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Environmental Impact of Geothermal Utilization in Tianjin, China

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ABSTRACT

Tianjin is assigned as the third particular developing area in China, after Shenzhen and Shanghai. Therefore the political and economical status of this area is very important. Geothermal resources are rich in Tianjin and are already widely utilized, providing considerable economic and environmental benefits. By the end of 2008, there were more than 318 geothermal production and injection wells in Tianjin, 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 Tianjin, the primary environmental problem is land subsidence. In this paper, the environmental impact of geothermal utilization is discussed. The connection between geothermal development and land subsidence is particularly emphasized.

1. INTRODUCTION

Tianjin is rich in low-temperature geothermal resources, with the temperatures from 40ºC to 100ºC. The present total volume of geothermal water production is more than 8 million m^3/yr. The geothermal space heating area is more than 3.6 million m^2. More than 40000 families and some ten companies benefit from geothermal space heating. The earth's crust in Tianjin is unstable. Land subsidence, soft soil groundsill and bank stabilization are the main geo-environment problems in Tianjin. 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 initiated by the utilization of geothermal energy. The main environmental effect of geothermal development are related to surface disturbances, the physical effects of fluid withdrawal, heat effects and discharge of chemicals. All these factors will affect the biological environment as well as all industrial activities, and there are also some social and economic effects (Kristmannsdottir and Ármannsson, 2003). The environmental and social impacts of a geothermal project must not be overlooked, and indeed should be considered as an integral part of project design (Rodríguez and de Arévalo, 2007). The impact of land subsidence should be of great concern in Tianjin, where geothermal resources are located in a sedimentary basin, where more than 70% of the waste water can not be injected. A monitoring system should be set up and the monitoring data should be analyzed carefully. At the same time, we should try to find the solution.

2. OVERVIEW OF TIANJIN

Tianjin is a city that is the economic center 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 center 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 favorable location, Tianjin enjoys great advantages and provides a channel for over a dozen provinces and cities in the north of China to communicate 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 city is 11,900 km^2, 189 km long from south to north and 117 km wide from east to west. The city proper covers an area of 7,418 km^2, and the rural area covers 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.

2.1 Physiography

Tinjin is located in lowlands, with an elevation from 0 to 2.0 metres, the lowest elevation is -1.0 m (in the north Haigu district). It is located in the north of the typical mud coast of China, west of Bohai Sea bay. It belongs to the alluvial-marine deposition and marine deposition low plains. 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 metres.

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 border lines between these physiographic units are obvious.

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 a great difference in temperature and a wide variety of scenery throughout the year. The average temperature in a year tops 12.3ºC, the average temperature in summer being about 27ºC, and average temperature in winter about -5ºC, the frost-free period lasting about 200 days. On the average, the annual precipitation is about 400 mm, 75% of which is concentrated in June, July and August. The sunshine time in this area is relatively long.

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 Jiyunhe canal water system. The Haihe river water system is made up of North canal, Yongding River, Daqing River, Ziya River and Nanyunhe canal. The Jiyuhe canal water system is made up of Chaobai River, Zhou River, Huanxiang River and Jiyuhe canal. Both systems have outflow to the sea to the east of Tianjin. Bei-dagang, Huanggang, Guangang and Qianquan reservoirs are located in this area.

2.4 Natural Resources

Tianjin enjoys a rich supply of natural resources, which is quite rare for large cities both at home and abroad. 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 19,235,500 tons of crude oil and 850,000,000 m^3 of natural gas per year. Secondly, with its coastline stretching 150 kilometers, 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 (10% of the total sea salt output 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 30ºC to 105ºC. 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 and low-temperature geothermal field in China. Fourthly, in this area, 200 km^2 of wasteland and shallows have great potential for development. Because most such land is located downstream of the Haihe River, where transportation is convenient, it is possible to develop the land at low cost. Such favorable conditions are not available in other large cities in China.

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 the major aquatic export product.

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 45 universities and colleges presently in operation, Tianjin possesses over 128 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 centers for engineering technology and 27 state-level ministerial technical testing centers. 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, automobile, 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 in one of the first groups of coastal cities 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 Binghai Area was brought into the stratagems of national development. So the political and economical status of this area is very important in China. In 2007, the GDP of the Tianjin reached 5050 billion yuan (≈720 billion dollar), a rise of 15.2% over 2006 in terms of comparable prices. Industry's share is 57.3%, and that of service 40.5%. The growth rate was not only the greatest after 1996 in Tianjin, but also among the greatest in major Chinese cities and provinces.

3. GEOTHERMAL SYSTEMS IN TIANJIN

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. There are ten geothermal fields, in which the average temperature gradient of the cover stratum is greater than 3.5ºC/100 m (the normal gradient in the Tianjin area).

The Tianjin area is located in the northeast part of the North China Plain subduction zone, where a hugely thick Cenozoic erathem loose alluvial stratum overlies the Paleozoic and Proterozoic floor. Except for some exposed parts of bedrock in the mountainous 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 are of low- to medium-temperature type, and belong to the static storage type. There are 10 geothermally anomalous areas. The total area of geothermally anomalous areas with temperature gradients greater than 3.5 ºC/100 m is about 2320 km^2. The highest temperature gradient is 8.8 ºC/100 m, the highest wellhead temperature is 105°C.

The north-northeast structure in the Tianjin region was formed by many large structural movements, and it controls the distribution of 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 is 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 reservoir.

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 field is 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 thickness of over 1200 m, forms the cover of the bedrock geothermal reservoirs. The temperature gradient is in agreement with 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 and 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 the south area 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 40-100 m^3/h, wellhead temperature 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 m3/h, wellhead temperature 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 the 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 corrosive.

The Jixian dolomitic limestone is widely distributed in the Tianjin area. The aquifer roof lies at 1700-4000 m depth, with 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 is very difficult to utilize.

In general, water quality is relatively good and the mineralization 1000-2000 mg/l. Hydrochemically, 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 Tianjin

The hydro-chemical character of the Tertiary system Minghuazheng group reservoir (Table 2): From north to south, the salinity gradually increases, from 500 mg/l 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.

The hydro-chemical character of the Tertiary system Guantao group reservoir (Table 3): In the west of the absent area, from north to south, the salinity gradually increases, from 1000 mg/l to 5000 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. The change is consistent with the flow direction of the geothermal liquid.

In the east of the absence area, from north to south, the salinity gradually increases, from 500 mg/l 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. Salinity increases with depth.

The hydro-chemical character of the Middle and upper Proterozoic Erathem (Jixian system Wumishan Group) reservoir: From north to south, the salinity increases considerably. The salinity of well ZL-4 (in the north of Tianjin) is 1030 mg/l; downtown, the salinity of reservoir 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 the geothermal water becomes more 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 the geothermal water in Middle and upper Proterozoic Erathem reservoir is of the Cl• HCO3• SO4 –Na type, salinity: 1670~1790 mg/l, pH: 7.7~8.36, Larson index: 2.13~2.8, slightly caustic. (Ruan et al., 2006)

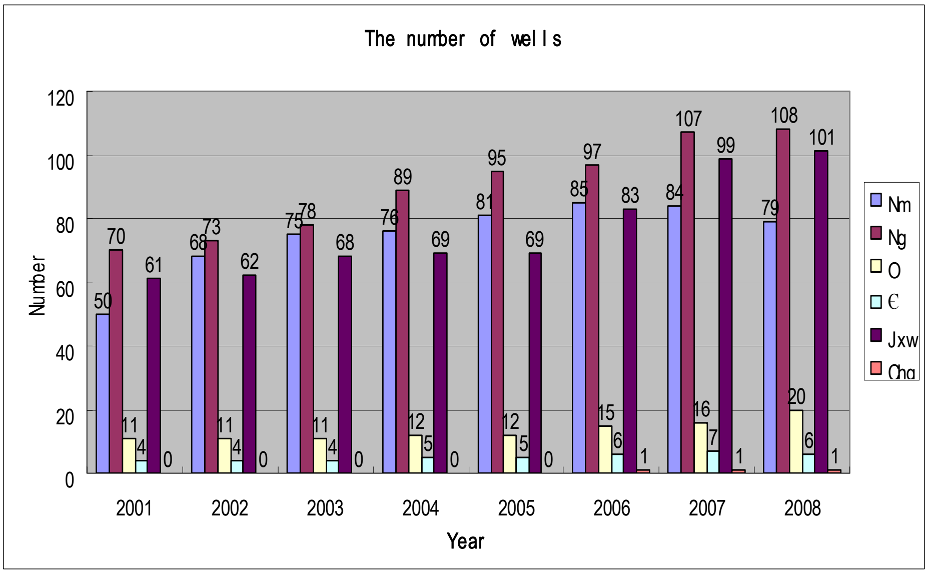
3.4 Geothermal Utilization

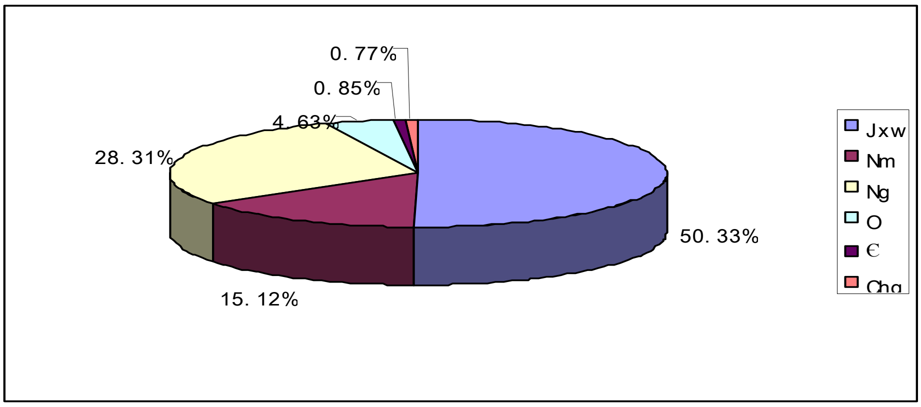
<u>3.4.1 Geothermal utilization in Tianjin</u>

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, 3 of which have been thoroughly explored. So far, 8 fields have been explored and the greatest depth explored is about 4000 m.

Since geothermal exploration and development in Tianjin started, multiple benefits have been realized. At present, the priority uses are district space heating and domestic water. Other uses are 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 saving on traditional energy sources but also clearly improving the environment, and thus it plays an important role in the development of the city.

By the end of 2008, there were 264 geothermal production wells in Tianjin, mainly used for space heating, domestic hot water, spas, industrial use, agriculture and fishing. In 2008, the total volume of geothermal water production was 2.60×10^7 m^3, the volume reinjected was 5.50×10^6 m^3 or 21.15% of the production (Figures 1, 2, 3). The Jixian system is the largest producing thermal reservoir, its annual production being 1.30×10^7 m^3, or 50.33% of the total production volume, next in size are the Ng (7.34×10^6 m^3) and Nm (3.92×10^6 m^3) groups. Geothermal space heating area covers about 12 Mm^2.





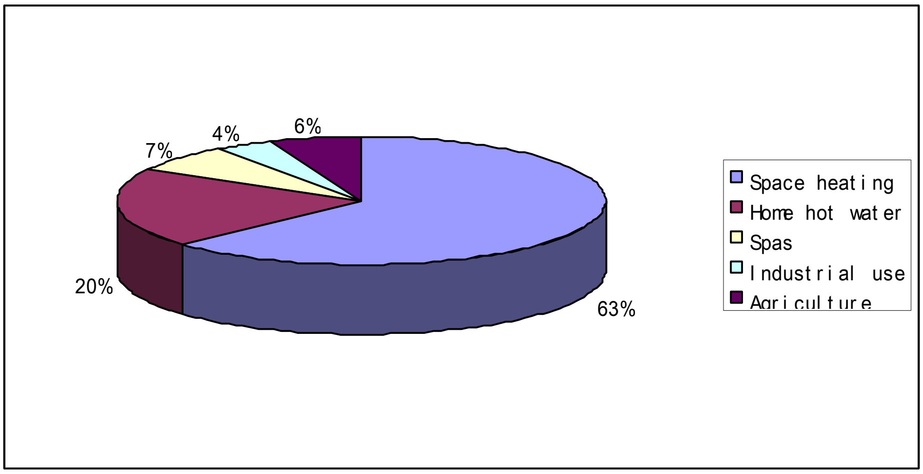


Figure 1, 2, 3: The number of geothermal wells and the production from different reservoirs in Tianjin 2008

Generally, the heating period is from the middle of November to the next March (the winter in north China), a total of 130 days. From the production columns (Figure 4), we can see the production from November to March. In these 5 months, the production is 82% of the yearly production. The geothermal water mined from the Jxw, O, Є reservoirs can be reinjected, and makes up 25% of the total production.

The largest geothermal utilization project is located in Dong-lihu, in which the space heating area will reach 800000 m^2 in the next two years with the aid of heat pumps, and the hot water will be supplied to 6000 families. There are three production wells that provide the heat energy to this uptown area and all the return geothermal water is reinjected into two reinjection 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 of energy increased fast. In 2005, the total energy usage in Tianjin amounted to 4.72×10^7 million tons of standard coal. The energy useage of homes is increasing too. The total area of space heating in Tianjin is 169.07×10^{6} m^{2}. The annual per capita energy consumption for non-production purpose (2001-2007) and the capability of space heating in Tianjin (2005-2007) are shown in Tables 1 and 2.

4.1.2 Environmental status

Tianjin is not only one of the biggest economic and trading centers 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 one of the biggest geo-environmental problems in Tianjin.

The potable water for Tianjin city depends on the water channeled from the Luanhe and/or Yellow Rivers. The quality of potable water from the Luanhe and Huanghe rivers is good, but lack of water resources is very serious. The surface water is contaminated with raw sanitation wastes, industrial waste 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 lowering of the water table have taken place in many areas, and cones of depression are increasing in size.

Table 1: Space heating capability in Tianjin (2004-2007)

Capacity of heat energy	Unit	2004	2005	2006	2007
Steam	T/h	3407	3294	3551	3620
Hot water	MW/h	10111	10563	12106	13866
Sold energy					
Steam	10^4G J/yr	1764	1966	1891	2092
Hot water	10^4G J/yr	6530	7572	8451	7830
Length of pipe	km	8038	8705	9494	9842
Heating area	10^6 m^2	114.41	140.41	156.11	169.08
#Domestic Dwellings	10^6 m^2	89.7	109.67	120.41	127.68

In 2005, the gross water resource was 1.06×10^{9} m^{3}, comprising surface water 7.13×10^{8} m^{3} (27.17% less than 2004), groundwater 4.44×10^{8} m^{3} (14% less than 2004). The gross precipitation was 517 mm, 15.05 % less than 2004. Tianjin is badly off regarding water. In 2005, the gross water supply was 2.27×10^{9} m^{3}, 6.10×10^{7} m^{3} more than 2004. The gross water supply from surface water was 1.60×10^{9} m^{3}, including the water channeled from the Luanhe (4.18×10^{8} m^{3}) and Yellow Rivers (1.93 ×10^{8} m^{3}). The gross water supply from groundwater was 6.55×10^{8} m^{3}, the regeneration water was 8×10^{6} m^{3} and the 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 603.61 million tons, a rise of 30.23% over 2003, and of that 300.81 million tons were industrial and 302.80 million tons were domestic wastewater. The SO_2 discharged reached 264.8 thousand tons, the soot discharged 90.90 thousand tons, and the industrial powdery dust discharged 19.30 thousand tons. The production of industrial solid waste was 11.23 million tons, a rise of 75.46% over 2003, and 98.27% of it is used synthetically. The production of domestic garbage reached 1452.10 thousand tons in the city, 80.30 % of which is disposed of innocuously.

Table 2: Annual per capita energy consumption for non-production purpose (2001-2007)

Year	2004	2005	2006	2007
Coal (kg)	91	86	72	69
Liquefied petroleum gas (kg)	10	7	7	7
Natural gas, Coal gas (m^3)	31	37	35	32
Electricity (kWh)	360	367	406	434
Geothermal (m^3)	-	2.43	2.46	2.55

Tianjin's main forms of energy are electricity, combustible gas and coal. The use of fossil fuel energy causes serious air pollution. Soot has become a major constituent of pollution with an annual average of 0.106 mg/m^{3}, sulphur dioxide emission is 0.077 mg/m^{3}, and nitrogen dioxide annual average discharge 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 the traffic on the road is 68 decibel, and the average noise in the city is 54.9 decibel.

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 2.59% of the GDP of the same year, an increase of 4.23% from 2004. The investment was used for the construction of the base environmental establishment, controlling the amount of industrial pollution, and improving the activity to include the control of 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 environment quality has improved greatly. Geothermal energy played an important and affirmative role in the process. Now, Tianjin has become one of the cleanest cities in China.

In 2007, the total energy use in Tianjin amounted to 47.15 million tons standard coal. The energy use of per million GDP amounts to 102 tons standard coal, reduced by 62 tons from 2000 (Figure 6). The total supply of geothermal energy equaled 476.84 thousand tons standard coal in the same year, or 1.01% of the total energy use. (Tianjin Government, 2007)

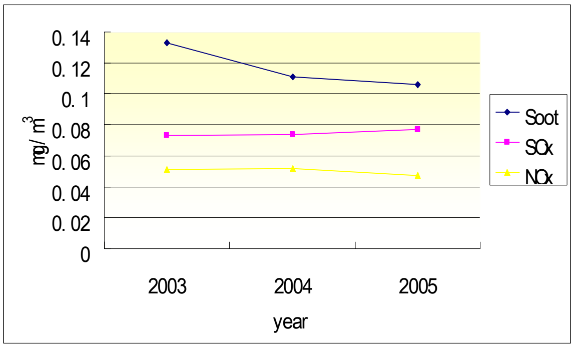


Figure 5: The main contamination of air in Tianjin (2003-2005)

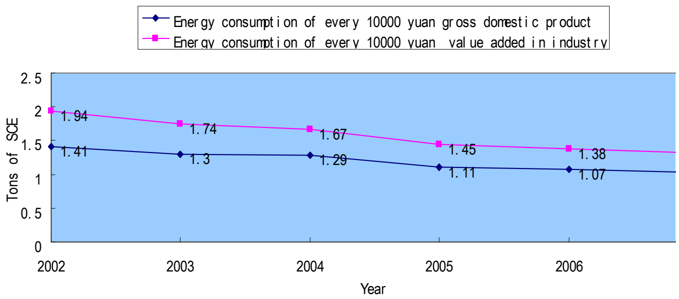


Figure 6: Energy consumption of every 10000 yuan gross domestic product and value added in industry (2002-2007)

4.2 Benefits of Geothermal Utilization in Tianjin

4.2.1 Benefits to the economy

By the end of 2008, there were 60 companies working in geothermal utilization projects. 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, correlative equipment production and correlative technology service. The production value of these institutes or companies is more than 160 million yuan each year.

The cost of the heat resource construction of 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 per year (total running cost per year divided by the total heating area), 8-10 yuan/m^2 less than conventional systems (coal boiler, oil boiler or gas boiler). The running cost of the advanced geothermal heating system which has been constructed in recent years is lower. So, by calculating the running cost, more than 108 million yuan is saved each year in Tianjin by using geothermal energy.

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-fired plant. Using geothermal energy can substitute 300,409 tons of coal each year in Tianjin. Let's suppose that coal is burned in a coal plant with decontaminative equipment, and the generation of 9781 tons of sulfur dioxide, small airborne particles and nitrogen oxide is avoided, it will still generate:

- 793,939 tons of carbon dioxide (CO_2), the primary human cause of global warming--as much carbon dioxide as would not be assimilated if 14.56 million trees were felled.
- 2145.72 tons of sulfur 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.
- 107.29 tons of small airborne particles, which can cause chronic bronchitis, aggravated asthma, and premature death, as well as a haze obstructing visibility.
- 2188.70 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.
- 154.50 tons of carbon monoxide (CO), which causes headaches and places additional stress on people with heart disease.
- 47.21 tons of hydrocarbons, and volatile organic compounds (VOC), which form ozone.
- 110.08 kg of mercury, arsenic, lead, cadmium and other toxic heavy metals.
- 120.16 million ton per km of coal transport (from the nearest coal mine), Coal dust blowing from coal trains or coal trucks contributes particulate matter to the air and soil.

Running the decontaminative equipment will cost 19.02 million yuan each year, so the benefit of geothermal utilization to the environment is obvious.

4.3 Environmental impact of geothermal utlization in Tianjin

4.3.1 Socio-economic impact of geothermal utlization

During the 1960s, when our environment was healthier than it is nowadays and we were less aware of any threat to the earth, geothermal energy was still considered a non-polluting energy source. 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 impact on the environment. 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.

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 exploratory/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—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 of 2000 m). These operations will modify the surface morphology of the area and could 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 plants, will also affect animal and plant life and the surface morphology. In Tianjin, the system was built in the city zone, so 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 very rare. In Tianjin, the quality of geothermal water in the Ng and Nm reservoirs is quite good, and thus 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, reinjected 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.

The withdrawal and/or reinjection of geothermal fluids may trigger or increase the frequency of **seismic events** in certain areas. However these are microseismic 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 the low-temperature direct utilization system, the noise is often lower than the noise of traffic in the 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 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 could reach detectable levels, in some cases of the order of a few tens of centimetres and even metres, and should be monitored systematically, as it could damage the stability of the geothermal buildings and private homes in the neighbourhood.

Land subsidence has become a word-wide geo-environmental problem in recent years. Land subsidence will result in lowering the elevation of land. With the rise of sea-level added, it will impact the construction, production and the 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.

Withdrawal of fluid from an underground reservoir can result in the reduction of formation pore pressure which may lead to compaction in rock formations having high compressibility and result in subsidence at the surface. 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 casing 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 field (New Zealand). This subsidence has caused: Compressional and tensional strain on pipelines and lined canals; deformation of drill casing; tilting of buildings and the equipment inside; breaking of road surfaces; 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 and the latter are generally in older rocks having lower porosity (Hunt, 2000).

Land subsidence is the primary geo-environmental problem in Tianjin, and has brought serious consequences to Tianjin: 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; asymmetric subsidence imperils the speedway, underground, pipelines and large buildings.

4.3.2.1 Data on land subsidence in Tianjin

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 centers are located downtown, in Tanggu district, Hangu district, Dagang district 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 more than 20 mm/yr in the littoral zone, especially in the Hangu district, where the rate is 40-50 mm/yr (Figure 7).

Land subsidence is the most serious geo-environmental problem in Tianjin. The accumulated total land subsidence is in many places greater than 1000 mm in this area, 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, and some zones are now below sea level. The project for controlling land subsidence was brought into effect and due to reduced exploitation of groundwater, the average subsidence value has been lowered from 100 mm/yr (1985) to 25-30mm/yr. Even now, land subsidence in this area is serious (Figure 8).

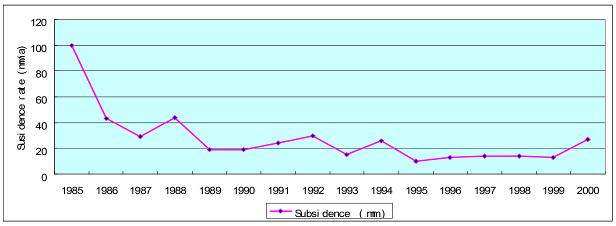


Figure 7: The graph of average subsidence rate in Tianjin (1985-2000)

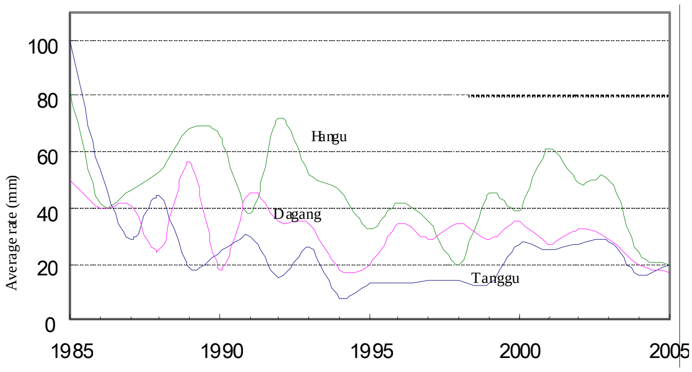


Figure 8: The graph of average subsidence rate in Tanggu district, Hangu district and Dagang district

The coastal protection dyke against the tide is located on soft soil. The average subsidence value for the coastal dyke in recent years is 15-30 mm. The average subsidence value of a part of the coastal dyke in Hangu district is 30-40 mm/yr, part of which is closed or under the fortified tide level.

The monitoring area 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 an area of 1100 km^2.

Tanggu district: The monitoring area covers 200 km^2, and average subsidence value was 20 mm in 2005. The maximum value was 25 mm, 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, 25 mm greater than that in 1998, and 10 mm greater than that before Luanhe 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 subsidence central is located in the Yangjiabai area (the north of Hangu district), and the average subsidence value was greater than 40 mm.

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 the 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 south region of Tianjin.

4.3.2.2 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. The calamitous storm tide recurred every 50 years until 1958 in the Tianjin littoral zone. After 1992, the 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 the city constructions 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 the underground and railway traffic.

The exploitation of groundwater, oil, natural gas, geothermal fluid; soft soil secondary-consolidation settlement can cause land subsidence. In Tianjin, the main cause of land subsidence is excessive exploitation of groundwater. Comparing Figure 9 to Figure 10, we find: that where there are centers of land subsidence, such as in the town centre, Tanggu district and Hangu district, there are also areas where groundwater is excessively exploited. For example, the permitted quantity of groundwater exploitation is 10 million m^3/yr in the town centre of Tianjin, but the maximum quantity of groundwater exploitation has been up to 120 million m^3/yr. In Tanggu district, where the permitted quantity of groundwater exploitation is less than 10 million m^3/yr, the maximum quantity of groundwater exploitation has been up to 50 million m^3/yr. The areas of extensive land subsidence and excessive exploitation of groundwater are connected. (Bai, 2007)

4.3.2.3 A geothermal reservoir's consolidation state.

A soil layer is the result of geological history, being deposited in a geo-chronological order. In order to classily 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 Over Consolidation Ratio (OCR, Pc/Po) ≈1, it means that the consolidation process reached the final consolidated state that under the lithostatic pressure during the soil layer deposit history.

b. Under-consolidated state: Pc<Po, or OCR <1, it means the degree of consolidation did not reach the final consolidated state was reached under the lithostatic pressure. The soil layer will drain slowly because of the lithostatic pressure, then the soil layer will be compressed slowly. Most of the marine deposits, lacustrine deposit soil layers are under-consolidated soil layers.

c. Over-consolidated state: Pc>Po, or OCR **>** 1, it means the degree of consolidation exceeds the final consolidated state was reached under lithostatic pressure. The reasons why soil layers became over consolidated state are mainly physico-chemical action, glacier action, denudation action, groundwater return after a long drought, and human construction activity.

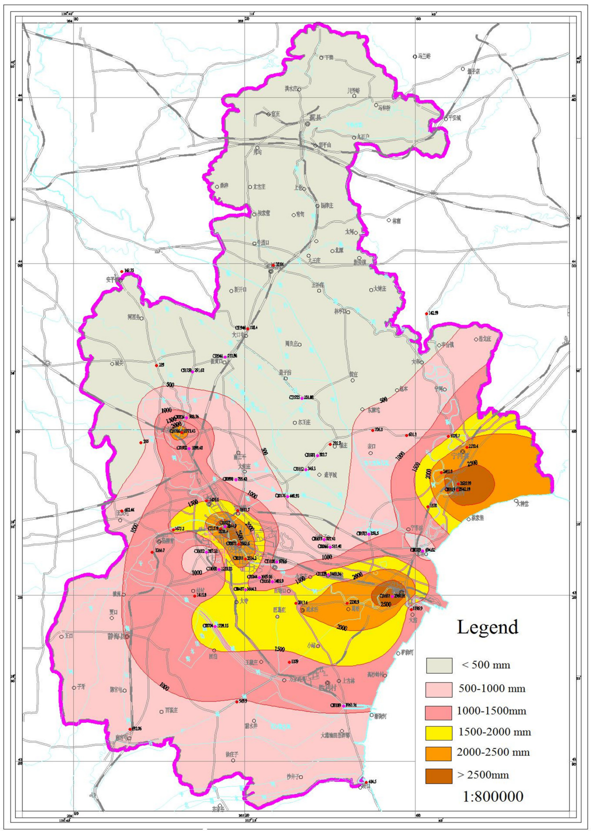


Figure 9: The isolines for total land subsidence in Tianjin (1967-2000)

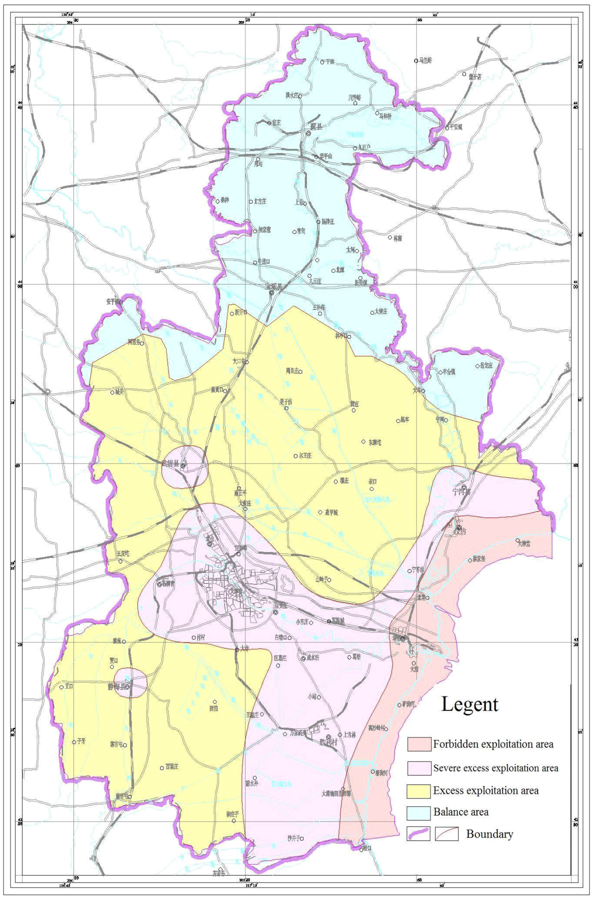


Figure 10: The actual exploitation of groundwater in Tianjin

In the Binhai Area, the main geothermal reservoirs are located in the Minghuazhen group (Nm) and Guantao group (Ng), at a depth from 500-2000 m. So Figures 11 and 12 show that the geothermal reservoirs are located in normally consolidated strata (Niu, 2003).

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.

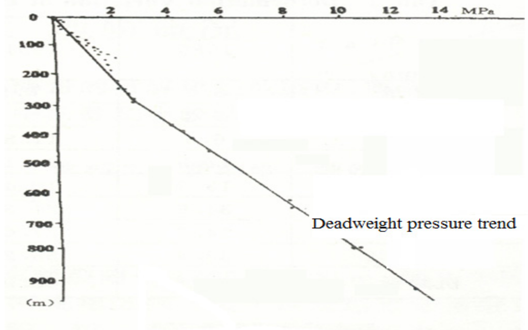


Figure 11: The information from a high pressure consolidation test. The data came from different strata of the town central (depth<200 m), Tanggu, Hangu and Dagang districts (depth **>** 200 m). Where the depth is more than 200 m the pre-consolidation pressure at different depths is equal to the deadweight pressure. It means that the strata below 200 m are normally consolidated.

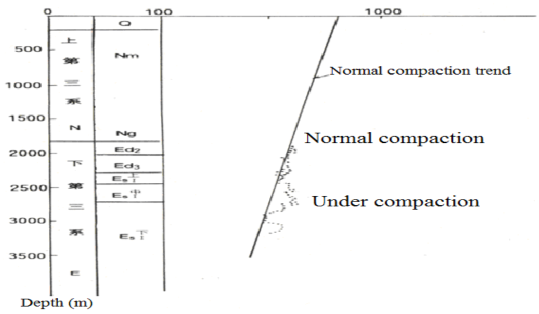


Figure 12: The actual compaction status compared to the normal compaction trend in the Huanghua downwarping region, supported with the data of oil well surveys. It means when the depth is less than 2500 m, the strata are normally consolidated. When the depth is greater than 2500 m, the strata are under consolidated.

4.3.2.4 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 be 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 the groundwater be mined and the water level drops, the balance of stress will be broken, and the pore water pressure will be reduced (Figure 13**)**. Then the effective stress will be increased, compressing deformation will set in, and cause land subsidence.

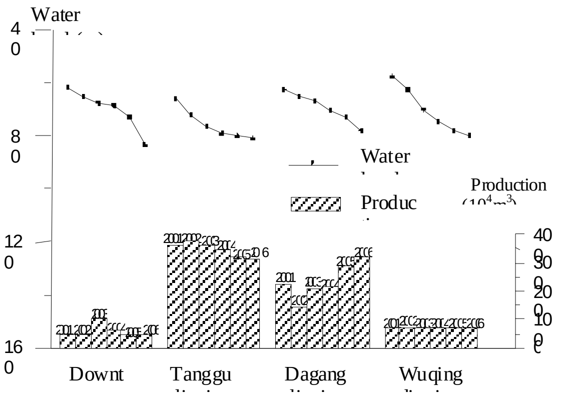


Figure 13: The graph of water level of Guantao group (Ng) reservoir in Tianjin

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

In Tianjin, 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 will be reduced. Then the effective stress will be increased, compressing deformation sets in and causes land subsidence. In the Huanghua down-warping region, if the depth is greater than 2500 m, the strata are under consolidated. The maximum pressure coefficient of an exceptional stratum is 1.552, at the depth 3702.7 m, in the Shahejie group. So in this area, if the geothermal reservoir is deeper than 2500 m, the exploitation will cause rapid land subsidence.

4.3.2.5 Evidence from monitoring data

In order to monitor the 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 the layer-built mark is 650 m, 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, and the elevation was 2.3848 m in 2002. The elevation fell 82 mm in ten years. The average subsidence rate was 8.2 mm/yr. when the subsidence caused by tectonic activity had been subtracted (2 mm/yr) (Huang, 2000), the average subsidence rate caused by the exploitation of the geothermal reservoir in the Guantao group (Ng) was 6.2 mm/yr (Figure 14).

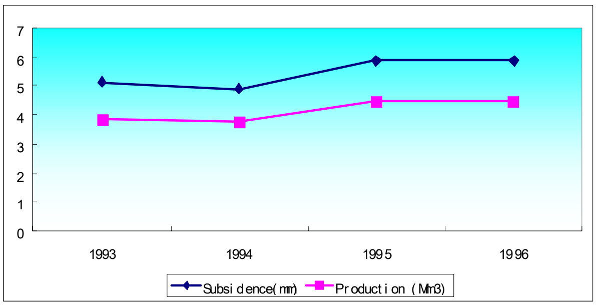


Figure 14: Relationship between the geothermal production and subsidence

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/yr, and the average subsidence rate at JC-899 was 23.2 mm/yr in the same period (1992 -2002). When the subsidence caused by tectonic activity (2 mm/yr) had been subtracted, the total land subsidence rate was 22 mm/yr. Therefore, the subsidence caused by the exploitation of the geothermal reservoir accounted for 28.16% of the total land subsidence in this area. The rest may be due to the exploitation of groundwater (8-13 mm/yr), tectonic activity (1.3-2.0 mm/yr), construction (3-5 mm/yr), etc.

4.3.2.6 Solution

In Tianjin, the main cause of land subsidence is excessive exploitation of groundwater. The centers of land subsidence are also the areas where excessive exploitation of groundwater takes place. In 2005, the gross water supply from groundwater was 6.55×10^8 m^3. In order to slow down the subsidence, most parts of Tianjin have been forbidden to exploit groundwater since 2007 (Figure 18). The amount of water from the Luanhe (4.18×10^8 m^3) and Yellow Rivers and direct use of seawater are increasing.

Anyway, the subsidence caused by the exploitation of geothermal fluid can not be ignored, though it is a small part of the total land subsidence. With the development of the economy, the demand for geothermal energy is increasing considerably. So, solutions will be needed with increasing geothermal production.

A new reservoir in an over-consolidated stratum. In Tianjin, exploration in 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 and it is thick. Moderate exploitation will not cause subsidence. Now, the testing of a well in the new reservoir is in progress. The results of a pilot study suggest that the exploitation potential is great.

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

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

The advantages of reinjection: stops most pollution, avoids fluid depletion, ensures longer lifetime of reservoirs, prevents temperature changes at surface, hinders formation of large ponds. Now, in Tianjin, reinjection is an integral part of the utilization of each geothermal system that is assessed when the governmental managing department issues the production license. To encourage reinjection, the tax is 70% lower for geothermal systems with reinjection.

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

There is a possibility that reinjection can cause re-elevation of the land. In the fact, the reinjection can restore the level of groundwater, but it cannot restore 70% of the water that was released because of drain from the layer. Thus the re-elevation is negligible. On the other hand, reinjection directs water into the reservoir, prevents draining, and further subsidence. So subsidence can be prevented or reduced by reinjecting geothermal waste water.

4.3.3 Monitoring system

4.3.3.1 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 the mass monitoring data, we can set up models of the geothermal systems. Through modeling, reservoir changes can be seen in advance (Figure 15).

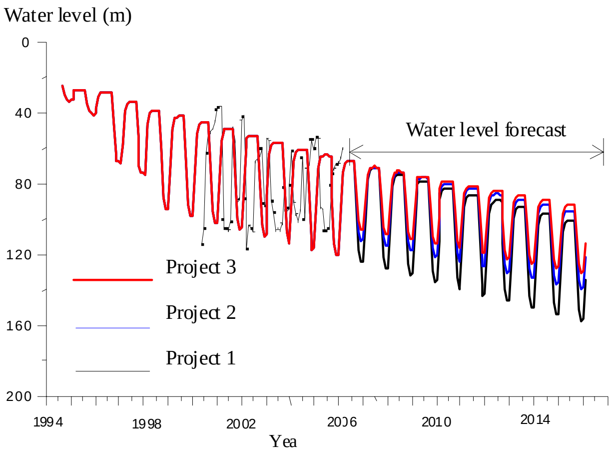


Figure 15: Water level forecast for the Guantao group (Ng) reservoir with different production: unchanged; reduction by 20%; 30% reinjection.

Geothermal monitoring projects started in Tianjin in the 1980s involving measurement of water level, temperature and flow rate in the geothermal wells. A geothermal monitoring system was set up in the mid 1990s with improvement of monitoring measurements and layout. The task of monitoring: 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).

Since 2006, an automatic Net-PC geothermal monitoring system has being installed. The system can measure the temperature, the flow rate and the pressure at the wellhead and/or the water level in the well automatically. The computer on the wellhead will record the data every hour and send data to the control center twice every day. With this system, the investigation involves checking the water level, temperature and flow rate of every geothermal well in the control center at any moment when he (she) wants. Based on the monitoring data, we can set up the models and produce maps of the geothermal systems with the help of a computer.

4.3.3.2 Monitoring system for land subsidence

A survey network has been set up in Tianjin. By the end of 2008, it comprised 5 GPS stations, 970 benchmarks, 7 groups of layer-built marks and 330 groundwater monitoring points in Tianjin.

Seven groups of layer-built marks which can at present monitor the extent of subsidence were installed. There are 49 layering wells, 6 long term observation wells, and 44 pressure probes for pore water. 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 point-times, the hydraulic head of pore water is monitored 517 point-times, and the elevation of layering wells is measured 732 point-times. The depth of monitoring is usually to 300 m or so, the deepest being 650 m.

In 2007, a new monitoring project named “Binhai Area forecast and signal system of land subsidence” was started. From 2007 to 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. Besides, a new GPS station will be built. The new monitoring system emphasizes particularly monitoring land subsidence caused by the exploitation of oil, natural gas and geothermal utilization.

5. CONCLUSIONS

Tianjin is a new development area in north China. In 2005, the development of Binghai was been brought into the stratagems of national development. Thus the political and economical status of this area is very important in China. The direct geothermal utilization started in the 1980s. Now, the geothermal space heating area covers more than 12 million m^2, and the total volume of geothermal water production per year is more than 26 million m^3. The benefits of geothermal utilization are obvious: More than 40,000 families benefit from geothermal space heating or hot water; some ten entertainment industry companies profit from offering the geothermal service; More than 300,409 tons fossil fuel are saved every year; contaminated gaseous discharges 336,688 tons every year are avoided.

The environmental impact of geothermal utilization in Tianjin is 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/yr 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 on the connection between geothermal production (with the wells depths from 1200 m to 2000 m) and land subsidence accurately. The Tianjin Institute of Geological Investigation is building six groups of new layer-built marks, whose depth are from 50 m to 1200 m. We shall thus obtain more accurate monitoring data in future years.

Anyway, land subsidence caused by the exploitation of geothermal water is actually taking place in the Binhai Area. The exploitation of geothermal water from the Guantao (Ng) reservoir should be controlled sternly. At the same time, exploration for new reservoirs and reinjection tests should be carried out. The drilling method and configuration of reinjection well, the equipment and the operation criterion for injection should be thoroughly investigated.

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