments and farmer practices in the past three decades have proved that brackish water with 2-5 mg/L in TDS can be used for irrigation and water-saving irrigation and brackish water use have great potential in NCP. Practices of water-saving irrigation in NCP have advanced somewhat, while irrigation quotas have been significantly reduced in the past decade. Water-saving irrigation and brackish water irrigation are the principal ways for sustainable use of groundwater in the plain. However, further extension of management practices to water-saving irrigation, brackish water irrigation, and restricting abstraction of deep fresh water is facing difficulty.

The reasons of irrational use of water or irrational abstraction of groundwater are mainly inadequate water management institutions and policies, including:

- Poor awareness and recognition of the public (especially private farmers in China) to water shortage and risk of irrational use of groundwater;
- Un-coordinated administration of a river basin;
- Multi-agency sharing of water resources management (leads to a situation where all agencies are partly responsible, but none is readily liable for the damage);
- Separation of water quantity management and pollution control;
- Low prices, even cost-free use of water for agriculture, leads to water wastage. Table 5 shows that the water price in NWC is in the order of 0.6 -7.5 cents per m^3 in 1998.

Table 5. Water price for agriculture use in North China in1998 (Yuan/m^3)

Provinces	Water price	Provinces	Water price
Beijing	0.020	Gansu	0.030
Hebei	0.075	Inner Mongolia	0.023
Shanxi	0.062	Ningxia	0.006
Tianjin	0.040	Qinghai	0.040
Heilongjiang	0.024	Shaanxi	0.039
Ji'ning	0.030	Xinjiang	0.018
Liaoning	0.030		

The above problems or constraints for sustainable exploitation of groundwater has received significant attention by scientists, economists and politicians in the past decade, but still remain unresolved.

Enacting Laws and Rules for Groundwater Management

To accommodate new water resource management concepts and challenges, China promulgated its first version of the Water Law in 1988 and a modified version of the Water Law in 2002. Related laws or rules include: Byelaw for Soil and Water Conservation (1982); Implementation Rules for License of Water Intake (1993); Law for Prevention and Cure of Water Pollution, promulgated in 1984 and modified in 1996; Implementation Rules to the Law for Prevention and Cure of Water Pollution, promulgated in 1989, modified in 2000; Administrative Rules to Water Resource Conservation for Construction Projects, promulgated in 2002; and so on.

According to these laws and rules, China's water program must serve as the regulatory framework for a system that rationalizes and substantiates water and the water infrastructure as public economic goods in the transition to a market economy, with a preeminent role for the Ministry of Water Resources (MWR) as the leading government body responsible for overall water planning, monitoring, research, and development. MWR also oversees national-level policymaking and inter-provincial policy coordination, and flood and drought protection and control. Ministry of Construction, Ministry of Land and Resources (MLR), Environmental Protection Agency (EPA) participates in planning, research, development and protection of water resources.

The policy shifted dramatically several years ago from primary emphasis on planned structural engineering interventions (*gongchengshuili in Chinese*) to address water supply and control problems, and to recognition of the need for a more comprehensive and diffuse notion of water as a resource (*ziyuanshuili in Chinese*) to be developed and managed in response to changing market criteria.

Specific laws and rules for groundwater development in major river basins are being drafted. This is very important to examine and approve permits to groundwater intake, especially in water scarce areas.

Implementation and enforcement of these laws and rules are still confronting difficulties. One of the reasons may be that the laws and rules are not adaptive enough to local situation and the market economy. The low water price maybe a reason resulting in water waste. However, to increase water price may bring more burden to poor farmers, which may cause conflict between farmers and water authorities. Obviously the capacity of water management is still not efficient and powerful enough.

Well Investigations and Evaluation of Groundwater Resources

China has done a lot of work on investigation and evaluation of groundwater and regional hydro-geological mapping, but the results in many cases are not presented in formats suitable enough for examining and approving permits to groundwater intake and practical schemes of groundwater exploitation. Schemes of groundwater development should be easily operational for policymakers at different levels and for individual water users.

Sustainable groundwater development and management is a complex task. As hydrologists or hydro-geologists or engineers of water resources, we should make our proposed schemes/planning of groundwater development user-friendly, easy to understand on the basis of well investigation and evaluations, and with consideration of user's demand. The proposed schemes should be optional for users or decision makers.

Future Directions

Achieving sustainable use of groundwater is a shared task or duty for scientists, decision makers and all individual water users. It is an issue of multiple disciplines, and needs efforts from all parties.

Scientific and Technical Aspects

Hydro-geologists and hydrologists have had compelling professional responsibilities for safe and reliable use of both surface and groundwater. These include the development of scientific principles and the application of these principles to satisfy the needs of society for sustained development.

Besides development of basic understanding and scientific principles of flow and transport of groundwater, further research needs to include:

- Development of more effective conceptual and numerical models for flow and transport in large heterogeneous media (especially in fractured and soluble rocks), including more refined transport models that couple flow and reactions.
- Better monitoring, investigation, evaluation of groundwater to establish user-friendly information systems at different levels for researchers, decision-makers and individual users.
- Better workable planning of groundwater development and utilizations, and user-friendly decision support systems for decision-makers. Based on sustainable use of water resources, this workable planning should be flexible to satisfy some biases of decision-makers and users and with enough consideration of all aspects related to water use, such as conjunctive use of surface and groundwater,

well locations, pumping rates and penetration depth to aquifers, regional and local economic development, environmental protection, etc.
- Better techniques, e.g. well-setup for both water pumping and injections in fine materials of aquifers with low flow rates, water-saving irrigation and drainage, harmful compounds clean up, etc.

Non-technical Aspects

According to our investigation, the main reason for irrational exploitation of groundwater is the gap among groundwater researchers, decision-makers and water users. Therefore we suggest:
- Strengthen public propaganda and education to enhance public awareness and knowledge of groundwater. Because of time constraints on planners, legislators and water managers, we can no longer assume that publication of articles in scientific journals, or even popular literature, will necessarily reach the appropriate decision-makers and stakeholders. Governmental institutions, universities, professional societies and other non-governmental organizations must devote efforts to develop programs to improve groundwater literacy of the public. It is particularly important for young children to become conscious of and sensitive to nature and the environment. These children are the future decision-makers. Such outreach will eventually demonstrate the desirability of funding for hydrogeology and related sciences (Back el al., 1997).
- Capacity building for sustainable water management, including adoption of laws and rules for groundwater management from national to river basin level, in order to force and guarantee that all planners, legislators, water managers and water users are serving to sustainable use of groundwater in their daily activities.
- Creating work environments for better communication and sharing data/ information among water managers, planners, decision-makers, scientists, water users and others to exchange ideas and knowledge for mending the gaps among different parties, including international exchange and cooperation.

Conclusions

- China is listed as one of the 13 most water-deficient countries in the world based on per capita water availability. The averaged total amount of water resources in China is 2826 billion m^3/yr, and the per capita water resource is about 2200 m^3, which is only 31 percent of the world average. The distribution of water resources in China is extremely uneven in time and space. In the South, there is abundant water but little land that can be used for agriculture while less water but more land are available in the north. Water shortage is limiting the development of China's economy.
- Groundwater is the most important or exclusive water source in arid or semi-arid regions of north and northwest China. Average groundwater recharge in China estimated to be 883.6 billion m^3/yr, approximating 31 percent of total water resources. Allowable yield of fresh groundwater resource is 352.8 billion m^3/yr.

Groundwater pollution occurs throughout China, being rather serious in urban areas. Main pollution sources are industrial and domestic pollution. Pesticides and fertilizers in some agricultural areas also pollute groundwater

- Total annual groundwater abstraction in China increased from 57.2 billion m^3/yr in the 1970s to 111.6 billion m^3/yr in 1999. Current groundwater consumption is approximating 20 percent of total water use of China. Groundwater in NCP accounts for 52 percent of total water use, where groundwater in Hebei province occupies 75 percent of total water supply and beyond 50 percent in Shanxi and Henan province.
  In most areas of northern China, especially cities, groundwater has been over-exploited, but groundwater in south China still has great potential for development.
- To accommodate new water resource management concepts and challenges, China has promulgated many laws and rules in the 1980s and the 1990s and still drafts complementarities and modifies previous ones.
  A dramatic policy shifted several years ago from primary emphasis on planned structural engineering interventions to address water supply and control problems and to recognize the need for a more comprehensive and diffuse notion of water as a resource to be developed and managed in response to changing market criteria.
- Achieving sustainable use of groundwater is a shared task or duty for scientists, decision makers and all individual water users. The most important things are to enhance public awareness and knowledge of groundwater and to create a work environment for better communication and sharing dada/ information among water managers, planners, decision-makers, scientists, water users and others to exchange ideas and knowledge and reduce the gaps between different parties, including international exchanges and cooperation.

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