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ENVIRONMENTAL IMPACT OF GEOTHERMAL UTILIZATION IN THE TIANJIN BINHAI AREA, CHINA

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ABSTRACT

In 2005, the development of the Tianjin Binhai area was brought into the strategy for national development in China. It is the third area to be developed (after Shenzhen and Shanghai). Therefore, the political and economic status of this area is very important. The Binhai area is rich in geothermal resources and they are already widely utilized, providing considerable economic and environmental benefits. By the end of 2006, there were more than 120 geothermal production and injection wells in this area, used for space heating, bathing, fish farming and other purposes. Although geothermal energy is generally perceived as environmentally friendly, development in the last 30 years has shown that it is not completely free of negative impacts on the environment. In the Tianjin Binhai area, the primary environmental problem is land subsidence. In this report, the environmental impact of geothermal utilization is discussed. The connection between geothermal development and land subsidence is particularly emphasized.

1. INTRODUCTION

The Tianjin Binhai area is rich in low-temperature geothermal resources, with temperatures from 4 to 100°C The present total volume of geothermal water production is more than 8 million m^3/a. The geothermal space heating area is more than 3.6 million m^2. More than 40,000 families and some ten companies benefit from geothermal space heating. The surface rocks in the Binhai area are unstable. Land subsidence, soft soil groundsill and bank stabilization are the main geo-environmental problems in the area. Although geothermal energy has particular advantages over fossil fuel energy and is, thus, already generally accepted as being an environmentally benign energy source, we cannot ignore the environmental problems generated by the utilization of geothermal energy. The main environmental effects of geothermal development are related to surface disturbances, the physical effects of fluid withdrawal, heat effects and the discharge of chemicals. All these factors will affect the biological environment as well as all industrial activities (Kristmannsdóttir and Ármannsson, 2003). There are also some social and economic effects.

The environmental and social impacts of a geothermal project must not be overlooked, and indeed should be considered an integral part of project design (Rodríguez and de Arévalo, 2007). Therefore, the impact of land subsidence should be of great concern in the Tianjin Binhai area, where geothermal resources are located in a sedimentary basin, where most of the waste water cannot be injected. A monitoring system needs to be set up and the monitoring data should be analyzed carefully. At the same time solutions need to be found.

2. OVERVIEW OF THE TIANJIN BINHAI AREA

2.1 About Tianjin

The city of Tianjin is the economic centre of North China, with a population of 11 million. Tianjin is geographically located at latitude 38°34' N - 40°15' N and longitude 116°43' E - 118°04' E. Tianjin belongs to the 8th eastern international time zone. At the centre of the Bohai Sea economic circle along the west coast of the Pacific Ocean, Tianjin backs onto North China, Northwest China and Northeast China and faces Northeast Asia; and it is only 120 km away from Beijing, the capital of China. Thanks to such a favourable location, Tianjin enjoys great advantages and provides ready access for over a dozen provinces and cities in North China for communication with foreign friends. As one of the four special municipalities directly under the central government of China, Tianjin is also the largest port city in the north. The total area of the community covers 11,900 km^2, stretching 189 km from south to north and 117 km from east to west. The city proper covers an area of 7,418 km^2, with the rural area covering 4,502 km^2. The circumference of the whole city is about 900 km, including a coastline of 153 km and a land line of over 700 km.

2.2 Tianjin Binhai area

The Tianjin Binhai area is located east of Tianjin, facing the Bohai Sea (Figure 1). It covers 2270 km^2, with a coastline of 152.8 km. The population is 1.3 million. It includes five districts: Dongli, Jinnan, Tanggu, Hangu and Dagang. There are three functional areas in Tanggu district: Tianjin port, the Tianjin economic and technological development area, and the Tianjin bonded warehouse area. In 2005, the development of the Tianjin Binhai area was brought into the stratagems of national development.

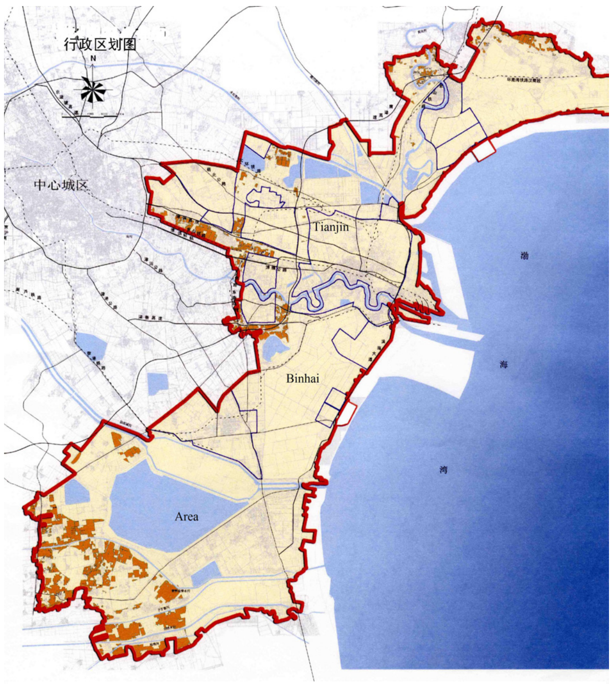

FIGURE 1: Map of the Tianjin Binhai area

2.2.1 Physiography

The Binhai area is located in the lowlands, with an elevation from 0 to 2.0 m, the lowest elevation is actually at -1.0 m (in the north Haigu district). It belongs to the north part of the typical mud coast of China, west of Bohai Sea Bay, with low plains consisting of alluvial-marine and marine deposition. At the coast there is an esplanade and a man-made beach, with a width from 3 to 7.3 m and a gradient from 0.4 to 0.6‰. Normally, the depth of the sea water is less than 10 m.

There are five main physiographic units from west to east in this area: the alluvial-marine deposition plain, the marine deposition plain, the shell beach ridge, the intertidal zone and the underwater sloping field. They are characteristic of the changes in sedimentation and the transformation from sea to land. The borderlines between these physiographic units are obvious.

2.2.2 Weather

Located in the warm temperate zone, Tianjin has a sub-humid continental monsoon climate. The four seasons are clearly distinguished, which results in great differences in temperature and a wide variety of scenery throughout the year. The average temperature in a year tops 12.3°C, the average temperature in summer being about 27°C, and the average temperature in winter about -5°C, the frost-free period lasting about 200 days. On average, the annual precipitation is about 400 mm, 75% of which is concentrated in June, July and August. The sunshine period in this area is relatively long.

2.2.3 Water systems and rivers

This area is located in the lower reaches of the Haihe river drainage area. There are two main water systems: the Haihe river water system and the Jiyuhe canal water system. The former is made up of North canal, Yongding river, Daqing river, Ziya river and Nanyunhe canal, while the latter is made up of Chaobai River, Zhou River, Huanxiang River and Ji-yuhe canal. Both systems have outflows to the sea to the east of Tianjin. The Bei-dagang, Huanggang, Guangang and Qianquan reservoirs are located in this area.

2.2.4 Natural resources

Tianjin enjoys a rich supply of natural resources, which is quite rare for large cities both in China and elsewhere. Most of the resources are located in the Binhai area. First of all, Tianjin has abundant oil and gas resources. Its Bohai and Dagang oil fields accommodate key state oil and gas projects, turning out over 13,000,000 tons of crude oil and 850,000,000 m^3 of natural gas per year. Secondly, with its coastline stretching 150 km, Tianjin has inexhaustible sea salt resources and takes pride in its Changlu salt field. With an annual output of 2,200,000 tons of salt, or 10% of the total sea salt production in China, Changlu Salt Field is the most famous sea salt production base in China. Thirdly, plentiful geothermal resources are available in Tianjin. The underground hot water temperature ranges from 30 to 105°C. In addition to its excellent quality, the hot water is found at a shallow depth. In ten areas with geothermal resources worth further prospecting and tapping, the total reserve is over 20 billion tons. This is the largest medium- or low-temperature geothermal field in China. Three of the geothermal fields are located in the Binhai area. Fourthly, in this area, 200 km^2 of wasteland and shallows have great potential for development. Because most of this land is located downstream of the Haihe River where transportation is convenient, it is possible to develop the land at low cost. Such favourable conditions are not available in other large cities in China.

In the Tianjin Binhai area, there are many species of plants (mostly re-vegetation) and animals and over 30 fish species. Aquatic Products Bohai Fishing covers 2100 km^2. They have developed a major aquaculture breeding and ocean fishery industry. The famous Bohai prawn is their major aquatic export product.

2.2.5 Social and economic aspects

Tianjin is one of the municipalities under the direct administration of the Central Government of the People's Republic of China. It is the biggest coastal open city and the economic centre of Northern China. Tianjin's educational, scientific and cultural institutions are also comparatively developed. With 20 universities and colleges presently in operation, Tianjin possesses over 150 institutions for natural science research and more than 600,000 technical personnel including 22 academicians from the Chinese Academy of Sciences and Chinese Academy of Engineering. The number of foreign specialists and scholars invited from abroad exceeds 10,000. There are 159 scientific research institutes, 8 state-level laboratories, 10 state-level research centres for engineering technology and 27 state-level ministerial technical testing centres. Tianjin is the economic and trading centre of northern China. Tianjin is also a bridge connecting east and west, south and north, playing an important role as a centre for business and trade. Tianjin is a major comprehensive industrial base in northern China. It has over 150 lines of industry consisting primarily of electronics, automobiles, metallurgy, pharmaceuticals, textiles, chemicals and mechanics. With strong industrial supportive abilities, Tianjin enjoys good conditions for sustainable and rapid development of industries. Tianjin has been an international trading port for China for many years. As the largest bulk goods trading port in northern China and one of the first of coastal cities to be opened up to the world, it has been active in foreign trade. It has established trade relations and marine links with more than 300 seaports in over 160 countries and regions around the world. Garments, textiles, machinery and electronic products are the main export items. In addition, 14 overseas banks have established branch offices in Tianjin. Tianjin serves as an important grain and vegetable production base for the Tianjin-Beijing area. Tianjin is a commercial and a financial centre. It boasts lower land, labour force and operating costs than Beijing, Shanghai, and Guangdong.

In 2005, the development of the Tianjin Binhai area was brought into the stratagems for national development. So the political and economical status of this area is important for China. In 2005, the construction of 69 base establishments started, 39 of which were completed in the same year. The investment is 17.5 billon yuan, a rise of 11.5% over the previous year. These base establishments include: a seaport, an airport, a railway, roadway traffic, bridges, an environmental project, a 220 kV transformer substation, waste water and garbage disposing centres, etc. The economy has maintained its momentum of continuous, rapid, coordinated and sound development.

In 2005, the GDP of the Tianjin Binhai area reached 160.86 billion yuan (≈21 billion dollar), a rise of 19.8% over 2004 in terms of comparable prices. Industry's share is 68.48%, and that of service 31.04%. The growth rate was not only the greatest after 1996 in Tianjin, but also among the greatest in large Chinese cities and provinces. Aggregate investment of capital assets was 6.39 billion yuan, a rise of 22.6% over 2004.

3. GEOTHERMAL SYSTEMS IN THE TIANJIN BINHAI AREA

3.1 Introduction

The geothermal resources in Tianjin are typical low-temperature geothermal resources in a sedimentary basin. They cover an area of 8,700 km^2, about 77% of the total area of Tianjin. The Tianjin area is located in the northeast part of the North China Plain subduction zone, where a very thick Cenozoic erathem loose alluvial stratum overlies the Paleozoic and Proterozoic floor. Except for some exposed parts of bedrock in the mountains north of Jixian County, most of the area is covered with a very thick Cenozoic alluvial plain. The geothermal resources are quite abundant and distributed over almost every region. The typical geothermal resources belong to the static storage type. There are 10 geothermally anomalous areas. The total area of these, where temperature gradients ≥ 3.5°C/100 m (the normal gradient in the Tianjin area), is about 2320 km^2. The highest temperature gradient is 8.8°C/100 m, the highest wellhead temperature is 105°C.

The main north-northeast structure in the Tianjin region was formed by many large structural movements, and controls the distribution of the geothermally anomalous areas. To sum up, the geothermal water in the bedrock is derived from ancient precipitation, the main recharge area being the Yanshan mountains in the north. The recharge dates from the last glacial period of the Quaternary, mixed with some modern precipitation. The flow path is from the northeast to the southwest along the Cangxian heave. It is suggested that the cold water in the northern mountains flows along the large faults to the geothermal reservoirs.

The reservoir in the basement zone is the main developing aquifer. The main feeding channels are the karst conduits in the weathering carbonate rock of the Proterozoic and lower Paleozoic. The main faults have a north-northeasterly, northeasterly and easterly trend. The geothermal areas are controlled by faults and the water quantity is large near the water conducting fault belts.

3.2 Characteristics of the major geothermal reservoirs

The geothermal systems in Tianjin can be divided into two primary groups depending on the formation of the reservoir: porous reservoirs in sandstone and fractured reservoirs in bedrock. The two groups of geothermal reservoirs are located in the main area. To the south of the Baodi faults, the Tertiary and Quaternary sedimentary formation, with a thickness of over 1200 m, forms the cover of the bedrock geothermal reservoirs. The temperature gradient follows the uplifts and depressions. The porous reservoirs in sandstone include two of the Minghuazhen (Nm) group and the Guantao (Ng) group from the upper Tertiary. The fractured reservoirs in the bedrock include three groups: an Ordovician system, a Cambrian system and a Jixian system. So, there are five different reservoirs in Tianjin.

The Minghuazhen (Nm) group extends across almost all of the area south of the Baodi fault. The aquifer roof varies from 300 to 600 m depth, and the thickness is 500-1400 m. The aquifer is mostly composed of mealy sand and fine sand. Water production from a single well is of the order 40-100 m^3/h, with a wellhead temperature of 40-70°C. In general, the mineralization is less than 1500 mg/l, but in one location the mineralization is higher than 3000 mg/l. Water quality is mostly (relatively) good.

There are local lacunas in the Guantao (Ng) group, for example south of the Wanglanzhuang (WLZ) field. The aquifer roof varies from 1200 to 2200 m, the thickness is less than 1000 m. The aquifer is mostly composed of mealy sand and medium sand. In general, water production of a single well is 60-130 m^3/h, at wellhead temperature of 50-80°C. The Guantao group is distributed across the depression area, and is the primary producing reservoir. In general, mineralization is less than 2000 mg/l.

There are lacunas in Ordovician-Cambrian limestone south of the WLZ field. The depth to the aquifer roof varies from 800-5000 m. Water production of a single well is 100-200 m^3/h, with wellhead temperature 60-90°C. The mineralization is 1500-~5000 mg/l, water quality is relatively poor, and the water is corrosive.

The Jixian dolomitic limestone is widely distributed in the Tianjin area. The aquifer roof lies at 1700-4000 m depth, with a porosity of 0.05-0.134. In general, water production of a single well is 100-200 m^3/h, with wellhead temperature 79-105°C. The Jixian dolomitic limestone group is the main aquifer developed for downtown Tianjin, but it is very deep in the depression area. For example, the aquifer roof is at more than 4000 m depth in the Baitangkou depression area, and this is very difficult to utilize. In general, water quality is relatively good and the mineralization 1000-2000 mg/l. Hydro-chemically, there is horizontal zoning from northeast to southwest. The waters are of 6 types with respect to the Nm group from HCO_3-Na to Cl·SO_4-Na and total dissolved solids. The waters of the Jixian group are of 5 types with respect to HCO_3·SO_4-Na to Cl-Na. The main characteristics of the explored geothermal reservoirs are shown in Table 1.

3.3 The hydro-chemical character of the main reservoirs in Binhai area

The hydro-chemical character of the Tertiary system Minghuazheng group reservoir is shown in Table 2. From north to south, salinity gradually increases, from 500 to 2500 mg/l; and the hydro-chemical type of the geothermal water becomes more complex, from HCO_3- Na type to Cl ·SO_4– Na type. This trend is consistent with the flow direction of the geothermal liquid. Salinity does not appear to change with depth (Figure 2).

TABLE 1: Main characteristics of explored geothermal reservoirs

Reservoir types		Reservoir character	Hydrogeology parameter
Continental deposit, sedimentary intergranular porous reservoirs	Tertiary system, Minghuazheng group	Depth to reservoir top: ~300-450 m; thickness: ~500-1500 m; with different thickness of half-cemented fine silt, fine sand and mudstone. Flow rate: ~50-100 m^3/h; Temperature: ~40-70°C; Water chemistry type: HCO_3-Na, HCO_3·CL-Na, SO_4·CL-Na; Salinity: Generally <1.5 g/l, local >3 g/l. No or slight causticity.	Permeability coefficient: ~0.4-2.2m/d; Transmissivity: ~44-484m^2/d; Elastic release coefficient: ~5-34.1×10^{-5}; Porosity: ~25-33.5%.
	Tertiary system, Guantao group	River type clastic rocks sediment; thick-thick cycle of sedimentation; may dimidiate into top sandstone sect reservoir (Ng1) and substratum sandstone-conglomerate sect reservoir (Ng2). Ng1: thickness: ~100-200 m, temperature: 55-65°C; Ng2: temperature ~60-80°C; flow rate ~80-130 m^3/h; Water chemistry type: HCO_3-Na, HCO_3·Cl-Na.	Permeability coefficient: ~0.5-2.0m/d; Transmissivity:~40-212m^2/d; Elastic release coefficient: ~2.9-7.3×10^{-5}; Porosity: ~18-36.6%.
Marine deposit, carst-fissure-pore reservoirs	Palaeozoic Erathem, Ordovician system	Depth of reservoir top: ~1000-2000 m, thickness: ~450-750 m, temperature: ~60-90°C. The reservoir is made up of dolomitic limestone, limestone, argillaceous limestone and mudstone. With full-grown carst fissure. Flow rate: ~100-200m^3/h; water chemistry type: SO_4-Cl-Na, HCO_3-Cl-Na; Salinity: ~1.8-5g/s, with strong causticity.	Permeability coefficient: ~0.2-2.5 m/d; Transmissivity: ~19-302 m^2/d; Elastic release coefficient: ~1-3.8×10^{-5}; Fissure ratio: ~2.0−6.25%.
	Palaeozoic Erathem, Cambrian system	Limey dolomite, thickness: ~40-120 m; Temperature: ~70-80°C, flow rate ~60-100m^3/h; Water chemistry type: HCO_3-Na, HCO_3-SO_4-Na; Salinity: ~1.0-2.0g/l; Intergranular porosity reservoir.	Permeability coefficient: ~0.2-3.7m/d; Transmissivity:~19-370m^2/d; Elastic release coefficient: ~3-4.6×10^{-5}; Fissure ratio: ~2.6-5.0%.
	Middle and upper Proterozoic Erathem	Coarse-crystalline dolomite, Chert-Zebra dolomite; Flow rate: ~100-200m^3/h; Temperature: >79°C. Depending on the location, the chemistry type is complex: HCO_3·SO_4-Na, Cl·HCO_3·SO_4-Na, Cl·SO_4·HCO_3–Na, Cl·SO_4–Na, Cl–Na; pH: ~7.5-8.5, Salinity: ~ 1.0-2.2 g/l.	Permeability coefficient: ~0.2-3.5m/d; Transmissivity:~27-318m^2/d; Elastic release coefficient: ~0.4-4.0×10^{-5}; Fissure ratio: ~2.7−5.8%.

TABLE 2: Chemical composition of well fluids in the Tertiary system Minghuazheng group reservoir (mg/l)

		NH-Guida			**TG-13**		
		2003	**2004**	**2005**	**2003**	**2004**	**2005**
Cations	Na^+	95	98.1	102.7	243.6	255.9	241.2
	Ca^{2+}	6	7.0	7	3	3.0	5
	Mg^{2+}	0.6	0.6	0.6	0.6	0.6	0.6
Anions	Cl^-	14.2	17.7	17.7	35.4	35.4	35.4
	SO_4^{2--}	26.4	4.8	28.8	48	43.2	62.4
	HCO_3^-	210.5	225.8	222.7	524.8	543.1	549.2
	F^-	0.6	0.75	0.66	4.28	4.06	4.38
Other items	SiO_2	24	23.8	24.8	26.6	27.0	26.5
	Total salinity	386.4	384.7	411.2	895.4	921.7	927.7
	Total hardness	17.5	20.0	20	10	10.0	15
	Total alkalinity	187.7	195.2	192.7	450.4	465.4	460.4
	pH	8.54	8.68	8.66	8.56	8.62	8.5
Larson index		~0.16-0.3			~0.21-0.25		
Water chemical type		HCO_3-Na			HCO_3-Na		

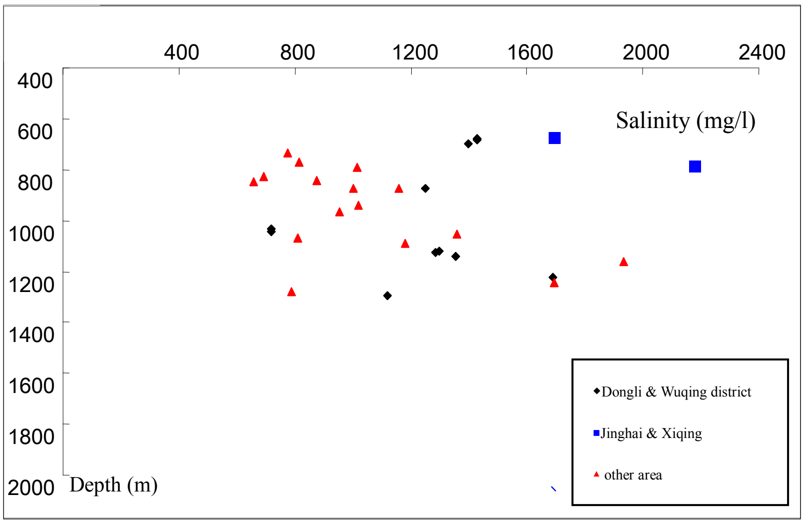

FIGURE 2: The relationship between depth and salinity in a Tertiary system Minghuazheng group reservoir

The hydro-chemical character of the Tertiary system Guantao group reservoir is given in Table 3. In the west part of this area, from north to south, the salinity gradually increases, from 1000 to 5000 mg/l; and the hydro-chemical type of geothermal water becomes more complex, from HCO_3- Na type to Cl ·SO_4– Na type. The change is consistent with the flow direction of the geothermal liquid.

In the east part of this area, from north to south, the salinity gradually increases, from 500 to 3000 mg/l; and the hydro-chemical type of the geothermal water becomes more complex, from HCO_3-Na type to Cl ·SO_4- Na type. This trend is consistent with the flow direction of the geothermal liquid. The salinity increases with depth (Figure 3).

TABLE 3: Chemical composition of well fluids in the Tertiary system Guantao group reservoir (mg/l)

		TG-16			**HG-01**		
		2003	**2004**	**2005**	**2003**	**2004**	**2005**
Cations	Na^+	498.1	495.2	522	438.7	430.1	471.8
	Ca^{2+}	10	11	10	16	17.0	15
	Mg^{2+}	1.2	1.2	1.2	3.6	3.0	4.3
Anions	Cl^-	322.6	320.8	320.5	214.5	212.7	218
	SO_4^{2-}	220.9	242.1	235.3	187.3	196.9	220.9
	HCO_3^-	558.3	537	546.1	656	625.5	634.6
	F^-	7.3	7.3	7.85	4.4	4.7	4.8
Other items	SiO_2	41	41	41.7	49.5	49.5	49.5
	Total salinity	1657	1659.8	1682.1	1578.1	1563	1634.4
	Total hardness	30	32.5	30	55	55.0	55
	Total alkalinity	457.9	450.4	447.9	538	538.0	530.5
	pH	8.29	8.4	8.26	8.26	8.46	8.37
Larson index		1.49	~1.55-1.59		~0.92-0.98		
Water chemical type		HCO_3·Cl -Na	Cl ·HCO_3 -Na		HCO_3 ·Cl -Na		

The hydro-chemical character of the Middle and upper Proterozoic Erathem (Jixian system Wumishan Group) reservoir (Table 4) shows that from north to south, the salinity increases considerably. The salinity of well ZL-4 water (in the north of Tianjin) is 1030 mg/l; downtown, the salinity of the reservoir water is 1600-1900 mg/l; in the Dasi area the salinity is about 2000 mg/l; and in Tangguantun, the salinity is 6000 mg/l. The hydro-chemical type of geothermal water becomes more

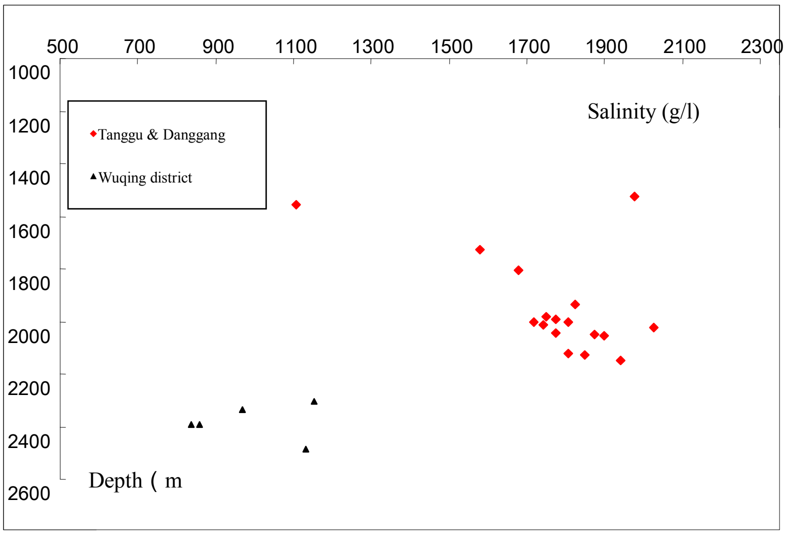

FIGURE 3: The relationship between depth and salinity in a Tertiary system Guantao Group Reservoir

complex from north to south. This trend is consistent with the flow direction of the geothermal liquid. The salinity does not change markedly with depth (Figure 4). In the Binhai area, the hydro-chemical type of geothermal water in middle and upper Proterozoic Erathem reservoir is Cl· HCO_3· SO_4–Na, the salinity is 1670-1790 mg/l, and the pH 7.7-8.36. The Larson index is 2.13-2.8 and the water is slightly caustic (Ruan et al., 2006).

TABLE 4: Chemical composition of well fluids in the Jixian system Wumishan group reservoir (mg/l)

		DG-47		DL-28		
		2004	**2005**	**2003**	**2004**	**2005**
Cations	Na^+	539.5	547	445.4	449.0	476
	Ca^{2+}	14	27.1	34.1	35.1	33.1
	Mg^{2+}	3.0	5.5	11.6	10.9	11.6
Anions	Cl^-	448.4	441.4	390.	388.2	386.4
	SO_4^{2--}	295.9	288.2	328.5	309.3	312.2
	HCO_3^-	421.0	496.9	436.3	433.2	442.4
	F^-	13.4	11.6	11	12.4	12.4
Other items	SiO_2	77.0	76.3	63.5	64.5	64.8
	Total salinity	1859.1	1909.2	1774.5	1766.4	1797.7
	Total hardness	47.5	90.1	132.6	132.6	130.1
	Total alkalinity	355.3	385.3	357.8	355.3	362.8
	pH	8.42	8.11	7.22	7.52	7.85
Larson index		~2.6-2.65		~2.39-2.48		
Hydro-chemical type		Cl·HCO_3-Na		Cl·HCO_3·SO4 -Na		

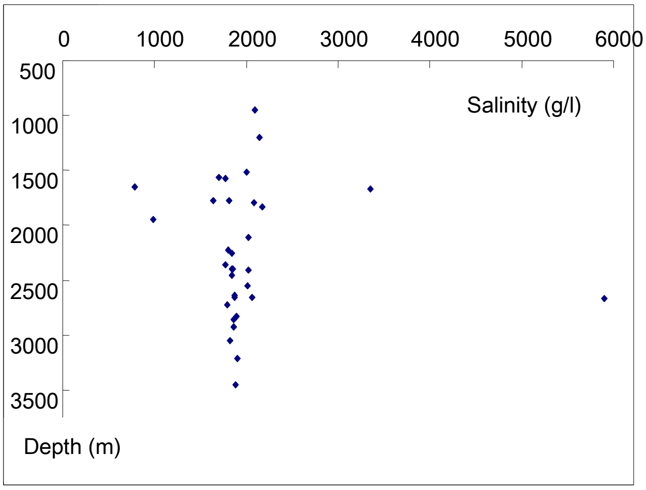

FIGURE 4: The relationship between depth and salinity in a Jixian system Wumishan group

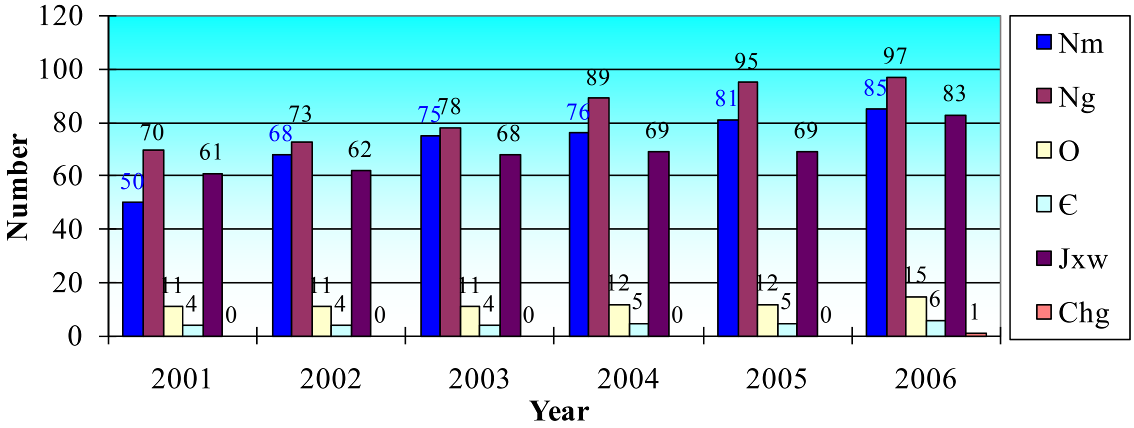

FIGURE 7: The increase of number of geothermal wells in different reservoirs in Tianjin in 2001-2006

3.4 Geothermal utilization

3.4.1 Geothermal utilization in Tianjin

Geothermal utilization in Tianjin can be traced back to the early 1970s, when Tianjin Municipal authority began to explore and develop geothermal energy with the aid of the United Nations Development Agency (UNDP). Ten geothermal areas were located, three of which have been thoroughly explored. So far, eight fields have been explored and the greatest depth drilled to is about 4000 m.

Since geothermal exploration and development in Tianjin started, multiple benefits have been realized. At present, the priority uses are for district space heating and domestic water. Other uses are for public bathrooms, swimming pools, greenhouses, fish farming, mineral water, industrial washing and drying. The total area heated by geothermal energy is 9.5 million m^2 and accounts for 7% of Tianjin's total space heating area or 60% of the total geothermal space heating area in China. Tianjin has become a true "geothermal city". The extensive utilization of geothermal energy not only saves on traditional energy sources but also clearly improves the environment; it plays an important role in the development of the city.

By the end of 2006, there were 287 geothermal production wells in Tianjin, mainly used for space heating, domestic hot water, spas, industrial use, agriculture and fishing. In 2006, the total volume of geothermal water production was 2.83×10^7 m^3, the volume re-injected was 3.50×10^6 m^3 or 12.36% of the production (Figures 5, 6 and 7). The Jixian system is the largest producing geothermal reservoir, its annual production being 1.36×10^7 m^3, or 37% of the total production volume; next in size are the Ng (7.59×10^6 m^3) and Nm (5.24×10^6 m^3) groups.

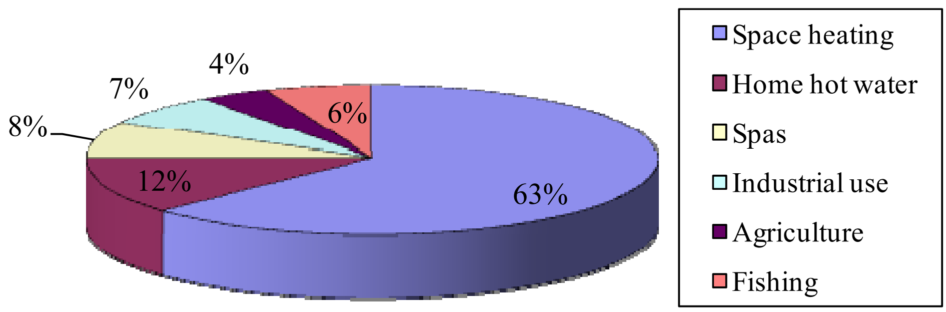

FIGURE 5: The geothermal utilization in Tianjin in 2006

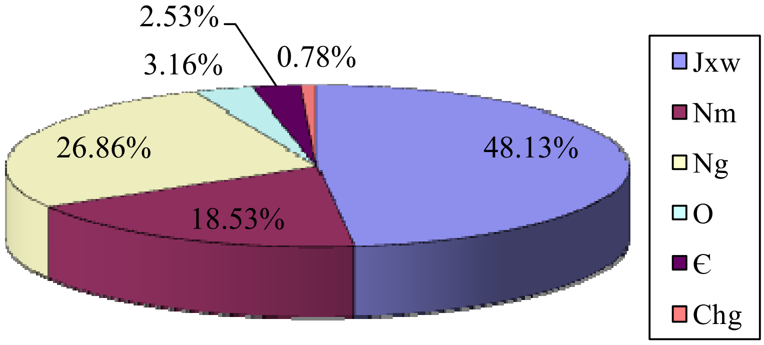

FIGURE 6: The relative production from different reservoirs in Tianjin in 2006

3.4.2 The geothermal development and utilization in the Binhai area

Geothermal exploration in the Binhai area started in the 1970s. By the end of 2005, two geothermal fields had been discovered, the Shan-Lingzhi and Binhai geothermal systems. The attainable reserves are 28.23 Mm^3/a (Table 5). In the 1980s, the first geothermal utilization project was carried out in the Tianjin Binhai area (Tanggu) with the aid of the United Nations Development Programme (UNDP). From then on, more and more projects were carried out in the Binhai area. Geothermal energy is now widely used for space heating, bathing, fish farming and spas in this area.

TABLE 5: Attainable geothermal reserves in the Binhai area

Geothermal field	Area (km^2)	Attainable reserves				
		Tertiary		Base rock		Sum ($10^6 m^3/a$)
		Temp. (°C)	Attainable reserve (10^6 m^3/a)	Temp. (°C)	Attainable reserves (10^6 m^3/a)	
Shan-Ling-Zi	375	40 25-40	2.71 3.30	50-102	11.78	17.79
Bin-Hai	1500	65-78	10.44			10.44
Total	1875		16.45		11.78	28.23

By the end of 2005, there were 120 geothermal wells in the Binhai area, including 4 injection wells. In 2005, the total volume of geothermal water production was $8.27\times10^6 m^3$, and the volume re-injected was 75×10^4 m^3 or 9.06% of the production (Figures 8 and 9). The Guantao group (Ng) is the largest producing thermal reservoir in the Binhai area, the annual production being 5.14×10^6 m^3, or 62.15% of the total production volume; next in size is the Minghuazhen group (Nm) (1.18×10^6 m^3). The geothermal space heating area covers 3.64 million m^2 in the Binhai area. The area of geothermal fish farming and green-houses is 42,900 m^2, for breeding balloon fish, crocodiles and tropical fish, and growing vegetables and flowers. Geothermal hot water was piped to 27,149

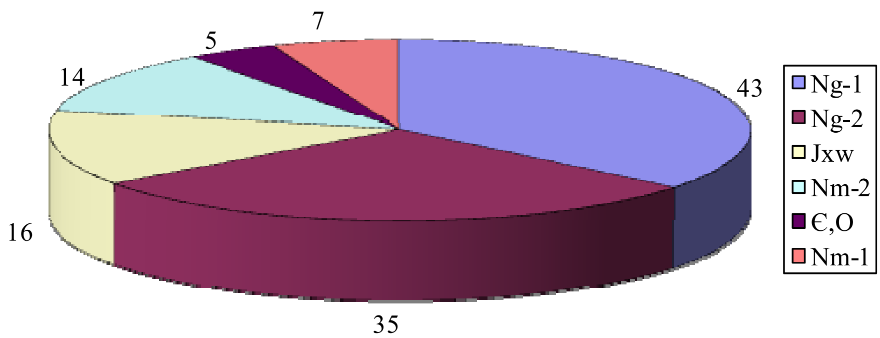

FIGURE 8: The number of geothermal wells in the Binhai area in 2005, related to the different reservoirs they produce from

families, and more than fifty spas or swimming pools. More than 1,570,000 man-hours had been spent in geothermal spas or swimming pools.

Generally, the heating period is from the middle of November through March (the winter in North China), a total of 130 days. Figure 10 shows that the main production is between November and March, with 82% of the yearly production. The geothermal water mined from the Jxw, O and Є reservoirs can be re-injected, and makes up 19% of the total production.

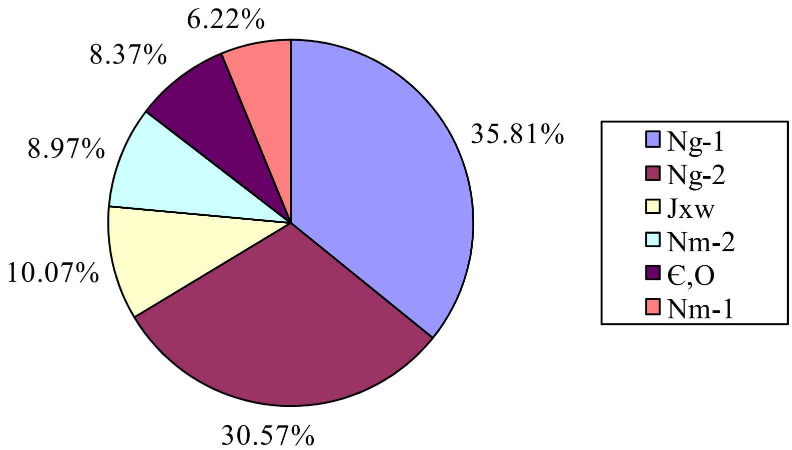

FIGURE 9: The relative production from different reservoirs in the Binhai area in 2005

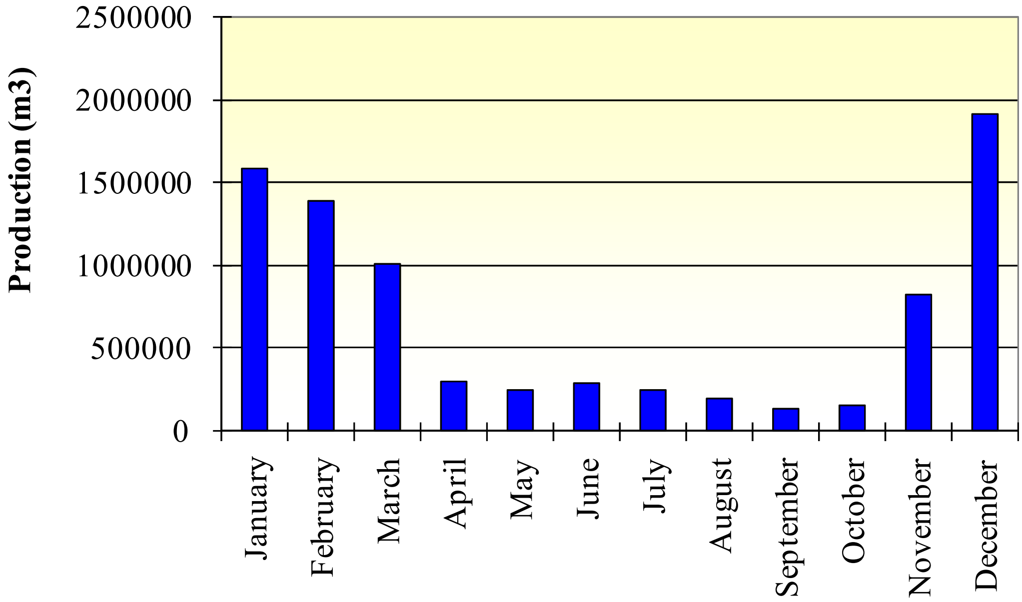

FIGURE 10: The geothermal production through the year in the Binhai area 2005

The largest geothermal utilization project is located in Dong-lihu, where the space heating area is expected to reach 800,000 m^2 in the next two years with the aid of heat pumps, and the hot water to be supplied to 6000 families. There are three production wells that provide heat energy for this uptown area and all the return geothermal water is re-injected into two wells in the same reservoir. The efficiency of heat energy utilization is 85%.

4. ENVIRONMENTAL IMPACT OF GEOTHERMAL UTILIZATION

4.1 The resource usage and environmental status in Tianjin

4.1.1 Resource usage

With rapid economic development, the demand for energy has increased fast. In 2005, the total energy use in Tianjin amounted to 4.51×10^7 million tons of standard coal. The energy use of homes is increasing too. The total area of space heating in Tianjin is 140×10^6 m^2. The resource usage in industry in 2005 is given in Table 6, the energy use of homes per day (2001-2005) in Table 7 and the capacity for space heating in Tianjin (2004-2005) is shown in Table 8.

TABLE 6: Resource uses in industry in2005,
65.7% of the total energy use in Tianjin

Name of resource	Unit	Consumption
Coal	ton	26,052,000
Extract coal	ton	4,833,200
Coke	ton	3,274,100
Coal gas	Billon m^3	0.95
Blast furnace gas	Billon m^3	5.44
Natural gas	Billon m^3	0.45
Base oil	ton	7,782,600
Ligroin	ton	103,300
Diesel oil	ton	236,100
Fuel oil	ton	546,500
Liquefied petroleum gas	ton	22,700
Refinery dry gas	ton	226,600
Other petroleum production	ton	711,600
Heat energy	Million GJ	4.67
Electricity	Million MWh	23.01

TABLE 7: Energy use of homes per day (2001-2005)

Year	2001	2002	2003	2004	2005
Coal (ton)	3800	2200	2500	2300	2400
Liquefied petroleum gas (ton)	295	263	293	245	195
Natural gas, coal gas (10^4 m^3)	160	105	82.5	78.9	105
Electricity (MWh)	7160	8040	8690	9160	10400
Geothermal (m^3)					68000

TABLE 8: Space heating capability in Tianjin in 2004 and 2005

Capacity of heat energy	Unit	2004	2005
Steam	ton/h	3407	3294
Hot water	MW/h	10111	10563
Sold energy			
Steam	10^4GJ/a	1764	1966
Hot water	10^4GJ/a	6530	7572
Length of pipe	km	8038	8705
Heating area	10^6 m^2	114.41	140.41
Domestic dwellings	10^6 m^2	89.7	109.67

4.1.2 Environmental status

Tianjin is not only one of the biggest economic and trading centres in north China, it is also an overpopulated city. Fast economic growth in recent years, industrialization and urbanization, accompanied by inadequate infrastructure investment and management capacity has unavoidably caused some serious environmental problems such as water contamination, water scarcity, air pollution, soil degradation and erosion, land subsidence, industrial and mine solid disposal and so on. Land subsidence is now one of the biggest geo-environmental problems in Tianjin.

The potable water for Tianjin city depends on the water channelled from the Luanhe and the Yellow River. The quality of potable water from the Luanhe and Huanghe rivers is good, but the lack of water resources is very serious. The surface water is contaminated with raw sanitation wastes, industrial waste, sand and agricultural chemicals. The pollution in the inshore Bohai Sea is also very serious, the main pollutants of the sea sector being inorganic nitrogen, oils, inorganic phosphorus and COD. Due to surface water contamination, the extraction of groundwater has been increased. As a result of over-extraction of groundwater, land subsidence and a lowering of the water table have taken place in many areas, and cones of subsidence are increasing in size.

In 2005, the gross water resource was 1.06×10^9 m^3, surface water comprised 7.13×10^8 m^3 thereof, or 27.2% less than in 2004, and groundwater 4.44×10^8 m^3, 14% less than in 2004. The gross precipitation was 517 mm, or 15 % less than in 2004. Tianjin is badly off regarding water. In 2005, the gross water supply was 2.27×10^9 m^3 or 6.10×10^7 m^3 more than in 2004. The gross water supplied from surface water was 1.60×10^9 m^3. Here, water channelled from the Luanhe contributed 4.18×10^8 m^3 and from the Yellow River 1.93×10^8 m^3. The gross water supplied from groundwater was 6.55×10^8 m^3, regenerated water was 8×10^6 m^3 and desalinated seawater was 2×10^6 m^3. Seawater used directly was 1.45×10^9 m^3 (Tianjin Bureau of Statistics, 2005).

In 2005, the wastewater discharge reached 604 million tons, a rise of 30% over 2003, and thereof 301 million tons were industrial and 303 million tons domestic wastewater. The SO_2 discharged reached 264.8 thousand tons, the soot 90.9 thousand tons, and the industrial powdery dust 19.3 thousand tons. The production of industrial solid waste was 11.23 million tons, a rise of 75.5% over 2003, and 98% of it is used synthetically. The production of domestic garbage reached 1452 thousand tons in the city, 80 % of which is disposed of innocuously.

Tianjin's main energy forms are electricity, combustible gas and coal. The use of fossil fuel energy causes serious air pollution. Soot has become a major constituent of air pollution with an annual average of 0.106 mg/m^3, sulphur dioxide emission is 0.077 mg/m^3, and the nitrogen dioxide annual average discharge is 0.047 mg/m^3. In 2005, sulphur dioxide discharge reached 0.26 million tons, of which 0.23 million tons are from industrial pollution. Sulphur dioxide pollution from heating applications is particularly severe. The increase of automobiles has led to exhaust gas from vehicles also becoming a major factor of air pollution. The average noise of road traffic is 68 decibels, and the average noise in the city is 55 decibels.

To improve environmental conditions, Tianjin municipality has made dedicated efforts to raise people's awareness of environmental protection together with economic development. In 2005, Tianjin's investment in environmental improvement was 9.45 billion yuan, or 2.6% of the GDP of the same year, an increase of 4% from 2004. The investment was used for the construction of a base environmental establishment, controlling the amount of industrial pollution, and improving efforts to control waste water, air pollution, landfill etc. In 2005, Tianjin continued to control the pollution caused by the burning of coal. Improvements of coalition networks for fossil coal fired burners using less than 10 tons (steam)/hour have been completed, 584 coal fired burners were dismantled or they were replaced by burners using other fuel; this decreased burning of coal by 418,000 tons, and reduced the SO_2 emissions by 8200 tons and soot discharge by 2700 tons (Tianjin Bureau of Environmental Protection, 2005).

Through these measures and actions, along with a package of administrative and supportive measures for legislation on environmental protection, control and treatment of pollution adopted in recent years, the environmental quality has improved considerably (Figure 11). Geothermal energy has played an important and affirmative role in the process. Now, Tianjin has become one of the cleanest cities in China.

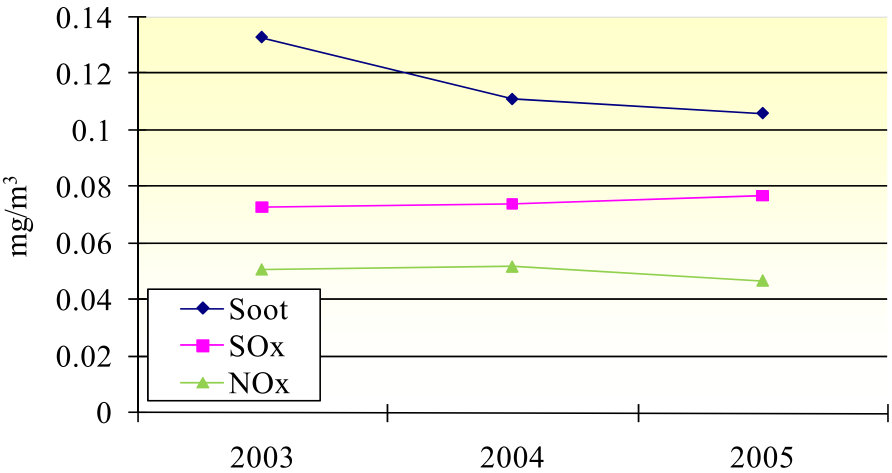

FIGURE 11: The main air contaminants in Tianjin (2003-2005)

4.1.3 The socio-economic actuality of Tianjin Binhai area

In 2005, the GDP of the Binhai area reached 161 billion yuan (~21 billion dollars), 44% of the total GDP of Tianjin. The gross export was 18.5 billion dollars. In the same year, the use of foreign capital was 18.7 billion dollars and domestic capital 22.3 billion dollars. Of the top 500 companies in the world, 152 have invested money to build new factories or to set up new subsidiary companies in this area. It is one of the hottest areas for foreign and domestic capital investment. In the Binhai area there is a large open port, a national development area, a bonded warehouse area, and a high technology industrial area. The Tianjin open port is not only the biggest port in north China, but also among the top 10 ports in the world. In 2005, the throughput of cargo was 2.41×10^8 tons, a rise of 16.7% over 2004, while the throughput of containers was 4.80 million, a rise of 25.8% over 2004.

The CIQ (Custom, Immigration, Quarantine) which is located in the Binhai area is also the biggest CIQ of North China. In 2005, the total value of imports and exports was 82 billion yuan. There are 6 main industries in the Binhai area: information industry, petroleum and ocean chemical industry, car and equipment making industry, high-grade steel making industry, biological technology and modern medicine industry, new energy and new material investigation and making industry. In 2005, the earnings from industrial handling and distribution were 400 billion yuan, of which the share of productions with high or new technology was 44%.

In 2005, the total energy use in the Binhai area amounted to 20.6 million tons standard coal. The energy use per million GDP amounted to 128 tons standard coal, a reduction by 36 tons from 2000. The total supply of geothermal energy equalled 101 thousand tons standard coal in the same year, or 0.5% of the total energy use (Tianjin Government, 2006).

4.2 Benefits of geothermal utilization in the Binhai area

4.2.1 Benefits to the economy

By the end of 2006, there were 60 companies dealing in geothermal utilization projects in the Binhai area. The total number of practitioners is about 400. There are 6 professional institutes or companies that deal in geothermal well drilling, geothermal utilization system construction, necessary equipment production and technological service. The production value of these institutes or companies is more than 140 million yuan each year.

The cost of the heat resource construction for a typical geothermal space heating system is about 60 yuan/m^2, half that of other conventional resources. The average running cost of a geothermal space heating system is about 12 yuan/m^2 a (total running cost per year divided by the total heating area), or 6-8 yuan/m^2 less than for conventional systems (coal boiler, oil boiler or gas boiler). The running cost of the advanced geothermal heating systems which have been constructed in recent years is lower. So, by calculating the running cost, more than 21.8 million yuan is saved each year in the Binhai area.

4.2.2 Benefits to the environment

Generally, the heat resource for space heating in China is a coal boiler or the waste heat of a coal plant. Geothermal energy can replace the burning of 127,000 tons of coal each year in the Binhai area. If that coal is burned in a coal plant with decontaminating equipment, the generation of 4100 tons of sulphur dioxide, small airborne particles and nitrogen oxide is avoided. Furthermore it prevents the generation of:

- 335,000 tons of carbon dioxide (CO_2), the primary human cause of global warming; as much carbon dioxide as it would take 14.56 million trees to assimilate.
- 905 tons of sulphur dioxide (SO_2), which causes acid rain that damages forests, lakes, and buildings, and forms small airborne particles that can penetrate deep into the lungs.
- 45 tons of small airborne particles, which can cause chronic bronchitis, aggravated asthma, and premature death, as well as a haze that obstructs visibility.
- 923 tons of nitrogen oxide (NO_x), as much as would be emitted by half a million recent-model cars. NO_x leads to the formation of ozone (smog) which inflames the lungs, burning through lung tissue making people susceptible to respiratory illness.
- 65 tons of carbon monoxide (CO), which causes headaches and places additional stress on people with heart disease.
- 20 tons of hydrocarbons, and volatile organic compounds (VOC), which form ozone.
- 20 kg of mercury, arsenic, lead, cadmium and other toxic heavy metals;
- 51 million ton per km of coal transport (from the nearest coal mine), with coal dust blowing from coal trains or coal trucks contributing particulate matter to the air and soil.

Running the decontaminating equipment will cost 8 million yuan each year, so, the benefit of geothermal utilization to the environment is obvious.

4.3 Environmental impact of geothermal utilization

4.3.1 Socio-economic impact of geothermal utilization

During the 1960s, when the environment was healthier than it is nowadays and people were also less aware of any threat to the earth, geothermal energy was still considered a non-polluting energy source. However, there is actually no way of producing or transforming energy into a form that can be utilized by man without making some direct or indirect impacts on the environment. Even the oldest and simplest form of producing thermal energy i.e. burning wood, has a detrimental effect, and deforestation, a major problem in recent years, first began when our ancestors cut down trees to cook their food and heat their houses. Exploitation of geothermal energy also has an impact on the environment, but there is no doubt that it is one of the least polluting forms of energy (Dickson and Fanelli, 2004).

Geothermal district heating systems are capital intensive. The main costs are initial investment costs, for production and injection wells, down-hole and transmission pumps, pipelines and distribution networks, monitoring and control equipment, peaking stations and storage tanks. Operating expenses are, however, comparatively lower than for conventional systems, and entail the cost of pumping power, system maintenance, control and management. A crucial factor in estimating the initial cost of the system is the thermal load density, or the heat demand divided by the ground area of the district. The heat density determines the economic feasibility of a district heating project, since the distribution network is expensive. Some economic benefit can be obtained by combining heating and cooling in areas where the climate permits. The load factor in a system with combined heating and cooling would be higher than the factor for heating alone, and the unit energy price would consequently improve (Gudmundsson, 1988).

The first perceptible effect on the environment is that of *drilling,* with a difference between shallow boreholes for measuring the geothermal gradient in the study phase, and deep exploratory or production wells. Installation of a drill rig and all the accessory equipment entails the construction of access roads and a drill pad. The latter will cover an area ranging from 300 to 500 m^2 for a small truck-mounted rig (max. depth 300-700 m) to 1200-1500 m^2 for a small-to-medium rig (max. depth 2000 m). These operations will modify the surface morphology of the area and may damage local plants and wildlife. Blow-outs can pollute surface water; blow-out preventers should be installed when drilling geothermal wells where high temperatures and pressures are anticipated (Lunis and Breckenridge, 1991). During drilling or flow-tests, undesirable gases may be discharged into the atmosphere. The impact on the environment caused by drilling ends once drilling is completed.

The next stage, *the installation of the pipelines* that will transport the geothermal fluids, and the construction of the utilization plant, will also affect animal and plant life and the surface morphology. In the Binhai area, the system is built in the city zone, so that this factor can be ignored.
Geothermal fluids (steam or hot water) usually contain *gases* such as carbon dioxide (CO_2), hydrogen sulphide (H_2S), ammonia (NH_3), methane (CH_4), nitrogen (N_2) and trace amounts of other gases, as well as dissolved chemicals whose concentrations usually increase with temperature. For example, sodium chloride (NaCl), boron (B), arsenic (As) and mercury (Hg) are a source of pollution if discharged into the environment. Some geothermal fluids, such as those utilized for district-heating in Iceland, are very dilute, but this is not common. In the Binhai area, the quality of geothermal water in the Ng and Nm reservoirs is quite good and, thus, this problem is minor.

Discharge of waste waters is also a potential source of chemical pollution. Spent geothermal fluids with high concentrations of chemicals such as boron, fluoride or arsenic should be treated, re-injected into the reservoir, or both. However, the low- to moderate-temperature geothermal fluids used in most direct-use applications generally contain low levels of chemicals and the discharge of spent geothermal fluids is seldom a major problem. Some of these fluids can be discharged into surface waters after cooling (Lunis and Breckenridge, 1991). The waters can be cooled in special storage ponds or tanks to avoid having effect on the ecosystem of natural bodies of waters (rivers, lakes and even the sea).

The withdrawal and/or re-injection of geothermal fluids may trigger or increase the frequency of *seismic events* in certain areas. However, these are micro seismic events that can only be detected by means of instrumentation. Exploitation of geothermal resources is unlikely to trigger major seismic events, and so far has never been known to do so.

The *noise* associated with operating geothermal plants could be a problem where the plant in question generates electricity. But for low-temperature direct utilization system, the noise is usually lower than the noise of traffic in a city zone.

4.3.2 Geo-environmental impact—land subsidence

Geothermal utilization may cause some geo-environmental problems, such as surface water or groundwater pollution, sea water inflow, subsidence and others. In the Binhai area, land subsidence is the most serious problem.

Extraction of large quantities of fluids from geothermal reservoirs may give rise to subsidence, i.e. a gradual sinking of the land surface. This can result from the reduction of formation pore pressure which may lead to compaction in rock formations having high compressibility and thus result in subsidence. This is an irreversible process, but by no means catastrophic, as it is a slow process covering vast areas. Over a number of years the lowering of the land surface can reach detectable levels, in some cases of the order of a few tens of centimetres and even metres. This should be monitored systematically, as it can damage the stability of buildings and private homes in the neighbourhood.

Land subsidence has become a world-wide geo-environmental problem in recent years. Land subsidence results in lowering land elevation. With the rise of sea-level added, it will impact construction, production and inhabitants' living conditions, especially in cities by the sea or on islands. Now, more and more scientists in the world pay attention to the problems of land subsidence. They want to discover the different causes of land subsidence and find solutions. Subsidence has also been observed in groundwater and petroleum reservoirs. Horizontal movements also occur. Such ground movements can have serious consequences for the stability of pipelines, drains and well casings in a geothermal field. If the field is close to a populated area, then subsidence could lead to instability in dwellings and other buildings; in other areas, the local groundwater systems may be affected.

The largest recorded subsidence in a geothermal field (15 m) is in a part of the Wairakei high-temperature field, New Zealand. This subsidence has caused compressional and tensional strain on pipelines and lined canals; deformation of drill casings; tilting of buildings and the equipment inside; breaking of road surfaces and alteration of the gradient of streams and rivers. Ground movements have been recorded in other high-temperature geothermal fields in New Zealand, in Cerro Prieto (Mexico), Larderello (Italy), and the Geysers (USA). Subsidence in liquid-dominated fields has been greater than in vapour-dominated fields, because the former are often located in young, relatively-poorly compacted volcanic rocks while the latter are generally in older rocks having lower porosity (Hunt, 2001).

Land subsidence is the primary geo-environmental problem in Tianjin, and has brought serious consequences. The frequency and the intensity of storm tides is increasing; the capability of flood discharge has diminished; it has become more and more difficult to prevent or control floods; and asymmetric subsidence imperils speedways, underground pipelines and large buildings.

4.4 Land subsidence in the Binhai area

4.4.1 Data on land subsidence in the Binhai area

Land subsidence has taken place in all the plain area south of the Baodi city zone in Tianjin, covering an area of 8800 km^2. The subsidence centres are located downtown, in the Tanggu, Hangu district, and Dagang districts and an industrial area in the lower reaches of the Haihe river. After effective work in controlling the subsidence over many years, the rate of land subsidence in Tianjin has clearly slowed down. The rate is, however, still greater than 20 mm/a in the littoral zone, especially in the Hangu district, where the rate is 40-50 mm/a.

The accumulated total land subsidence in the Binhai area is in many places greater than 1000 mm, and the area where the accumulated total land subsidence exceeds 2500 mm is 184 km^2. The maximum accumulated total land subsidence is over 3000 mm, leading to some zones being below sea level now. Hence, the project for controlling land subsidence was brought into effect. Due to reduced exploitation of groundwater, the average subsidence value has been lowered from 100 mm/a in 1985 to 25-30mm/a. Even now, land subsidence in this area is serious (Figures 12 and 13).

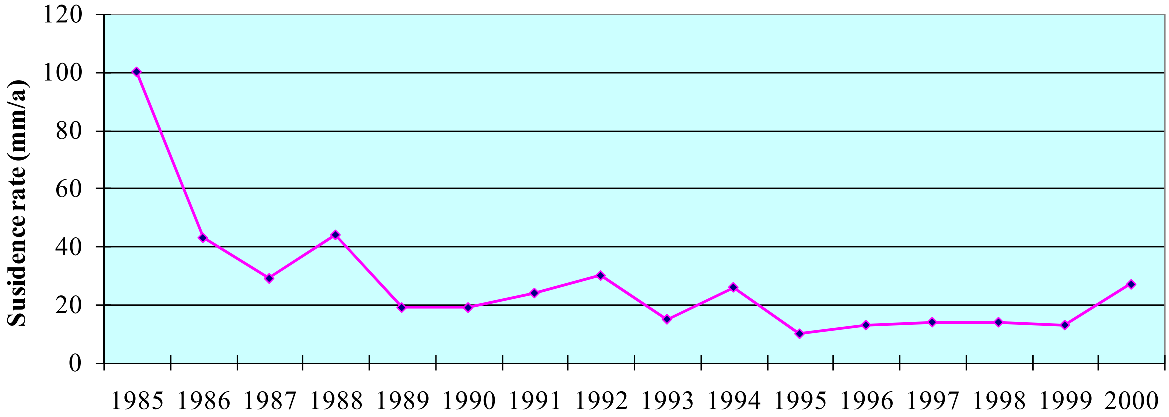

FIGURE 12: Average subsidence rate in the Binhai area in 1985-2000

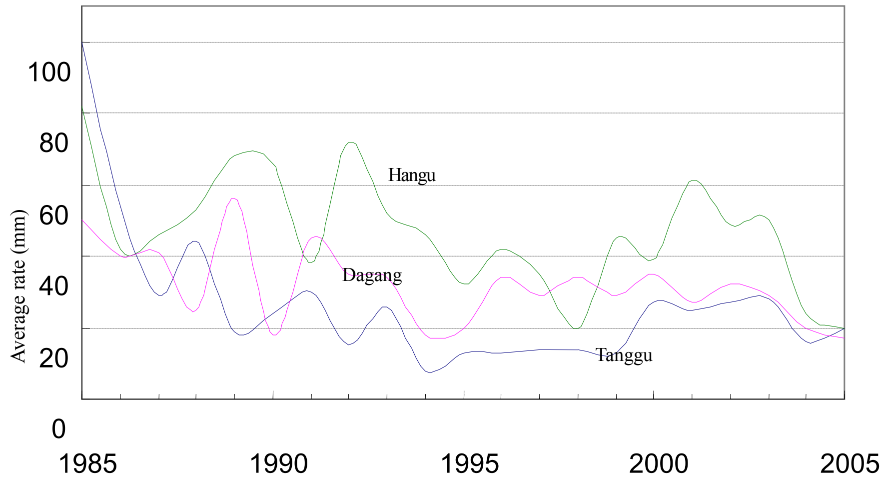

FIGURE 13: Average subsidence rate in Tanggu, Hangu and Dagang districts

The coastal protection wall against the tide is located on soft soil. The average subsidence value for it in recent years is 15-30 mm. The average subsidence value of a part of it in Hangu district has even reached 30-40 mm/a, part of which is close to or well below fortified tide level (Figure 14).

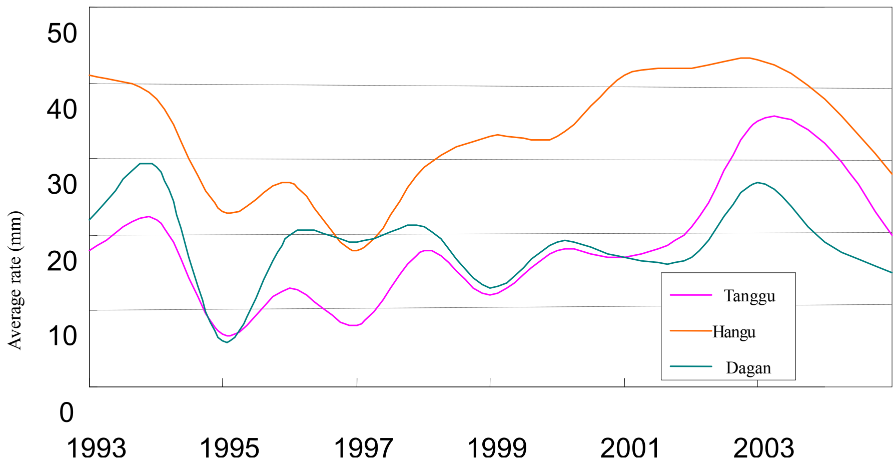

FIGURE 14: Average subsidence rate of the coastal wall protection against the tide

The area monitored for land subsidence in Tianjin includes downtown Tianjin, the suburban area, and the coastal area, covering an area of 1635 km^2. Most of the monitoring stations are located in the Binhai area, covering 1100 km2. The status of land subsidence in the Binhai area is shown in Figures 15 and 16 while Figure 17 shows the total land subsidence for the whole of Tianjin.

Tanggu district: The monitoring area covers 200 km^2. The average subsidence value was 20 mm in 2005. The maximum value, 25 mm, was located in the third-team of Tanggu farm in Heizhuhe. The settlement funnels are located in the town centre of Tanggu, Ninchegu (north of Tanggu) and Wuxia street (west of Tanggu).

Hangu district: The monitoring area covers 270 km^2. The maximum accumulated value for subsidence was 2.84 m from 1957 to 1999. The average subsidence value in 1999 was 45 mm, i.e. 25 mm greater than in 1998, and 10 mm greater than before Luanhe river was diverted to Tianjin in 1997. The maximum value was 88 mm, located in the first sub-farm of Hangu farm between Haigu and Lutaizhen. In 2005, the average subsidence value was 20 mm. The centre of subsidence is located in the Yangjiabai area (the north of Hangu dietrict), and the average subsidence value there was greater than 40 mm.

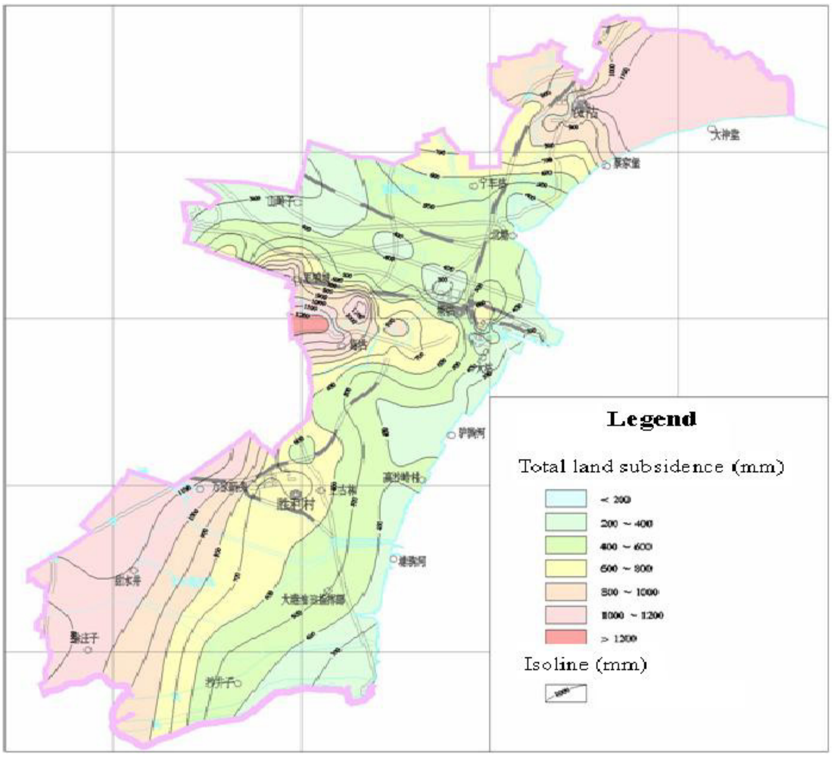

FIGURE 15: Iso-lines for total land subsidence in the Binhai area in 1985-2005

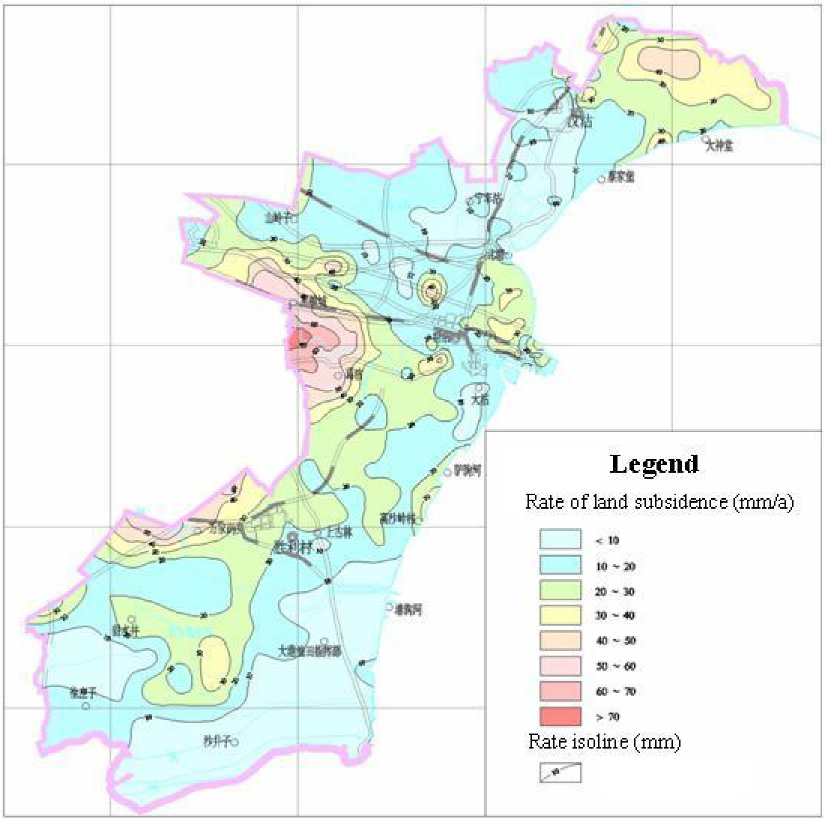

FIGURE 16: Iso-lines for the subsidence rate in the Binhai area in 2004-2005

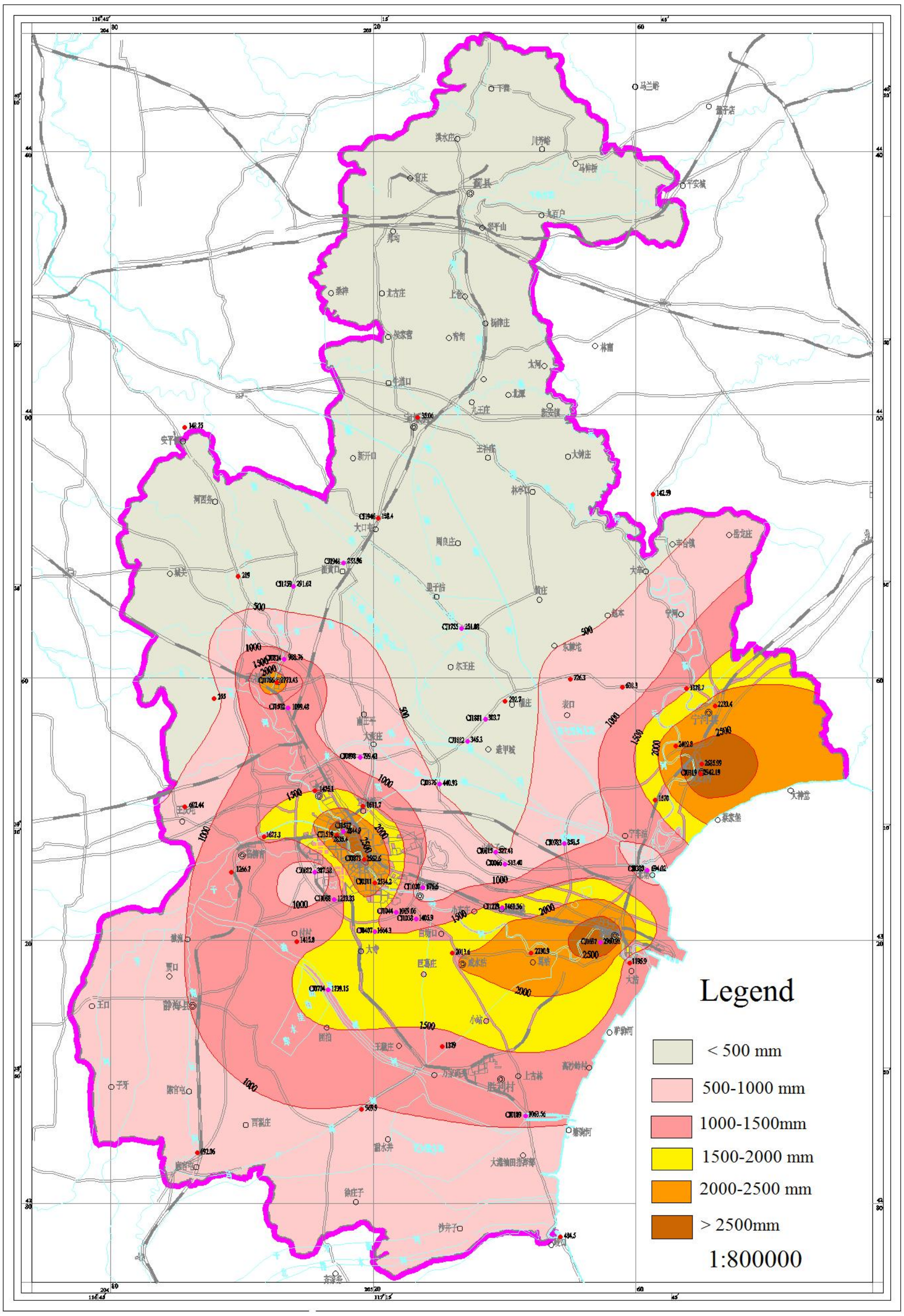

FIGURE 17: Iso-lines for total land subsidence in Tianjin in 1967-2000

Dagang district: The monitoring area covers 295 km^2. In 1999, the average subsidence value was 29 mm, 5 mm less than that in 1998. In the town centre of Dagang the subsidence was 32 mm on average. The maximum value was 57 mm, located at Xiaohuangzhuang of Xixiaozhan. In 2005, the average subsidence value was 17 mm, 3 mm less than that in 2004. The settlement funnels are located in Zhongtangzheng, Dasuzhuang farm and Shajingzi.

The industrial area in the lower reaches of Haihe River: This covers an area of 330 km^2, and the average subsidence value in 1999 was 35 mm, a little less than that in 1998. The maximum value was 72 mm, located in Gaozhuangzi, in the southern region of Tianjin.

4.4.2 Damage due to land subsidence and the causes

In the littoral region, land subsidence will not only result in lowering the elevation of land, but also initiate other calamities, such as pricking up the storm tide, sea water encroachment and soil salinization. A calamitous storm tide recurred every 50 years until 1958 in the Tianjin littoral zone. After 1992, a calamitous storm tide has recurred every 4 years because of land subsidence and the rise of sea-level. In 2003, the cost incurred by the storm tide was 1.31 billion yuan.

Land subsidence endangers city construction in five ways: by ruining buildings, ruining pipelines (especially flow pipes), reducing the navigability and capacity for flood discharge, causing loss of elevation and interfering with underground and railway traffic.

The exploitation of groundwater, oil, natural gas, geothermal fluid, and soft soil secondary-consolidation settlement can cause land subsidence. In Tianjin, the main cause of land subsidence is excessive exploitation of groundwater. Comparing Figures17 and 18, it can be seen that centres of land subsidence, such as in the town centre, Tanggu district and Hangu district, coincide with areas

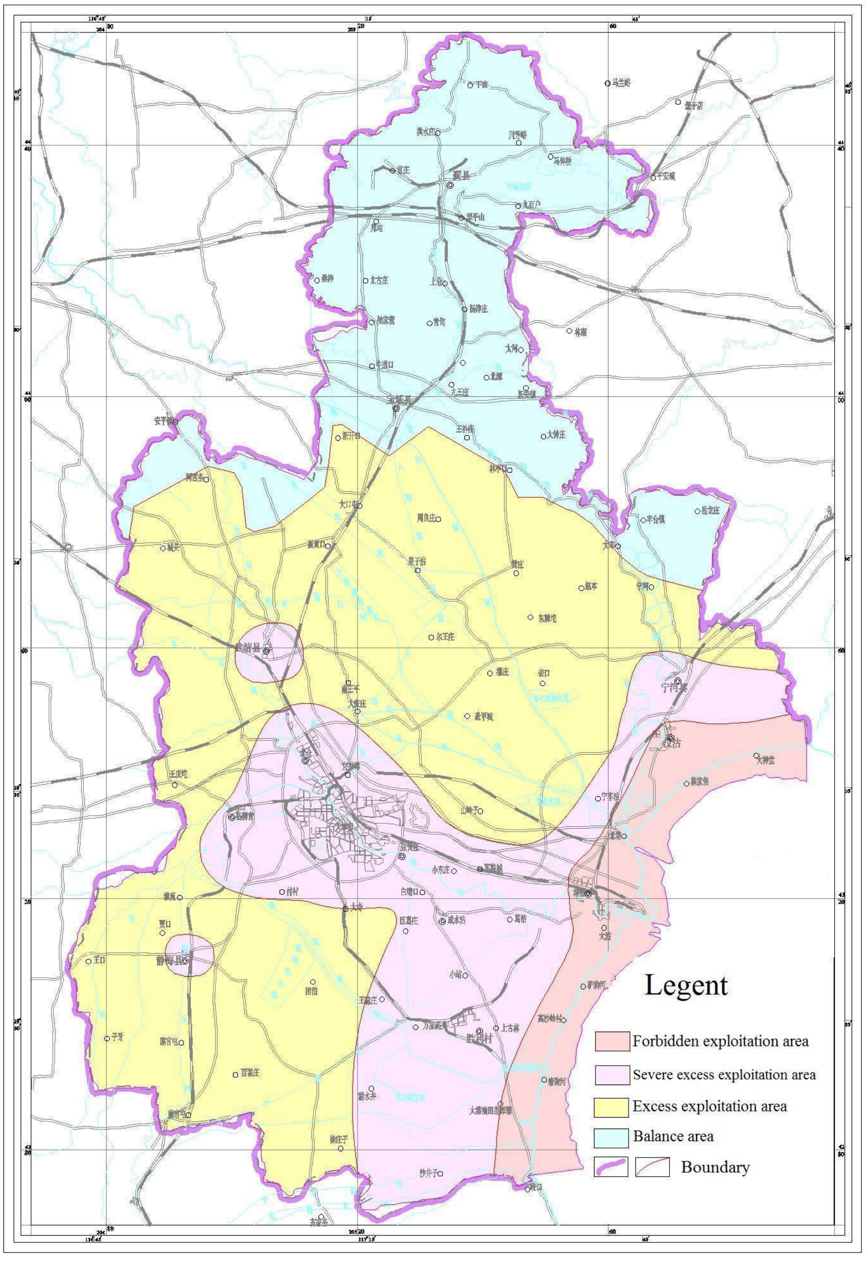

FIGURE 18: The actual exploitation of groundwater in Tianjin

where groundwater is excessively exploited. For example, the permitted quantity of groundwater exploitation is 10 million m^3/a in the town centre of Tianjin, but the maximum quantity of groundwater exploitation has been up to 120 million m^3/a. In Tanggu district, where the permitted quantity of groundwater exploitation is less than 10 million m^3/a, the maximum quantity of groundwater exploitation has been up to 50 million m^3/a. The areas of extensive land subsidence and excessive exploitation of groundwater are connected (Bai, 2007).

4.4.3 Geothermal reservoir's consolidation state

A soil layer is the result of geological history, being deposited in a geo-chronological order. In order to classify the soil layer's consolidation state, we compare the lithostatic pressure (Po) to the pre-consolidated pressure (Pc). The consolidation can be separated into three states: Normally consolidated state, under-consolidated state and over-consolidated state.

a) *Normally-consolidated state:* Pc≈Po, or the OCR (Over Consolidation Ratio) Pc/Po~1. This means that the consolidation process reached the final consolidated state under the lithostatic pressure during the soil layer deposit history.
b) *Under-consolidated state:* Pc<Po, or OCR <1. This means that the degree of consolidation has not reached the final consolidated state under the lithostatic pressure. The soil layer will drain slowly because of the lithostatic pressure, so the soil layer will be compressed slowly. Most marine deposits, lacustrine deposit soil layers are under-consolidated soil layers.
c) *Over-consolidated state:* Pc>Po, or OCR>1. This means that the degree of consolidation exceeds the final consolidated state under lithostatic pressure. The reasons why soil layers become over consolidated are mainly physico-chemical action, glacial action, denuding action, groundwater return after a long drought, and human construction activity.

In the Binhai area, the main geothermal reservoirs are located in the Minghuazhen group (Nm) and Guantao group (Ng), at a depth of 500-2000 m. Figures 19 and 20 show that the geothermal reservoirs are located in normally consolidated strata (Niu, 2003).

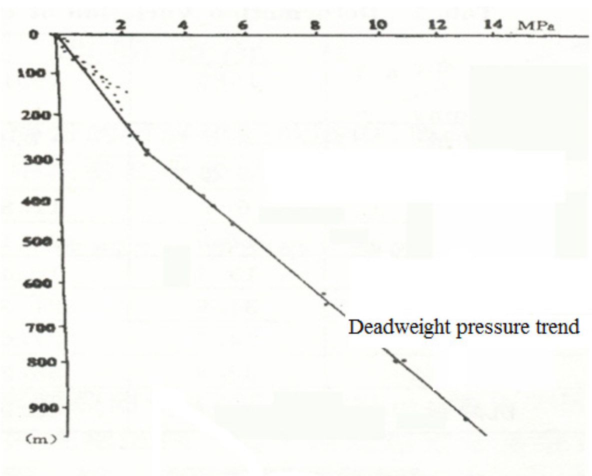

FIGURE 19: Information from a high-pressure consolidation test. The data came from different strata in the town centre (depth<200 m), Tanggu, Hangu and Dagang districts (depth>200 m). Where the depth is greater than 200 m the pre-consolidation pressure at different depths is equal to the lithostatic pressure; it means that the strata below 200 m are normally consolidated

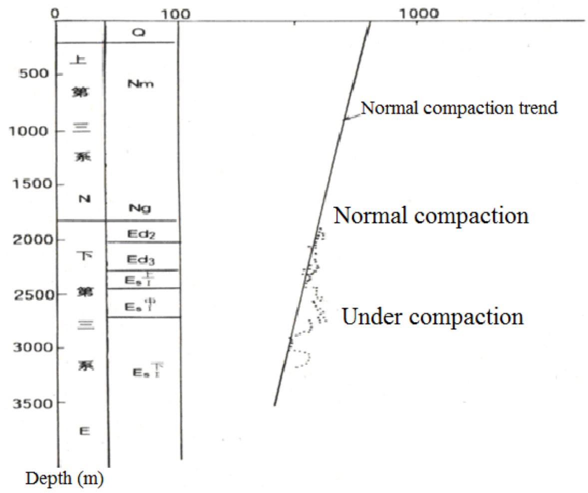

FIGURE 20: The actual compaction status compared to the normal compaction trend in the Huanghua down-warping region, supported with data from oil well surveys; showing that when the depth is less than 2500 m, the strata are normally consolidated; when the depth is greater than 2500 m, the strata are under-consolidated

4.4.4 The connection between consolidation state and the land subsidence

Under-consolidated state. The strata will drain slowly because of the lithostatic pressure, and the strata will be compressed slowly. So, even without groundwater exploitation, it will cause land subsidence. If groundwater is mined from these strata, the land subsidence will be accelerated.

Normally-consolidated state. The stress of the strata is balanced, and will not cause land subsidence. But, if groundwater is mined and the water level drops, the balance of stress will be broken, and the pore water pressure will be reduced (Figure 21). Then the effective stress will be increased, compressing deformation will set in, and cause land subsidence.

Over-consolidated state. There is a critical water level in over consolidated strata. If the groundwater level is not below the critical water level, exploitation will not cause land subsidence.

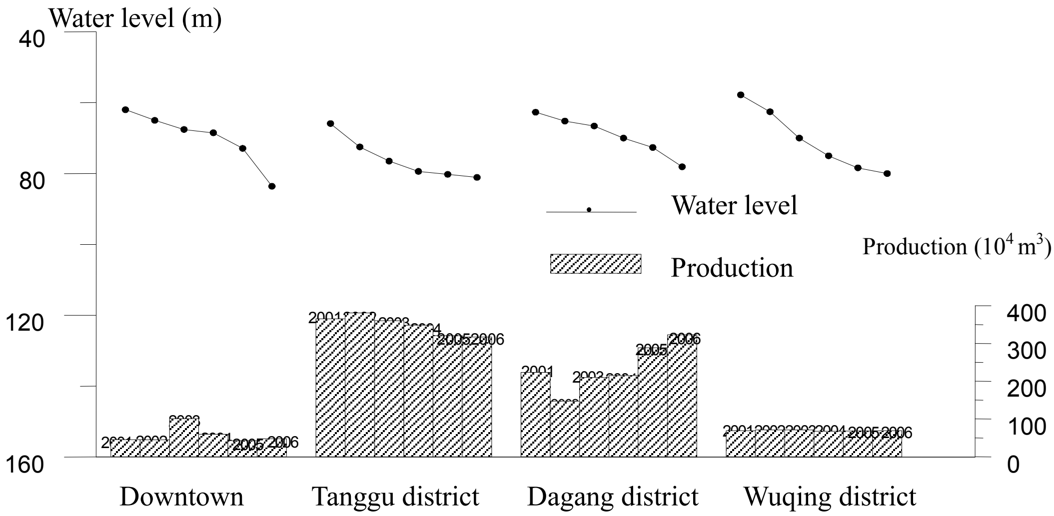

FIGURE 21: Water level of the Guantao group (Ng) reservoir in Tianjin

In the Binhai area, the main geothermal reservoirs (Ng) are located in normally consolidated strata. So, when the geothermal water is mined, the water level drops, the balance of stress is broken, and the pore water pressure is reduced. Then the effective stress will be increased, compressing deformation sets in and causes land subsidence. In the Huanghua down-warping region, the strata are under consolidated if the depth is greater than 2500 m,. The maximum pressure coefficient of an exceptional stratum in the Shahejie group is 1.552 at 3702.7 m depth. In this area, geothermal exploitation at deeper levels than 2500 m will cause rapid land subsidence.

4.4.5 Evidence from monitoring data

In order to monitor land subsidence caused by the exploitation of a geothermal reservoir in the Guantao group (Ng), a layer-built mark was constructed in Tanggu district in 1992. The depth of it is 650 m, and it is located on the top stratum of the Guantao group (Ng). The elevation of the surveyor's pole was 2.4671 m when the layer-built mark was built in 1992, but in 2002 it was 2.3848 m. In ten years, the elevation was reduced by 82 mm, with the average subsidence rate 8.2 mm/a. When subsidence caused by tectonic activity had been subtracted (2 mm/a, Huang, 2000), the average subsidence rate caused by the exploitation of the geothermal reservoir in the Guantao group (Ng) between 1992 and 2002 was shown to be 6.2 mm/a (Figure 22).

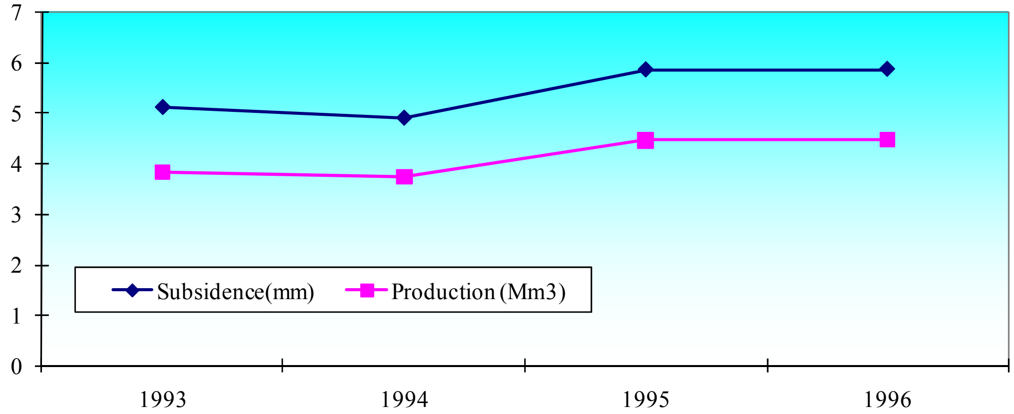

FIGURE 22: Relationship between geothermal production and subsidence in the Ng reservoir in Tanggu district

There are two benchmarks near the layer-built mark: NO.424 and JC-899. The average subsidence rate at NO.424 was 22.8 mm/a, and at JC-899 it was 23.2 mm/a in the same period (1992 -2002). When the subsidence caused by tectonic activity (2 mm/a) had been subtracted, the total land subsidence rate was 22 mm/a. Therefore, subsidence caused by the exploitation of the geothermal reservoir can be accounted for 28% of the total land subsidence in this area. The rest is due to the exploitation of groundwater (8-13 mm/a), tectonics (1.3-2.0 mm/a), construction (3-5 mm/a), etc.

4.4.6 Solutions

In Tianjin, the main cause of land subsidence is excessive exploitation of groundwater. The centres of land subsidence are also the areas where excessive exploitation of groundwater takes place. In 2007, most parts of the Binhai area have been forbidden to exploit groundwater (Figure 18) in order to slow down subsidence. Instead, the amount of water taken from the Luanhe river (4.18×10^8 m^3) and the Yellow river and direct use of seawater are increasing.

However, the subsidence caused by the exploitation of geothermal fluid cannot be ignored, even though it is only a small part of the total land subsidence. With the development of the economy, the demand for geothermal energy is increasing considerably. So, new solutions are needed.

A new reservoir in an over-consolidated stratum. In the Binhai area, exploration of the Dongying group of the Palaeogene system has been under way since 2005. A new reservoir has been found in sandstone and sandy conglomerate. This reservoir is in the over-consolidated stratum. The porosity is 18-25%, the area is large (covers most of the Binhai area) and it is thick. Moderate exploitation will not cause subsidence. Currently, well testing in the new reservoir is in progress. The results of a pilot study suggest that the exploitation potential is great.

Restrictions of production from the Guantao group (Ng). The average water level of geothermal wells in the Guantao group (Ng) in the Binhai area was 70-85m in 2006, with the fall rate 3-5 m/a. The output should be reduced to avoid subsidence caused by geothermal exploitation. Presently, the exploitation of every geothermal well is planned and controlled by the governmental managing department. As a policy for resource protection, the resource tax is doubled if the output exceeds the planned production.

Re-injection. Geothermal re-injection started out as a method for waste-water disposal for environmental reasons (~1970). Now, it is also used to counteract pressure draw-down, i.e. as water recharge, and to extract more thermal energy from reservoir rocks. In many cases it increases the production potential considerably. Re-injection should be considered an integral part of any modern, sustainable, environmentally friendly geothermal utilization.

Among the advantages of re-injection are stopping most pollution, avoiding fluid depletion, ensuring longer lifetime of reservoirs, preventing temperature changes at surface and hindering formation of large ponds. In Tianjin, re-injection is now an integral part of the utilization of any geothermal system that is assessed when the governmental managing department issues the production license. To encourage re-injection, the tax is 70% lower for geothermal systems with re-injection.

Re-injection tests in sandstone in the Tertiary system (Ng) started in Tanggu in 1987. The artesian re-injection flow is 20-45m^3/h, and with a pump pressure in the re-injection pipe 2 kg/cm^2, the re-injection flow reaches 50-85m^3/h. Owing to the short testing time (less than 3 months), the data needs to be further evaluated.

Possible re-establishment of land elevation with re-injection has been discussed. In fact, re-injection can restore the level of groundwater, but it cannot restore 70% of the water that was released with compaction in the layer. Thus, the re-elevation is negligible. On the other hand, re-injection directs water into the reservoir, prevents draining, and further subsidence. So subsidence can be prevented or reduced by re-injecting geothermal wastewater.

4.6 Monitoring systems

4.6.1 Monitoring system for geothermal utilization

Information should be continuously gathered throughout the exploration and production history of geothermal systems. The most important information about a geothermal system is obtained through careful monitoring of its response to long-term production. Monitoring is an indispensable part of any successful management program. With mass monitoring data, we can set up models of the geothermal systems. Through modelling, reservoir changes can be seen in advance (Figure 23).

Geothermal monitoring projects started in Tianjin in the 1980s involving measurements of the water level, temperature and flowrate in the geothermal wells. Then, a geothermal monitoring system was

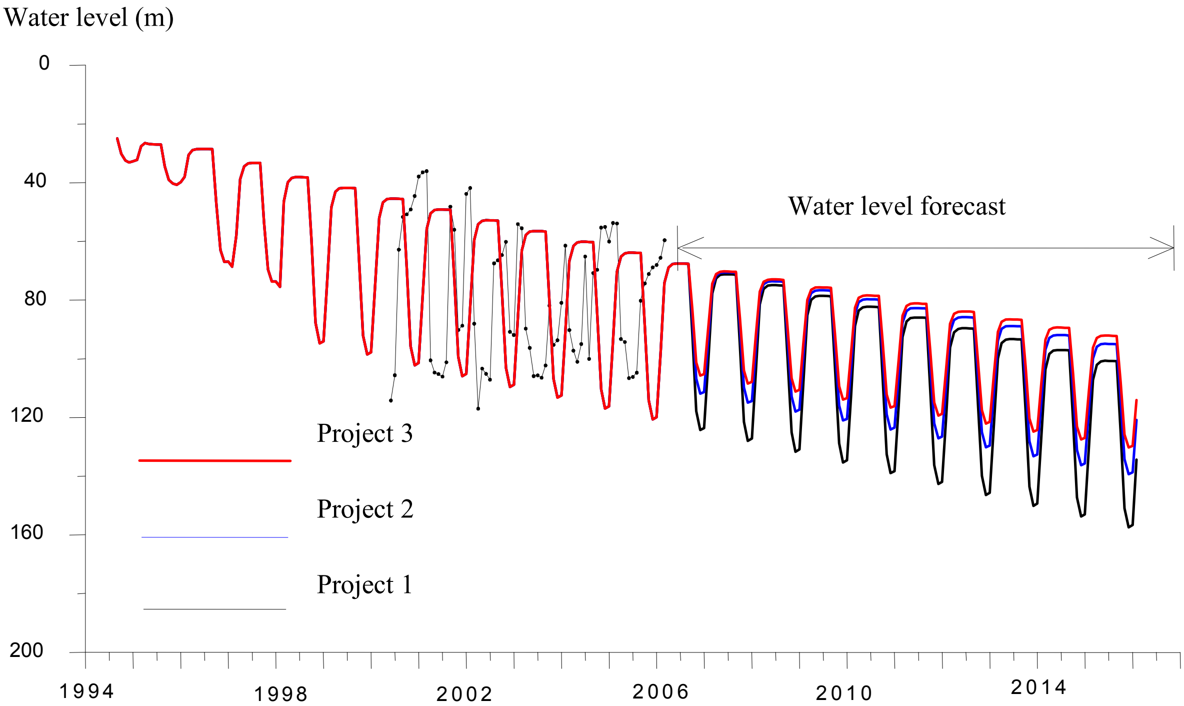

FIGURE 23: Water level forecast for the Guantao group (Ng) reservoir with different production scenarios, a) unchanged; b) reduction by 20%; and c) with 30% re-injection

set up in the mid 1990s improving monitoring measurements and layout. The task of monitoring in Tianjin now involves measurement of temperature, water level and/or wellhead pressure; measurement of flow rate, and total production; geothermal water sampling, complete analysis (50% of the wells per year) and isotope analysis (5% of the wells per year); measurement of the pressure at the well bottom and temperature logging (5-10 wells per year).

In 2006, an automatic Net-PC geothermal monitoring system was installed. The system automatically measures the temperature, the flowrate and the pressure at the wellhead and/or the water level in the well. The computer on the wellhead records the data every hour and sends data to the control center twice every day. With this system, the investigation involves checking the water level, temperature and flowrate of every geothermal well in the control centre at any moment when he(she) wants. Based on the monitoring data, models can be made and maps produced (Figures 24 and 25) of the geothermal systems with the help of a computer.

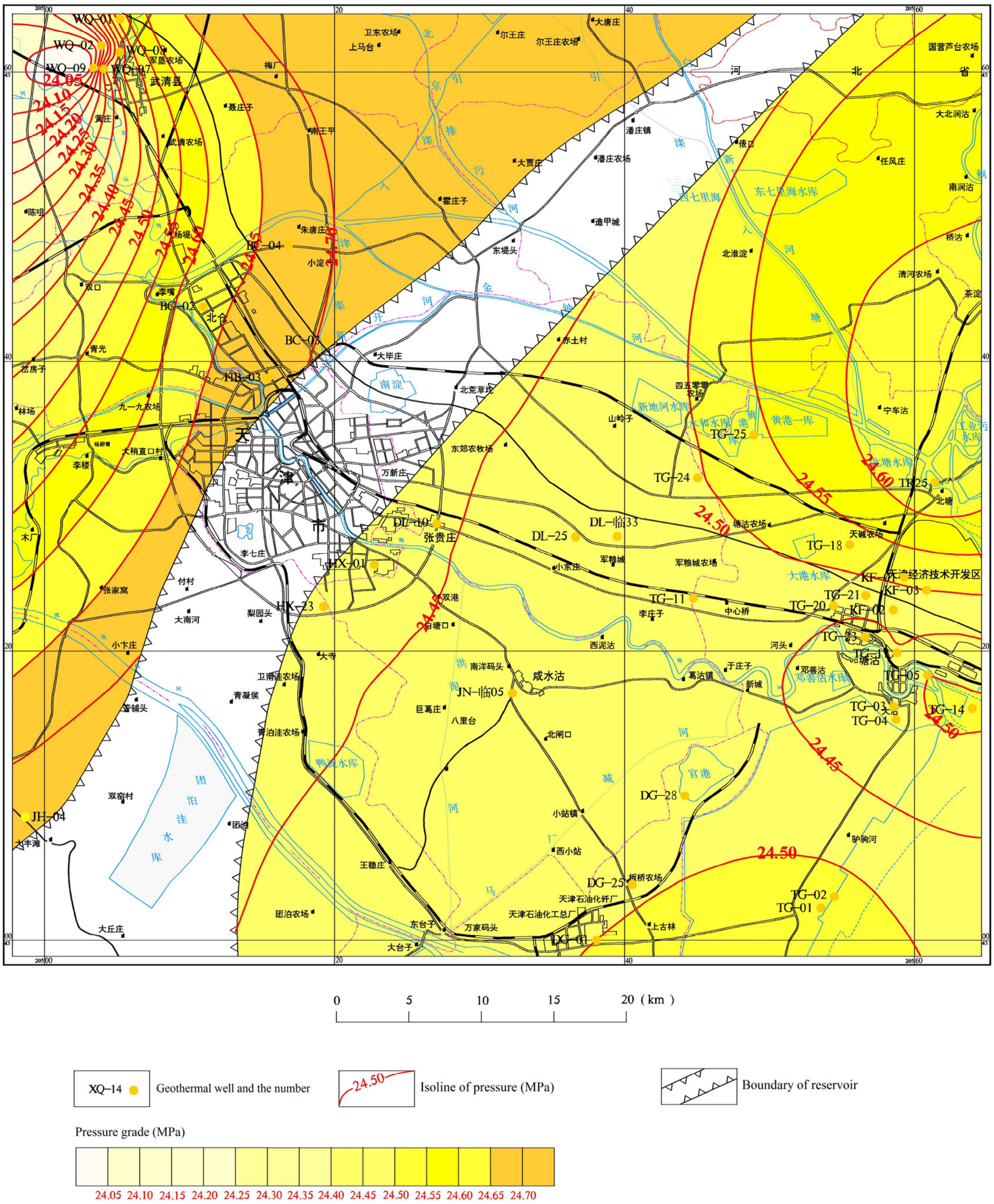

FIGURE 24: Iso-lines for reservoir pressure (MP_a) in the Guantao group (Ng), Tianjin in 2006

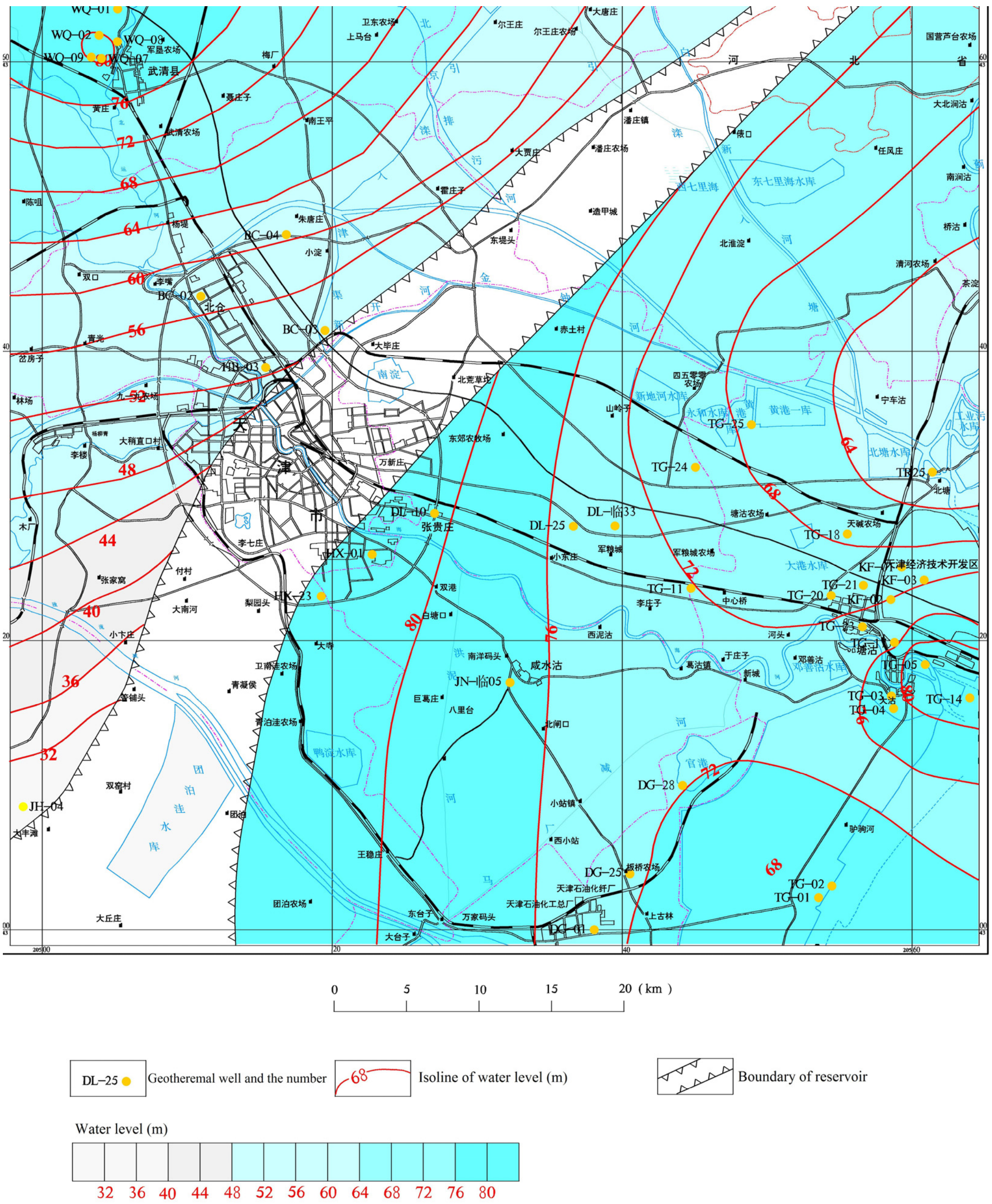

FIGURE 25: Iso-lines for reservoir water level (m) in the Guantao group (Ng), Tianjin in 2005

4.6.2 Monitoring system for land subsidence

A survey network has been set up in the Binhai area. By the end of 2006, it comprised 3 GPS stations, 970 benchmarks, 6 groups of layer-built marks and 330 groundwater monitoring points (Figure 26). Six groups of layer-built marks which can at present monitor the extent of subsidence in the Binhai area were installed. There are 49 layering wells, 6 long term observation wells, and 44 pressure probes for pore water. The long term observation wells and pressure probes in the Dagang layer-built marks are monitored once every 10 days. The others are monitored once every month. The elevation of layering wells is measured once a month. In a whole year, the groundwater hydraulic head is monitored 273 times, the hydraulic head of pore water is monitored 517 times, and the elevation of layering wells is measured 732 times. The depth of monitoring is usually ~ 300 m, the deepest being 650 m.

In 2007, a new monitoring project named "Binhai area forecast and signal system of land subsidence" was started. In 2007-2009, 6 groups of new layer-built marks will be built, including 13 layer formats and 5 pressure probes for pore water, the greatest depth being 1200 m. Also, a new GPS station will be built. The new monitoring system will particularly monitor land subsidence caused by the exploitation of oil, natural gas and geothermal utilization.

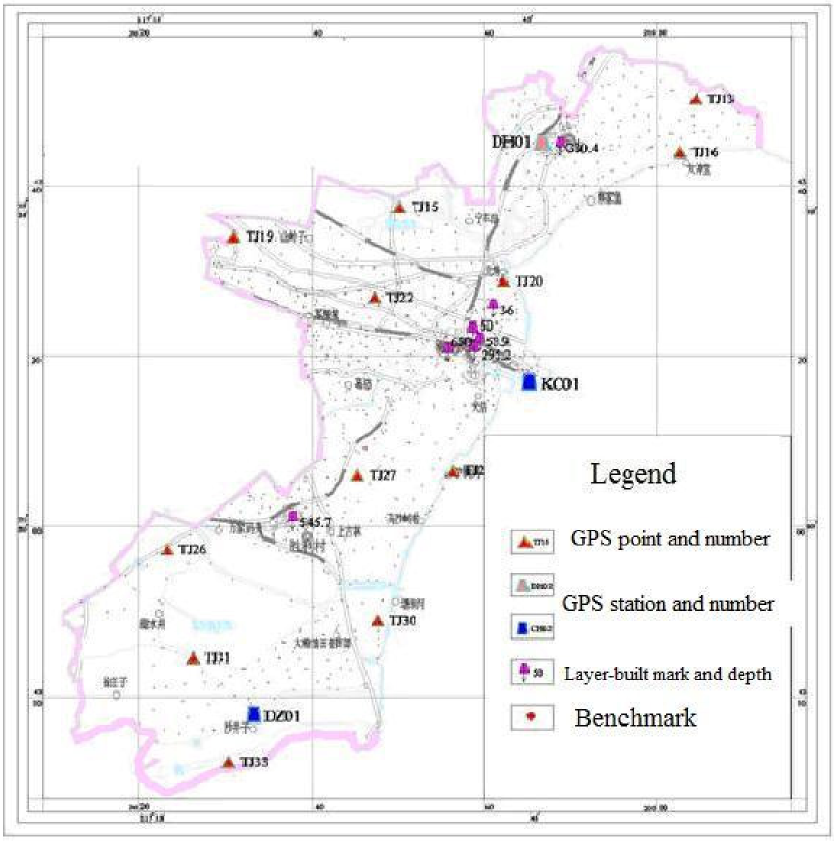

FIGURE 26: The network of land subsidence in the Binhai area

5. CONCLUSIONS

The Tianjin Binhai area is a new development area in North China. In 2005, the development of Binhai was brought into the stratagems for national development. The political and economical status of this area is very important in China. Direct geothermal utilization in the Binhai area started in the 1980s. Now, the geothermal space heating area covers more than 3.5 million m^2, and the total volume of geothermal water production per year is more than 8 million m^3. The benefits of geothermal utilization are obvious: More than 30,000 families benefit from geothermal space heating or hot water; some ten entertainment industry companies profit from offering the geothermal service; more than 126,500 tons of fossil fuel are saved every year; and contaminating gaseous discharges totalling 337,000 tons every year are avoided.

The environmental impacts of geothermal utilization in the Binhai area are mostly benign. Most of the geothermal utilization located within the city has not added to the environmental problems such as air pollution, noise, surface water pollution, underground pollution, conflicts with cultural and archaeological features, chemical or thermal pollution.

The primary environmental impact of geothermal utilization is land subsidence. Based on the existing monitoring data, the average rate of land subsidence caused by the exploitation of geothermal water is 6 mm/a in recent years, or 27% of the total subsidence. Because of the depth of the layer-built marks (~650 m), the monitoring data may not reflect the connection between geothermal production (with well depths of 1200-2000 m) and land subsidence accurately. The Tianjin Institute of Geological Investigation is building six groups of new layer-built marks, whose depths will range from 50 to 1200 m. We shall, thus, obtain more accurate monitoring data in future years.

Land subsidence caused by the exploitation of geothermal water is, however, actually taking place in the Binhai area. The exploitation of geothermal water from the Guantao (Ng) reservoir should be strenuously controlled. At the same time, exploration for new reservoirs, and re-injection tests, should be carried out. Furthermore, the drilling method and configuration of re-injection wells, the equipment and the operational criteria for injection should be thoroughly investigated.

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