CHAPTER 17
Intensive use of groundwater in some areas of China and Japan

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ABSTRACT: In Japan and China, climate and landform are greatly different even in East Asia. The viewpoint of the groundwater flow system, which reflects climate and landform conditions, is required to compare groundwater in those regions. In Japan, where the average precipitation amount is 1,700 mm/yr and the distance from the mountains to the sea is less than 100 km, freshwater discharges as groundwater into the sea. In the China North Plain, where the distance from the mountains to the sea is more than 300 km and precipitation is about one third of that in Japan, it is not possible for freshwater to discharge directly into the sea, and its salinity rises even in the inland side from the coast and salt accumulation has generated. Those regions are economically important places and groundwater is utilised for various uses, such as domestic/business industrial and agricultural purposes. Due to heavy pumping in these areas, serious groundwater problems, such as the decline in the groundwater level, salt accumulation and land subsidence, have occurred. Those conditions are discussed in this chapter.

1 GENERAL DESCRIPTIONS

Raskin *et al.* (1996) have pointed out that the essence of sustainability or sustainable development is to reconcile the objectives of socio-economic development, environmental quality and ecosystem preservation into a resilient foundation for the future. As for water and sustainability, Raskin *et al.* state that there are three dimensions: meeting human requirements today and in the future, ensuring water security and conflict resolution and satisfying ecosystem requirements.

The water and sustainability problem in China is often stated in different terminology, such as water resource sustainable utilisation and scientific management of water resources in order to ensure socio-economic sustainable development. This is the problem that all water related scientists are increasingly concerned about, especially where there is a shortage of water, as in North China. While the above-mentioned statement and definition are simple and clear, it is necessary to add one more dimension, i.e. the dimension of ensuring environmental requirements. They include the necessary water management measures for global or regional climate change protection and the latter cannot be included in the ecosystem dimension. The first dimension of *meeting human requirements* should be changed to *reconcile human requirements today and in the future with water resource availability and environmental allowance*.

2 SCARCE WATER SITUATION IN CHINA

Chinese water problem scientists often use water resource *per capita* to evaluate the water sufficiency situation. Water resource evaluation work has been carried out repeatedly for the whole country and all provinces, regions and cities by many institutions, and their resources are basically clarified. With reference to the water barrier demarcation of Falkenmark & Widstrand (1992), as shown in Table 1, but using evaluated water resource figures instead of renewable water resources, Table 2 shows the scarce water situation of the country and its five big administrative regions.

Table 1. Water barrier demarcations [Falkenmark & Widstrand (1992)].

Index (m^3 *per capita*)	Condition
> 1,700	No stress
1,000–1,700	Stress
500–1,000	Scarcity
< 500	Absolute scarcity

Table 2. Water sufficiency situation for the whole country of China and its five regions [Liu & He (1996)].

	Total resource (km^3)	Resource per person (m^3 *per capita*)	Resource per cultivated land (10^3 m^3/ha)	Total withdrawal (km^3)	Use/resource (%)
Whole country	2,746.0	2,408.8	28.70	459.8	16.7
NE Region	152.9	1,530.0	9.42	28.1	18.4
N China	168.5	555.6	5.65	105.1	62.4
NW Region	223.5	2,787.6	19.49	77.9	34.9
SW Region	1,275.2	5,721.9	92.29	45.6	3.6
SE Region	925.9	2,134.9	38.10	203.0	21.9

Using the water barrier demarcation concept to analyse the water sufficiency situation, there is no stress in water resources for the whole country of China (Taiwan, Hong Kong and Macao regions are not included) at present. However, if the population increases to 1,600 million by the year 2050, then water resources will be 1,717 m^3 *per capita*, and the whole country will be very close to or even enter into the range of countries where water resources are under stress.

Among all the five large administrative regions, the North China Region is the region with a water scarcity problem. Notwithstanding its arid climate, the North West Region appears from the water barrier demarcation concept to be a region where water resources are not under stress due to its relatively low population. This is surely not true and proves to be the methodology's serious shortcoming.

Using the use/resource ratio as a supplementary indicator to the water barrier concept to analyse the water sufficiency situation of China, the whole country has the use/resource ratio of 16.7%. As a reference (Liu 1992), it was suggested that for European countries, if the ratio is below 5%, then there are no serious problems to solve water issues, and if it is higher than 20%, then water issues will significantly affect the country's economic development. Such a classification is still under discussion and different learners raised different suggestions. However, the ratio of 16.7% for China implies that, as a country as a whole, its total water resources are being utilised heavily. And if there is any severe widespread drought, or if the country wants to withdraw a lot more water for different purposes, certain difficulties might occur, although the country's total water resources at present are still not under serious stress. Meanwhile, the use to resource ratio for the five regions gives a helpful picture to learn about the water tension situation. The North China Region has the highest use to resource ratio of 62.4%, which again shows that this region is indeed suffering a serious water resource stress problem. The North West Region has a use to resource ratio as high as 35%, and this to a certain degree remedies the shortcoming of the water barrier method, reflecting the region's real scarce water resource situation.

Table 3 shows the present water use pattern for the whole country and the five regions. Like all other developing countries, China uses 95% of its water resources for agricultural production. This is understandable, as China has to feed its 1,200 million people with its limited land resources, and therefore irrigation has been the utmost measure to ensure stable and high agricultural production. However, from the water resource viewpoint, reducing agricultural water consumption becomes a major task.

Table 3. Current annual water withdrawals [Liu & He (1996)].

	Agriculture	Municipality and industry	Total
Whole country	438.9	20.9	459.8
Northeast	24.8	3.3	28.1
North China	99.9	5.2	105.1
Northwest	76.5	1.4	77.9
Southwest	43.9	1.7	45.6
Southeast	193.8	9.2	203

3 WATER RESOURCES IN THE NORTH CHINA PLAIN

The North China Plain (NCP) is located in the eastern part of China and it belongs to the littoral and semi-arid climatic zone. This is one of the very large agricultural areas in China at present, but clear changes in land use began in the 1970s. Namely, the very rapid development of agriculture and industry resulted in the increase in water for industry and agriculture, and thus the shortage of water resources has become a serious restraining factor for the economic development of the area. Furthermore, pumping groundwater is beginning to have an adverse effect on the environment, such as the fall in the groundwater level and land subsidence.

Since a great deal of water has been exploited for the rapid development of industry with urbanisation, the supply of water resources for agriculture has declined. In addition to this, rural water has been polluted by drainage from cities. Consequently, the irrigated area with a low water standard, which does not have enough water, is about 1.1 million ha, and the irrigation water shortage is more than 1,600 Mm^3 in the NCP (Huang-Huai-Hai Plain) today. On the other hand, development needs to expand irrigation lands, and water requirements from both urban-industry and agriculture have exceeded the potential bearing capacity of natural water. For example, although the grain output of the NCP takes about 27% of the total yield of the country, there are millions of hectares of cultivated lands waiting for irrigation at present. More than half of its total farm cultivated lands need irrigation. Several cities need to increase their water supply in the NCP.

Agriculture and industry are expected to be developed here in the future, thus increasing the pumping of groundwater, and the environment will most probably deteriorate further. Therefore, this area is one of the regions in China where the deterioration of the environment by the change in land use is feared to be the most serious in the future.

3.1 *Outline of geology and hydrogeology*

The North China Plain (NCP) is a very important region of agriculture in China in terms of its large area of about 26,000 km^2 and huge population of about 70 million (Fig. 1). Annual rainfall ranges between 400 and 600 mm in the study area, while potential evaporation is about 1,000 mm/yr. The monsoon climate affects temporal rainfall distribution in the area with about 70% of the total rainfall precipitated from June to September and 10% or even less from March to May, when evapotranspiration from the winter wheat field may be as high as 6 mm/d (Wu *et al*. 1997).

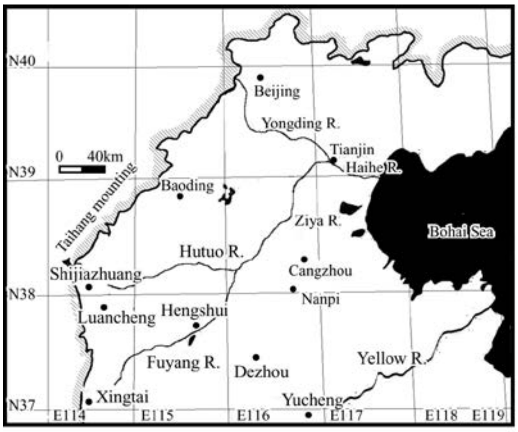

Figure 1. Location of the North China Plain.

Studies show that quaternary formations are deep in the NCP, generally reaching 400–600 m in depth, and are divided into four aquifers. The depths of the boundaries of each aquifer and the underlying layer are 40–60 m, 120–170 m, 250–350 m and 400–600 m, respectively. All the aquifers consist of sand and gravel, fine sand and silt. The constituents of the first and third aquifers are large grained and homogeneous. Their sand layers are thick and their groundwater resources are large. The first aquifer contains unconfined groundwater, while the second, the third and the fourth aquifers contain confined groundwater. Thus the groundwater within the quaternary formations is pumped as agricultural and industrial waters. The first and the third aquifers, particularly, are major sources of water and a large amount of water has been pumped.

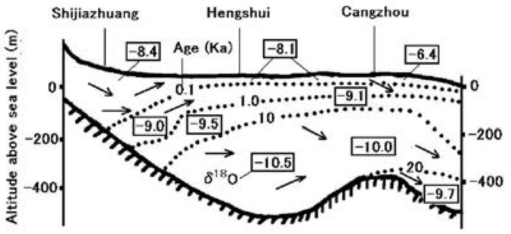

Figure 2. Groundwater flow profile from Taihang Mount to Bohai Bay (refers to the arrow in Fig. 1) in the NCP (modified after Zhang *et al.* 2000).

The groundwater table, corresponding to the seasonal rainfall change, is highest in the summer and lowest in the spring. The groundwater depth in the alluvium near the western mountain of the NCP may be as low as 25 m due to excessive groundwater exploitation in the last 20–30 years, while it is around 2–8 m in the eastern part of the NCP due to the complicated multiple-layer structure of the aquifer system, which discharges groundwater originating from the far west Taihang Mount area in terms of the groundwater flow system (Fig. 2), and the impacts of huge amounts of water diverted from the Yellow River (Chen *et al.* 2001a).

3.2 *Land use and water resource development*

Changes in water resource development are closely related to changes in land use. The amount of usable water resources is limited. Intensive use of land and urbanisation, however, increase the demand for water. When water resources are used beyond the limit, the groundwater level falls and eventually the groundwater will dry up. This will be a serious environmental deterioration.

The Hebei Province has the fourth largest agricultural area of all the provinces in China and thus agriculture is the major economic activity of this province. Therefore, a major use of water resources here is agriculture. The use of water for agriculture in the NCP was 12,109 billion tons/yr in 1997 and it represented 78% of the total use of water (15,760 billion tons/yr) of that year. Water use for agriculture is not only affected by annual precipitation, irrigation technology and irrigation methods, but also by land use. In recent years in the NCP, the average amount of water use for irrigation has been 3,900 tons/ha, and groundwater use has increased by 2.7% with an increase in arable land of 1.1% (Fig. 3).

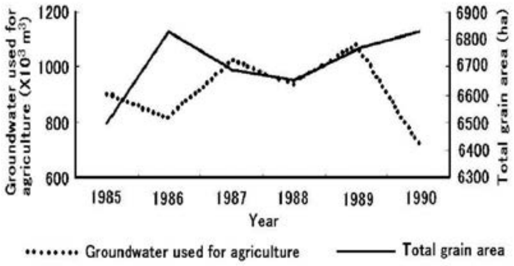

Figure 3. Related chart of agricultural water use and total grain area.

Industrial water represents 11% of total water use, but it has been pumped intensively from specific wells, which has been deteriorating the environment. The amount of industrial water is determined by economic conditions (for example, Gross Domestic Product –GDP). Currently, the intensity of industrial water used per GDP is 43 tons/US$, and during 1985–1995, the GDP increased by 10.6%–14.3% and industrial water use increased by 6.3%. Domestic water represents 8% of the total water use. In recent years, water used for daily life per person is 216 L/d in urban areas, and 55 L/d in farming areas. The increase in population is about 0.8% per year, whereas water for daily life pumped from groundwater increased rapidly at 8.5% per year. This increase is believed to accompany a gradual rise in living standards. The water for daily life per person in urban areas was 130 L/d in the late 1970s and it rose to 216 L/d in 1990, and in farming areas it was 30 L/d in the late 1970s and it rose to the present 55 L/d.

3.3 *Groundwater and its effect on the environment*

Before the 1970s, the pumping of groundwater was low, and neither unconfined nor confined groundwater was affected by human activities. Thus, the groundwater level kept fluctuating within a specific range in accordance with annual precipitation. After the 1970s, the increase in pumping groundwater began to result in the fall in the groundwater level, land subsidence and other environmental problems.

3.3.1 *Overpumping and groundwater level changes*

A water exhaustion example proves that the piedmont plains in the western and northern parts of the North China Plain (NCP) are nourished by moderate rainfall and further replenished by runoffs from the Taihang and Yan Mountains in the west of the plains. Originally, water resource conditions were good. Since the 1970s, however, a series of changes have drastically altered the water situation. The rapid development of cities and industries and extensions in farmland irrigation have doubled the water demand. The consequence is overuse of surface water resources and the excessive exploitation of groundwater in the area. For example, the Shijiazhuang City district, located in the piedmont plain of the Taihang Mountains, is a high-output region of grain in the NCP with 537 mm/yr of rainfall. In the late 1980s, its average grain output was 12,000 kg/ha, and water consumption was around 850 mm/yr. Aside from mountain runoff, irrigation water came from under the ground. The annual average excessive groundwater exploitation amounted to between 80 and 100 mm, which resulted in an annual decline in the buried shallow groundwater table of more than 0.8 m from the 1970s–1980s and 1–1.2 m in the 1990s.

Since the particle size of alluvium decreases from piedmont in the recharge zone to alluvial plain in the transition area and then to alluvial plain in the discharge zone near the coast, permeability reduces correspondingly from the recharge, the transition zone and then to the discharge zone, from the point of view of geomorphology evolution. Therefore, nitrate may move down easily in the recharge zone in contrast to that in the transition zone and in the discharge zone. In addition, the downward water head in the recharge zone may speed up this movement.

Generally, the NCP's transition zone has been an area with a high crop yield since the early 1980s. Unfortunately, the groundwater table has been going down continuously since 1978 due to the excessive exploitation of groundwater for irrigation together with the dry trend in the last 20 years. The change in the groundwater depth in the Luancheng station of the Chinese Academy of Sciences is used as one example to indicate this situation (Fig. 4).

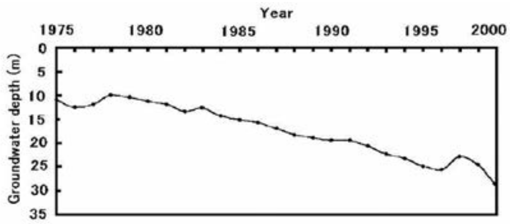

Figure 4. Yearly groundwater depth has increased in the last 25 years in Luancheng station.

The fall in the unconfined groundwater level in the past 30 years in the NCP was greater near the mountains and the average was 12–25 m, and it was smaller in the central part and near the coast with average values of 2–10 m. For example, the falling rates at Shijiazhuang, Hengshui, and Soushuu were 0.67 m/yr, 0.17 m/yr, and 0.11 m/yr, respectively. The flow of unconfined groundwater has changed, flowing naturally in the SEE direction, but it now joins near cities.

3.3.2 *Salinization in the North China Plain*

Generally, groundwater tends to evolve chemically towards the composition of seawater. This evolution is normally accompanied by the following regional changes in dominant anion species (Freeze & Cherry 1979):

Travel along flow path (Increasing age)

$$HCO_3^- \rightarrow HCO_3^- + SO_4^{2-} \rightarrow SO_4^{2-} + HCO_3^- \rightarrow SO_4^{2-} + Cl^- \rightarrow Cl^- + SO_4^{2-} \rightarrow Cl^-$$

In the NCP, annual average rainfall is less than 600 mm and the distance from the Taihan mountain region to the Bohai Sea is more than 300 km. For that reason, the activity of groundwater circulation is assumed to be low and creates severe groundwater problems, which are the decline in the groundwater level and salinization, not only by its national condition, but also by pumping for irrigation, city and industrial water use.

Figure 5 shows the vertical distribution of the electric conductivities along the section from Baoding to the Bohai Sea. Figure 6 shows the vertical distribution of Carbon 14 (percent modern carbon, pmc) in the same cross-section. The local groundwater flow system can be seen in Figure 5, which is recharged at the mountainside of Baoding and discharges at the central part of this section. The regional groundwater system is assumed to recharge at the foot of Taihang Mountain and discharges near the coastal area of the Bohai Sea. From Figure 6, it is clear that the local groundwater flow system creates a surface high concentration group of Carbon 14. The discharge of the regional groundwater flow system is not clear from Figure 6, because there is no data in the surface layer near the Bohai Sea. Figure 7 shows the vertical distribution of the electric conductivities along the section from Shijazhuang to the Bohai Sea. This shows the same trend as Figure 5, in which the zone of fresh groundwater extends from the surface zone near Shijazhuang downward to the depth of 400 m of the central part of this section. This chemical data reveals that salinization in the central part of the NCP is influenced by the discharge of the local and intermediate groundwater flow systems. Salinization near the Bohai Sea is affected by the discharge of the regional groundwater flow system. However, this fact is not confirmed by the chemical data because there is no data in the surface layer near the Bohai Sea. The rise and fall in the unconfined groundwater level is closely related to the salinization of the soil. In the past 50 years, the source of irrigation water has changed many times from groundwater to surface water, and again from surface water to groundwater. The area of salinized soil has fluctuated with these changes. For example, in a certain county, water was irrigated from shallow wells 50 years ago and the salinized area was stable. But in the 1960s, water was irrigated from the Yellow River, without clearly thought out plans, and this resulted in the rise in the groundwater level, the increase in salinized land, and the decrease in food production. Later, channels were dug, groundwater was drained and shallow well irrigation was revived. The result was the fall in the groundwater level, the gradual

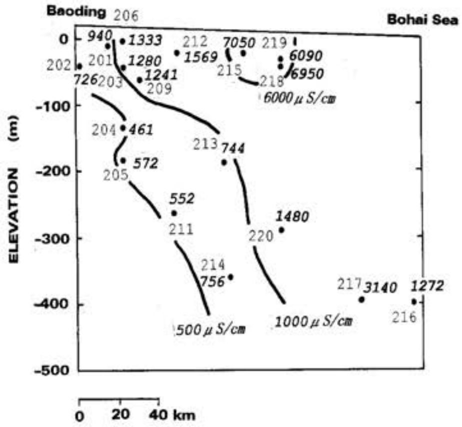

Figure 5. Vertical distribution of electric conductivities (μS/cm) along the section from Baoding to the Bohai Sea. Dots show the bottom of the pumping well.

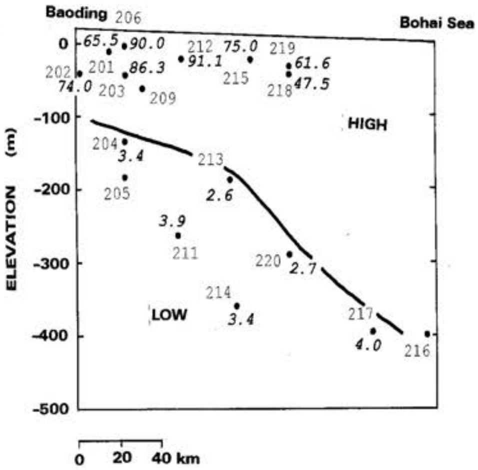

Figure 6. Vertical distribution of Carbon 14 (pmc) in the same cross-section as Figure 5.

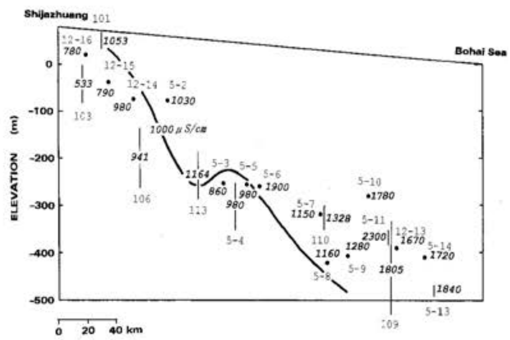

Figure 7. Vertical distribution of electric conductivities along the line from Shijazhuang to the Bohai Sea. The dots show the location of the bottom of the pumping well and the vertical lines show the screen of the pumping well.

decrease in salinized land, and the gradual increase in food production.

In addition, seawater intrusion is a typical problem caused by fresh groundwater exploitation in the coastal belt. One of the most severe disaster areas located in the northern coastal plain is Laizhou City, China, whose total seawater invaded area ($Cl^- > 300$ mg/L) was 125.6 km^2 in 1993, the widest invaded area inland is 10 km, which has resulted in the salinization of large areas of cultivated land, the rejection of water supply wells, and, therefore, has restricted the development of local industry, agriculture and social economy and has affected the health of local people. Many researchers have paid a lot of attention to this issue and have put forward their own views. For example, some thought that seawater intrusion proceeded inland-wards forming a wide transitional belt; bedrock interface was the limit boundary of seawater intrusion; and paleochannels were the main passage ways of seawater intrusion, etc. But the counter engineering measures taken, based on the above understanding, produced very little effect and the disaster is still expanding.

The remaining saltwater and brine water evolved from paleomarine progression in Quaternary, and bedrock is one of the resources of freshwater salinization in the coastal belt. This recognition is very significant for research on the mechanism of seawater intrusion. According to the ratio of SO_4/Cl and the comprehensive analysis of hydrogeology, three types of seawater intrusion areas were divided, i.e. modern seawater intrusion area, quaternary saltwater and brine water intrusion area, bedrock saltwater and brine water intrusion area, which provided a scientific basis for the remedy of seawater intrusion.

3.3.3 *Land subsidence in the North China Plain*

The storage coefficient of confined groundwater is low and thus the fall in the water level is faster than that of unconfined groundwater. The rate of this fall is larger near the coastal part of the plain and in 60% to 70% of the area the groundwater level fell 20–60 m.b.s.l. The rate of the fall in the groundwater level is 1.44 m/yr at Shijiazhuang near the mountains, 2.28 m/yr at Hengshui in the central part of the plain, and 3.33 m/yr at Soshuu near the coast. The area of land subsidence expanded near the coast caused by the drastic fall in the groundwater level. The accumulative subsidence is 253 mm on average and the maximum is 1,131 mm (Fig. 8).

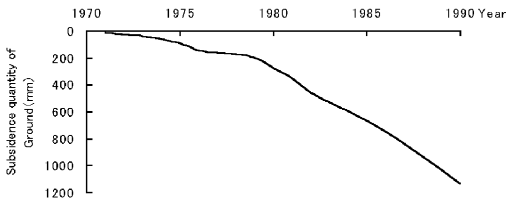

Figure 8. Land subsidence in Changzhou City.

3.3.4 *The nitrate pollution pattern in groundwater, based on the groundwater flow system and land use in the North China Plain (Chen* et al. *2001b)*

Even though supplying crops with adequate N is necessary for food supplies both nationally and internationally, environmental problems may arise due to the excessive use of N that may then leach out of the soil and eventually contaminate the groundwater. Methaemoglobinaemia and cancer are two special concerns related to the toxicity of nitrate and public health by using polluted groundwater as drinking water. The geological deposit of N may also contribute the majority of nitrate to groundwater. There is currently considerable concern about health, economic, resource conservation, and sustainable development aspects of nitrate leaching into groundwater. As a result, it has been well investigated, and the public health standard for nitrate (45 mg NO_3^-/L, or 10 mg N-NO_3^-/L) in public drinking water supplies has been set up (Follett 1989).

Nitrogen cycling is closely related to water movement in the continuum of groundwater, soil, plant and atmosphere, driven by the energy summation of radiation, gravitation, and matrix potential. Nitrogen from either natural sources (rainfall, geologic deposit, forest, forage, pastoral agriculture, etc.) or non-natural sources (fertiliser, waste material, etc.) may undergo the following processes (Komor & Anderson 1993).

Land use in the NCP has remained the same in the last 20–30 years, except for the metropolitan suburb, where urbanisation is transforming more and more agricultural land into new buildings and paved areas, and cereal crop fields into vegetable land use.

Crop yield requires not only the input of nutrients, such as from chemical fertiliser (N, P, K) and manure, but also the input of water, which is critical in such a semi-arid area. Water use efficiency in the discharge zone is about 11.25, 6.3, and 19.5 kg/ha/mm for winter wheat, soybean and summer maize, respectively, based on data from experiments over about 10 years in the Yucheng Station (Chen & Wu 1997). The optimal N-fertiliser rates in the NCP were given as follows based on the results of 500 field fertiliser experiments: 90–225 kg N/ha for wheat with a yield of 5,250–6,750 tons/ha, 150–250 kg N/ha for maize with a yield of 7,500–9,000 tons/ha, 180–270 kg N/ha for Chinese cabbage with a yield of 75,000–120,000 tons/ha and 255–315 kg N/ha for water melon with a yield of 80,000–100,000 tons/ha (Huang *et al.* 1989, Yang *et al.* 1991, Jin *et al.* 1995), i.e. it requires 0.89, 0.51 m^3 water and 0.017–0.033, 0.02–0.028 kg N-fertiliser to produce 1 kg of wheat and maize, respectively. The ratio of N-fertiliser to water is about 1/51,917–1/26,700 for wheat and 1/25,500–1/18,360 for maize, i.e. 19–37 mg/L for wheat and 39–54 mg/L for maize. The ratio may be higher in the dry year, if the same amount of fertiliser is applied.

The average annual N-fertiliser application in China increased dramatically from about 130 kg/ha in the 1980s to the current 211 kg/ha. In some high yielding crop regions in the NCP it may even reach 500 kg/ha/yr (Zhang *et al.* 1996). On the other hand, crop water consumption has remained rather stable or has even decreased since 1980, and thus increases the potential N-pollution of the groundwater.

Anion and cation faces or chemical patterns change gradually along the groundwater flow path, reflecting the physical and chemical processes from the recharge zone to the transition zone and then to the discharge zone (Stuyfzand 1999, Toth 1999). Based on the results analysed, it was found that ion faces evolve from the piedmont region and the fluvial region to the coastal region in the following sequence as groundwater flows from Taihang Mount to Bohai Bay.

Such a groundwater flow system was also confirmed by the analyses of Tritium and Carbon 14, which showed that groundwater may flow to the east at a rate of 4 m/d (Shimada *et al.* 2000).

Though nitrate follows the same flow path to the east, it is much more difficult to trace due to the effects of denitrification and bacteria activity (Eweis *et al.* 1998). Since nitrate pollution in groundwater has only arisen in that last 20–30 years due to the excessive application of N-fertiliser to improve the crop yield, it is anticipated that the vertical movement rather than the horizontal movement is dominant.

Series data, obtained from the analysed results of samples of Yucheng and Qihe city in Shandong Province in May, September and December 2000 show that nitrate in groundwater remains rather stable even with the fluctuation of the groundwater depth from about 1.5 m to 4 m. Among 136 non-repeated water samples, 36 were found to have more than 1 mg/L of nitrate, 13 to have more than 45 mg/L of nitrate, i.e. about 26% of the total samples was detectable and about 10% has already been polluted by nitrate regardless of the well depth.

Nitrate in groundwater in the NCP shows a spatial pattern corresponding to the flow system, with specific characteristics for the recharge zone, the transition zone and the discharge zone, respectively (Fig. 9). Since it is difficult to distinguish the recharge from the transition zone, the data of the Hebei Province in Figure 9 was not classified and the same symbol was used.

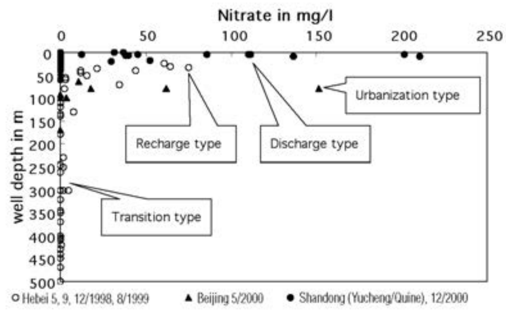

Figure 9. Nitrate in groundwater with the well depth pollution pattern.

Nitrate pollution in the recharge zone (unfilled dots in Fig. 9) mainly occurs in the layer of 20 to 50 m, with the maximum generally less than 100 mg/L. The fact that it is easy for nitrate to flow down further and then follow the groundwater flow direction in this region without accumulating in one layer may probably explain this phenomenon. Since local people pump water from this layer as drinking water, potential harm is expected for those who use nitrate-polluted water. Nitrate pollution in the transition zone is normally undetectable due to the deep groundwater depth, which may be as deep as 25 m in some high yielding crop regions in the NCP, such as Luncheng in the Hebei Province. Nitrate pollution in the discharge zone (filled dots in Fig. 9) mainly occurs in the shallow layer of less than 5 m with the maximum as more than 200 mg/L. As mentioned above, the groundwater depth fluctuates due to rainfall and/or diverted water from the Yellow River in this region, enabling a strong interaction between groundwater and soil water that is high in nitrate content. Even though nitrate is rather high in the layer of less than 5 m, it does not go down further due to the water head difference, i.e. the groundwater of the deep layer is moving up in this region. Filled triangles in Figure 9 represent another type of nitrate pollution in groundwater, which has occurred in the field growing vegetables for more than 20 years in the suburb of Beijing city. Nitrate may leach out to the groundwater as deep as 70–80 m.

At the same time, another type of nitrate pollution is related to urbanisation and the change in land use in the suburb in the last 20–30 years, i.e. from cereal crops to vegetables, which require far more water. For example, the annual average irrigation for vegetable, paddy and other cereal fields in Beijing is around 14,445–14,955, 10,440–13,020 and 3,330–3,810 m^3/ha/yr, respectively. With the development of urban economy and construction and the increase in population, vegetable fields increased by about 53% in Beijing, whilst paddy fields decreased by 51% due to the constraint of water resources (Table 4) from 1978 to 1995. Since irrigation for vegetable fields is about 1,444–1,495 mm, combined with about 600 mm of rainfall, i.e. the total is two times that of potential evaporation (about 1,000 mm) in this area, nitrate leaches inevitably to the groundwater aquifer, even to a depth of 70–80 m, as indicated in Figure 9.

Table 4. Yearly change in land use for agriculture in Beijing city (ha) [Economic Yearly Book of Beijing (1996)].

Year	Paddy	Vegetable	Cereal	Economic crop	Other
1978	48,691	29,304	264,132		
1984	44,062	24,719	266,793		
1990	32,663	34,650	263,925	15,408	66,233
1995	23,658	44,822	235,558	17,942	77,639

Nitrate pollution in groundwater is not only related to the excessive application of N-fertiliser, but also closely to the geological background, groundwater flow system and change in land use. The former provides the N source, while the latter decide the flow and accumulation patterns of nitrate as indicated in four types for the recharge, transition and discharge zones and the urban area. The integration of the analysis of fertiliser application with the groundwater flow system and change in land use may reveal the possible distribution of nitrate pollution in time and space.

4 COUNTERMEASURES FOR GROUNDWATER EXPLOITATION IN THE NORTH CHINA PLAIN

Based on the above principle and considering environmental impacts of groundwater exploitation, we suggest some major countermeasures as follows:

- Strict stopping of the intensive mining of deep groundwater aquifers in areas where depression cones appear of deep groundwater found.
- Developing artificially recharging groundwater aquifers by using storm rainfall and treated wastewater from urban industries.
- Increasing water use efficiency through the application of biological technology, employing water saving irrigation techniques, including pipe irrigation and sprinkling irrigation.
- Effectively using both wells and ditches for irrigation in a conjunctive way in flooding irrigated regions, for example in the lower reaches of the Yellow River.
- Building up better drainage systems against soil salinization and waterlogging in saline shallow groundwater areas.
- Developing the application of brackish groundwater for cropping in the Heilonggang River basin.
- Careful control of sewage discharge from both urban and rural areas in terms of preventing groundwater pollution, etc.

Obviously, sufficient consideration should be given to these proposals in order to lessen and avoid the negative environmental impacts of groundwater exploitation and to obtain a higher benefit from the water supply. With regard to the environmental impact of a groundwater project, the larger the project's scale is, the greater the impact on the environment. In general, the uncertainty of the project affecting the environment is in a direct proportion to the project's scale. Therefore, from an environmental point of view, decreasing these impacts may lie in minimising the project's magnitude. As a result, instead of limiting water requirements in terms of water demand, control is highly advisable. In this way water-saving measures can be a good help. In fact, in 1995 the growth rate of the total production output of Beijing was 14.5%, while water withdrawal was reduced by about 66 Mm^3.

All in all, besides practising water economy, it is necessary to supplement the water supply in the North China Plain with conservation layout in an appropriate way.

5 GROUNDWATER IN JAPAN

5.1 *Natural and social conditions in Japan*

Japan is an island country located in East Asia in the North-West Pacific Ocean. Japan has an area of about 380,000 km^2. Japan is made up of many islands, including 4 large islands: Hokkaido, Honshu, Shikoku, and Kyushu. The country has diverse natural environments due to the variety of climates found there.

Four fifths of the land area is mountainous, with mountain ranges running from the north to the south. There are also a few spacious plains. On the whole, Japan's rivers are short and rapidly flowing streams. Therefore, the nation is often troubled with water shortages in spite of an abundance of precipitation. Many peninsulas and capes complicate the coastlines and form diverse scenery.

The climate of Japan is generally mild with an average temperature of about l5º C. The four seasons are pronounced in Japan. The average precipitation amount is 1,700 mm/yr and most of the rain falls in the typhoon season from September to October and during the rainy season in June. The climate along the Sea of Japan differs from that along the Pacific coast. In fact, among densely inhabited areas, the area along the coast of the Sea of Japan is one of the areas receiving the most snow in the world. However, the annual *per capita* precipitation of Japan, which is obtained by multiplying the annual precipitation by the total land area and then dividing the product by the population, is only about 5,200 m^3/yr per person, or about one-fifth of the world annual average of 27,000 m^3/yr per person. Thus, precipitation in Japan is not necessarily abundant compared with that of other countries.

The population of Japan is about 120 million. The population is concentrated in the three large urban areas of Tokyo, Nagoya, and Osaka. Heavy industries have contributed a great deal to a high rate of economic growth since the latter half of the l950s. Recently, service industries have also grown markedly. As a result, the population engaged in primary industries is about 6% in total, which tends to be decreasing, 33% in secondary industries and 62% in tertiary industries, on the basis of the number of workers by industries.

Japan is divided into 47 prefectures, which are further subdivided into municipalities. The capital is Tokyo. The cities with more than 500,000 residents, which are designated by cabinet order, possess most of the authority of prefectural governments. Municipalities are categorised based on population and other factors as cities, towns, or villages.

5.2 *Groundwater as a water resource*

Water from groundwater has several advantages: it is generally better quality and varies less in temperature and no large storage or supply facilities are required because it is taken from wells. With technological development and increased demand, the use of groundwater has expanded from shallow groundwater in springs and unconfined groundwater to deep water under pressure whose level or temperature is not very subject to the weather, such as rains. Therefore, groundwater is utilised for various uses such as domestic/business, industrial and agricultural purposes. Furthermore, taking advantage of the more constant temperatures of groundwater, it is used for fish farming, cooling, melting snow and so on.

There have been various attempts at artificially recharging ponds in order to conserve and use groundwater effectively and appropriately.

Although it is difficult to determine the exact amount of groundwater used because individual users build their own wells, the total amount of groundwater for urban (including domestic/business and industrial water) and agricultural use is estimated at 12,990 Mm^3, or about 14% of the total intake from groundwater in 1994. Groundwater utilised for urban use totals about 9,110 Mm^3, or about 28% of the total intake from groundwater, as shown in Figure 10 (National Land Agency of Japan 1997).

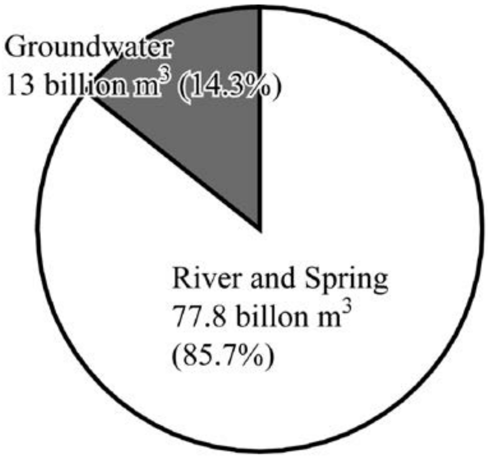

Figure 10. Use of water resources in Japan (National Land Agency 1997).

Use in fish farming and buildings amounts to about 1,800 Mm^3 and about 980 Mm^3, respectively. The annual total of groundwater use is estimated at l5,770 Mm^3/yr, as shown in Figure 11.

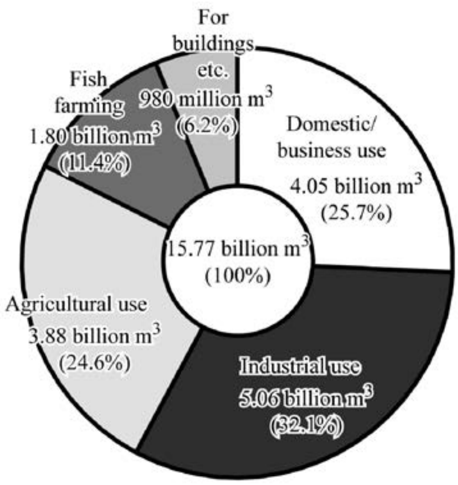

Figure 11. Use of groundwater in Japan (National Land Agency 1997).

Recent changes in the use of groundwater of the country show that industrial water is a decreasing trend, but domestic business water has been increasing. As a result, the total urban water is in a flat trend.

5.3 *Appropriate use of groundwater*

5.3.1 *Use of groundwater based on its characteristics*

With people's growing desire for a richer and higher-quality life, the importance of groundwater has been more recognised in terms of quality, as well as quantity. There are an increased number of cases of using excellent qualities of groundwater, including more constant temperatures, cleanness, and appropriate content of minerals. Taking its quality into consideration, the value of groundwater has increased. Its excellent characteristics should be used effectively with appropriate management to avoid problems that may be derived from its use.

Groundwater that is warmer in winter and cooler in summer is used as a valuable thermal energy source for melting snow to secure the means of local transportation, removing snow from roofs, cooling/heating and hot water supply with heat exchange equipment, such as a heat pump, in cold areas in winter.

Technologies to store heat energy in aquifers have been further developed. There is an increasing number of cases of heat storage in aquifers, which is a more effective mode of use than the simple use of groundwater.

Groundwater is also used for fish farming or to make sake. There are products, such as mineral water and canned beverages, and daily items, such as shampoo and toilet water, with a groundwater content as an added value, which have been developed and used.

In some areas, groundwater and springs have been incorporated into city planning to create and conserve spaces for playing with water, such as spring parks.

5.3.2 *Artificial recharging and use of groundwater*

Although the amount of intake groundwater has not changed very much in recent years, a large amount of water is still taken out from there. On the other hand, there is a great demand for high quality groundwater, and also an additional demand for it to conserve or revive springs to create a rich and good water environment.

With the expansion of urban areas and the increasing coverage of the ground with impermeable materials, the water supply capacity to groundwater has become less and less. Consequently, there have been various attempts at artificial groundwater recharging in many areas.

Artificial recharging is aimed at increasing the groundwater to be developed and used, and using groundwater in an appropriate way. The main goals of this technology are to raise the groundwater level and increase the flow by increasing stored water, and to improve water quality by permeating it through strata.

Most attempts at artificial groundwater recharging have been aimed at dealing with groundwater hazards in alluvial plains. The process involves injecting water into the aquifer through wells in many cases and permeating water through artificial recharge ponds that allow the ground to infiltrate water in some cases. Other recharging technologies include permeating dams, rainwater infiltrating frames, and permeable pavement. These structures are also used for surface water control. There are some cases of recharging groundwater not only to increase the amount of groundwater, but also to improve water quality in rivers in other countries.

Most groundwater recharging technologies are still under study or trial, so a number of problems remain unresolved. However, these technologies are expected to bring about a safe and stable water supply.

5.3.3 *Subsurface Dam Projects in Japan*

Kawasaki *et al.* (1993) and Nagata *et al.* (1993) reported the geotechnical development of the subsurface dam project in Japan as follows.

The agriculture on the Ryukyu Islands in the south-west of Japan is deeply dependent on unstable rainfall. The annual amount of rainfall on the islands depends on the passage of typhoons. When there are no typhoon passes through the islands, a severe drought may hit the area. Though the mean rainfall on the Ryukyu Islands is 2,000 mm/yr, it is very unstable year by year, varying from 1,000 to 3,000 mm/yr. The geology of the majority of the islands consists of an elevated coral reef limestone, known as Ryukyu Limestone, which is highly pervious. The majority of the rainfall infiltrates the ground due to the high permeability of the limestone. The fluvial system on the islands is, therefore, less developed and characterised by a small catchment area and small rivers. The groundwater discharges into the sea without being used through the permeable Ryukyu Limestone and seawater intrudes into the coastal aquifer of Ryukyu Limestone by excessive pumping up of the groundwater.

Subsurface dams under construction on the Ryukyu Islands, in the most south-western part of Japan, have two main purposes. The first is to dam up and store groundwater, which quickly discharges into the sea, by constructing cut-off walls, and to use it effectively for agricultural purposes. The second is to prevent saltwater intrusion into fresh reserved water near the seacoast and to separate saltwater and inland groundwater by cut-off walls. As an example, a schematic diagram of a saltwater cut-off type subsurface dam is shown in Figure 12 (Nagata *et*

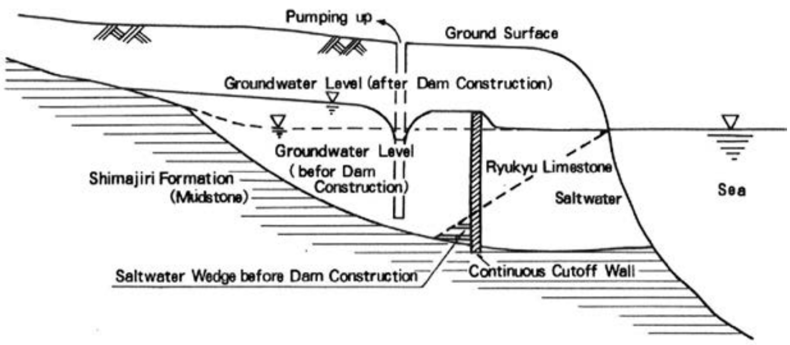

Figure 12. Schematic diagram of subsurface dam of saltwater cutoff type.

al. 1993). The Ministry of Agriculture, Forestry and Fisheries of the Government of Japan (MAFF) has conducted the subsurface dam development programme on the islands to develop groundwater resources by a subsurface dam that can dam up groundwater flow into an aquifer and reserve groundwater that has been wasted into the sea without use since 1974 to date. An irrigation project with subsurface dams of a considerable size is now under implementation based on the know-how obtained through the programme.

5.4 *Groundwater pollution and its countermeasures*

At present, about 30% of water for the urban activity comes from groundwater. Recently, groundwater pollution by trichloroethylene, tetrachloroethylene and other pollutants was revealed. According to the surveys of groundwater by the Environment Agency in 1993, groundwater pollution was detected in 1,151 areas. As a result of the monitoring by prefectural governments, we know that groundwater pollution has been increasing every year.

General groundwater surveys were conducted in 1,498 municipalities in the fiscal year of 1994. These surveys found groundwater contamination by trichloroethylene (11 out of 3,996 wells in excess of assessment standards, and other pollutants).

The surveys conducted in the 1980s found widespread groundwater contamination in Japan. Based on this survey, the Environment Agency amended the Water Pollution Control Law in June 1988 stipulating the prohibition to infiltrate discharge with toxic substances and the monitoring of groundwater by prefectural governments, which is subsidised by the Environment Agency. After this amendment, the purification technology for groundwater reached a practical use level and although groundwater contamination was still discovered in many areas, the importance of the purification of polluted groundwater based on a legal system had been pointed out.

In February 1996, the Central Environment Council submitted a report concerning purification measures in order to present pollution groundwater. Based on this report, the Environment Agency amended the Water Pollution Control Law in May 1996. The amended law, which will be enforced in the fiscal year of 1997, stipulated that the prefectural governor can order that the polluter purifies contaminated groundwater.

The Environment Agency established the Environmental Quality Standards (EQS) for groundwater in March 1997, aiming at further promotion of the comprehensive conservation of the groundwater environment. These Environmental Quality Standards are applied to all groundwater, and the same standard values are established as the standard for protecting human health with the 23 substances of the EQS for public water resources. It was established to "make every effort to be attained and maintained immediately" because it is related to human health. From now on, conservative administration of groundwater is conducted with the aim of attaining and maintaining this environmental standard.

5.5 *Land subsidence and its countermeasures*

Cumulative changes in land subsidence in the famous area in Japan are shown in Figure 13. Land subsidence is caused by excessive pumping of groundwater in unconsolidated and deposited sediments. Once subsided, the ground level does not return to its original elevation.

Land subsidence began to be observed in Koto Ward, Tokyo, in the 1910s and in Osaka in the 1920s. It causes the destruction of buildings and damage by floods and high tides, and became a public concern. The damage to industry in World War II around 1945 reduced the industrial use of groundwater thereby stopping land subsidence. However, subsidence began again, particularly in metropolitan areas, in the 1950s when industry revived and groundwater demand increased rapidly.

The control of groundwater pumping rates as countermeasures against land subsidence began in the l960s, and since then the rate of subsidence in metropolitan areas has been slowing. However, in some regions large amounts of groundwater are pumped for domestic/business water, agriculture and snow melting, as well as for industry. At present, marked land subsidence is occurring in the suburbs of metropolitan Tokyo (the northern part of the Kanto Plain), rural regions in the Chikugo-Saga Plain, Saga Prefecture and in snowy regions in Minami-Uonuma, Niigata prefecture, among other places.

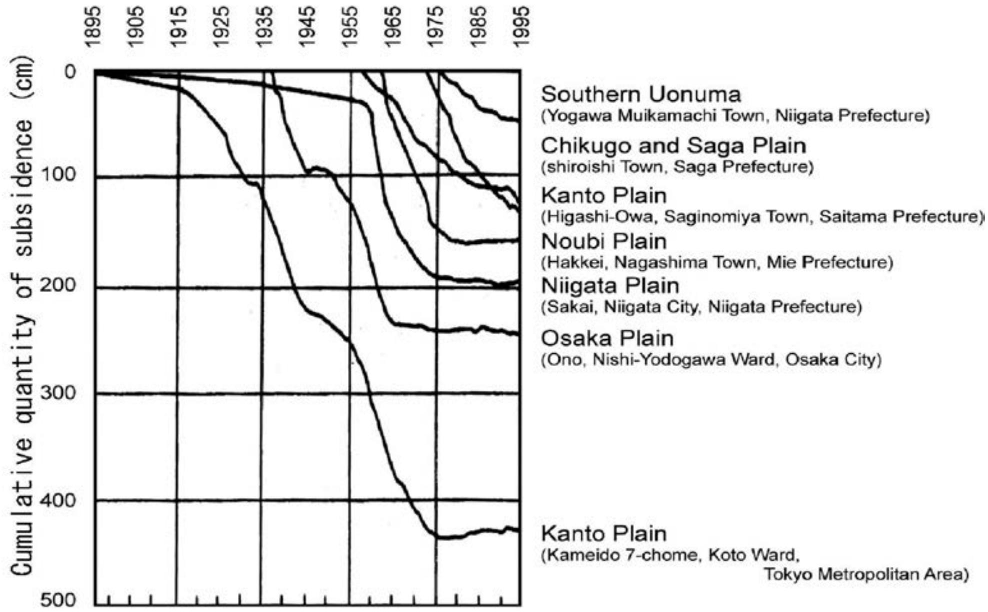

Figure 13. Cumulative changes of groundwater subsidence in the famous area in Japan (National Land Agency 1997).

Progressive damage caused by land subsidence made the public aware that controlling the pumping-up of groundwater is necessary to prevent such problems. Two laws have been enacted and enforced to reduce the yields of groundwater. The *Industrial Water Law* and the *Law Concerning the Regulation of the Pumping-up of Groundwater for Use in Buildings* were enacted in l956 and 1962, respectively. At present, parts of ten prefectures are regulated under the former law and parts of four prefectures are regulated under the second. Apart from these laws, the control of the pumping-up of groundwater has been exercised by ordinances of local governments. In addition, industry makes various attempts to reduce its use of groundwater with voluntary restraints and rationalisation of groundwater use. Construction projects have been carried out to supply additional surface water thereby reducing the demand for groundwater.

In greatly subsided areas, buildings damaged by land subsidence have been repaired and structures have been erected to prevent damage by floods and high tides.

In order to implement comprehensive countermeasures in the greatly subsided areas (Fig. 14), *Outlines of Measures Preventing Land Subsidence* were established by the council of Ministers concerned for the Nobi Plain, around Nagoya and for the Chikugo-Saga Plain and for the northern part of the Kanto Plain. These outlines control limits on the total yields of groundwater and promote other countermeasures, such as obtaining substitute water from alternative sources.

From now on, there needs to be a policy including groundwater, spring and whole ground environment. It is referred to in the Basic Environment Plan as follows:

“The Government will promote measures to conserve the ground environment, through preventing land subsidence and maintaining groundwater circulation environmentally”.

In 1994, when almost all the nation suffered from drought, land subsidence became intensified in areas such as the north of Kanto Plain, Chikugo and Saga Plains. To monitor the rapid lowering of the groundwater level at the time of drought, considering the necessity of introducing the telemeter system to strengthen and sophisticate the real-time monitoring system of the groundwater level, the Environment Agency is establishing observation stations in several monitoring wells in Chikugo and Saga Plain, Saga Prefecture and North of Kanto Plain, Saitama Prefecture (Environment Agency 2000). The National Land Agency shows the state of land subsidence in the fiscal year of 1995 (Fig. 14).

Recently, underground buildings for the railroad station deeper than 50 m below the surface have been constructed in the metropolitan city of Tokyo. On the other hand, the pumping regulation was enforced, since land subsidence has occurred since the 1970s. At present, the recovery of the deep groundwater level is remarkable. As a result, the need to prevent the rebound of the underground construction by a buoyancy effect has been occurring.

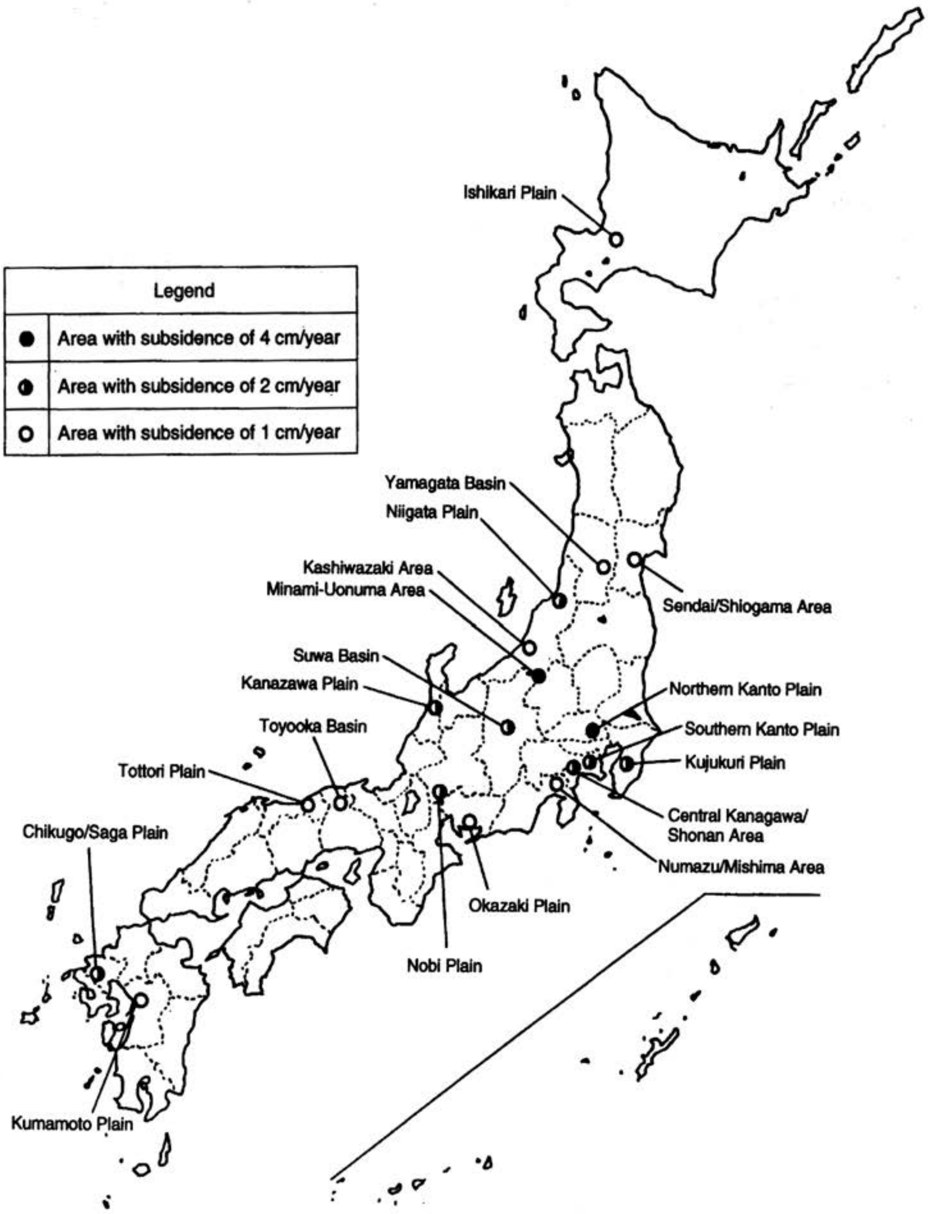

Figure 14. State of land subsidence during fiscal year of 1995 (National Land Agency 1997).

Table 5. Comparative hydrogeology from the viewpoint of groundwater flow systems in the North China Plain and Japan.

East Asia	Climate condition: Precipitation (mm/yr)	Topographic condition: Distance from main divide to sea (km)	Groundwater circulation intensity and problems due to heavy pumping
North China Plain	< 600	> 300	Low, decline in groundwater heads, subsidence and salinization
Central Japan	> 1,200	< 100	High, decline in groundwater heads and subsidence

6 CONCLUDING REMARKS

In Japan and China, climate and landform are quite different even in East Asia. The characteristics of the hydrogeological situation are summarised in Table 5 from the viewpoint of the groundwater flow system in those regions. In Japan, where the average precipitation amount is 1,700 mm/yr and the distance from the mountains to the sea is less than 100 km, freshwater discharges as groundwater into the sea. Due to heavy pumping, the decline in the groundwater level and land subsidence have occurred in the coastal mega cities since the beginning of the 20th century. However, the quantity of groundwater was not a great problem because those cities could use alternative water resources, such as river water. On the contrary, in the North China Plain, where the distance from the sea is more than 300 km and precipitation is about one third that of Japan, it is not possible for freshwater to discharge directly into the sea. As a result, the decline in the unconfined groundwater level in the past 30 years has been greater near the mountains to reach 12–25 m and the salt accumulation has been generated due to the recent agricultural activities for crop productions.

Many scientists are recognising ecologically oriented water management as the only correct way for water and sustainability. However, it is still under discussion. It addresses a series of scientific, methodological, institutional, and other challenges.

Challenge for scientific research: along with all the traditional problems, it is necessary to strengthen research in the following problems.

The interaction of the evolution of the continental water sphere and all other spheres: ocean sphere, biosphere, atmosphere, lithosphere, etc. The purpose of such research is to delineate appropriate water management requirements to maintain the ecological balance and to protect the regional climate condition.

Methodology and applied technology for ecologically oriented water management.

The complex problem contains research of integrating natural scientific and engineering problems with economical, demographic and even geopolitical researches. This serves as the important basis of working out appropriate strategies to realise water management measures.

A bridge to the water end users and decision-makers is capability and infrastructural constructions. Ecologically oriented water management is a highly integrated work in the context of not only the integrated research of different sciences, but also involving the joint efforts and activities of different people: scientists, water management workers, end users, decision-makers. To make the latter integration realistic, the only way is to strengthen capability and infrastructural constructions. The contents about these constructions have been stated by many scientists, as well as by these authors, and will not be repeated here. No doubt, if there is no significant progress in those constructions, water and sustainability can only be an imagination.

REFERENCES

Chen, J.Y. & Wu, K. 1997. Preliminary analyses for crop water consumption by using Lysimeter. *The Journal of Chinese Geography* 7(3): 64–71.

Chen, J.Y.; Tang, C.Y.; Sakura, Y.; Kondoh, A.; Shen, Y.J. & Ouyang, Z. 2001a. The impacts of diversion from the Yellow River on the local aquifer: case study in Shandong Province, China. In K. P. Seiler & S. Whonlich (eds.) *New approach characterising groundwater flow*. Balkema Publisher: 1143–1147.

Chen, J.Y.; Tang, C.Y.; Sakura, Y.; Kondoh, A. & Shen, Y.J. 2001b. Nitrate pollution pattern in groundwater, based on groundwater flow system and land use change in the North China Plain (NCP). In *Proceedings of spring meeting in Japanese association of Groundwater Hydrology*: 26–31.

Economic Yearly Book of Beijing 1996. *Chinese Statistic Press* (In Chinese). Beijing.

Environment Agency 2000. *Water Environment Management in Japan*. 41 pp.

Eweis, J.B.; Ergas, S.J.; Chang, D.P.Y. & Schroeder, E.D. 1998. *Bioremediation Principles*. McGraw-Hill: 110–114.

Falkenmark, M & Widstrand, C. 1992. Population and water resources: a delicate balance. *Population Bulletin* 47(3). Population Reference Bureau, Washington, DC.

Follett, R.F. 1989. Groundwater quality concerns about nitrogen. In R.F. Follett (ed.). *Nitrogen management and groundwater protection*. Elsevier: 1–34.

Freeze, R.A. & Cherry, J.A. 1979. *Groundwater*. Prentice Hall. 604 pp.

Huang, D.M.; Wu, S.M.; Xu, Q.M.; Zhang, X.Z.; Li, X.; Zhang, F. & Zheng, X.J. 1989. Effects of NPK-fertiliser on Chinese cabbage in suburb of Beijing. In B. Lin *et al.* (eds.). *Studies of fertiliser application in China*. Beijing Scientific and technological Press, Beijing: 25–27. (In Chinese).

Jin, J.Y.; Zhang, N.; Liang, M.Z. & Wu, R.G. 1995. *Balanced fertiliser for high yield and efficiency by systematic approach to soil nutrients for high yield and efficiency*. Soil and Fertiliser Institute of CAAS, Beijing, 29 pp. (In Chinese).

Kawasaki, S.; Sugahara, T.; Miyakita, J.; Kotoku, M.; Nagata, S.; Enami, N.; Nishijima, T. & Azuma, K. 1993. Geotechnical development of subsurface dam project. In Y. Sakura (ed.). *Selected Papers on Environmental Hydrogeology* Vol. 4, International Association of Hydrogeologists: 215–228.

Komor, S.C. & Anderson, H.W.Jr. 1993. Nitrogen isotope as indicators of nitrate sources in Minnesota sand-plain aquifers. *Groundwater* 31(2): 260–270.

Liu, C.M. 1992. Conjunctive use of agricultural water in the lower reaches of the Yellow River. In J. Shalhever *et al.* Water efficiency in agriculture. Priel Publishers.

Liu, C.M. & He, X.W. 1996. Water problem strategy for China's 21st century. Science Press. Beijing. China. Pp. 5.

Nagata, S.; Enami, N.; Nagata, J. & Katoh, T. 1993. Design and construction of cut-off walls for subsurface dams on Amami and Ryukyu Island In the most southwestern part of Japan. In Y. Sakura (ed.). *Selected Papers on Environmental Hydrogeology*, Vol. 4. International Association of Hydrogeologists: 229–245.

National Land Agency of Japan 1997. *Water resources in Japan*. 100 pp.

Raskin, P.D.; Hansen, E. & Margolis, R.M. 1996. Water and sustainability, global pattern and long-range problems. *Natural Resource Forum* 20(1). Elsevier Science Ltd., pp. 2, 7, 13, 14.

Shimada, J.; Tang, C.Y.; Iwatsuki, T.; Tanaka, T.; Sakura, Y.; Song, X.; Yang, Y.H.; Tian, K.X.; Zhang, G.L. & Sun, J.C. 2000. Groundwater flow system study of the NCP area-Preliminary results revealed by environmental isotopes. In T. Tanaka (ed.). *Proceedings of International workshop on sustainable development of water resources in the North China Plain*: 20–24.

Stuyfzand, P.J. 1999. Patterns in groundwater chemistry resulting from groundwater flow. *Hydrogeology Journal* 7: 15–27.

Toth, J. 1999. Groundwater as a geologic agent: An overview of the causes, processes and manifestations. *Hydrogeology Journal* 7: 1–14.

Wu, K.; Chen, J.Y.; Liu, S.P. & Xie, X.Q. 1997. The research on water-consumption characteristics of crops and water use efficiency in agriculture in the Yucheng Area, The North China Plain. In C.M. Liu & H.N. Yu (eds.). *Study on water movement experiment in soil-plant-atmospheric continuum*. Meteorology Press, Beijing: 131–138. (In Chinese).

Yang, S.C.; Chen, L.S.; Mao, D.R. & Liu, G.S (eds.) 1991. *Optimal fertilisation and soil management techniques of main crops in the Plain of Huang-Huai-Hai River Valley.* Chinese Agricultural Scientific Press, Beijing, 228 pp. (In Chinese).

Zhang, W.L.; Tian, Z.X.; Zhang. N. & Li, X.Q. 1996. Nitrate pollution of groundwater in northern China. *Agriculture, Ecosystems and Environment* 59: 223–231.

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