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ENVIRONMENTAL IMPACT OF GEOTHERMAL DEVELOPMENT IN TIANJIN, CHINA

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ABSTRACT

Environmental Impact Assessment (EIA) has played an important role in environmental protection, especially in developing countries. It is an aid to decision-making and to the minimization or elimination of environmental impacts at an early planning stage. For geothermal energy, which currently plays an important part as a clean energy supply, a well-prepared Environmental Impact Assessment (EIA) can significantly minimize or eliminate the environmental impacts at an early planning stage. For the sustainable development of geothermal resources, at present, many countries have developed their own EIA systems as applied to energy. Geothermal resources are rich in Tianjin, China and are already widely utilized, providing considerable economic and environmental benefits. From the 1970s to the end of 2003, more than 200 geothermal wells have been drilled in Tianjin and used for space heating, bathing and other use. This has brought great benefit to urban air quality improvement and economic development. In this report, the benefits of geothermal development, environmental impacts, mitigation methods, and measures to promote geothermal sustainable development in Tianjin are discussed.

1. INTRODUCTION

Geothermal energy has particular advantages over fossil fuel energy, and is thus already generally accepted as being an environmentally benign energy source. Tianjin is rich in low- to medium-temperature geothermal resources. The geothermal resources are employed for space heating and bathing. 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.

Today, the environmental aspects of geothermal development are receiving increasing attention with a shift in attitude towards the world's natural resources. Although the impacts of geothermal development projects are often positive, different types of geothermal fields and geothermal development have varying impacts. The purpose of this paper is to use the Environmental Impact Assessment method to study the environmental impacts of geothermal development in Tianjin.

2. ENVIRONMENTAL IMPACT ASSESSMENT

2.1 Introduction

Environmental Impact Assessment (EIA) is a process carried out to ensure that the likely significant environmental effects of certain projects are identified and assessed before a decision is made on whether a proposal should be allowed to proceed. This means that the most environmentally favourable option, or at least the environmentally acceptable option, can be identified at an early stage and projects can then be designed to avoid or minimise environmental effects.

Since the first Environmental Impact Assessment (EIA) system was established in USA in 1969, EIA systems have been set up worldwide and become a powerful environmental safeguard in the project planning process. Many countries have adopted their own EIA procedures. Some national and international organizations or legislatives refer to the World Commission on Environment and Development that espoused the principle of sustainable development in its 1987 report; and the 1992 United Nations Conference on Environment and Development established to adapt human activities to nature's carrying capacity (Morris and Therivel, 1995), seeking to influence the relationship between development and the environment. Today, Environmental Impact Assessment is the tool most widely used in environmental management and its objective is to determine the potential environmental, social and health effects of a proposed development in order to provide decision-makers with an account of the implications of a proposed course of action before a decision is made.

2.2 The process of Environmental Impact Assessment

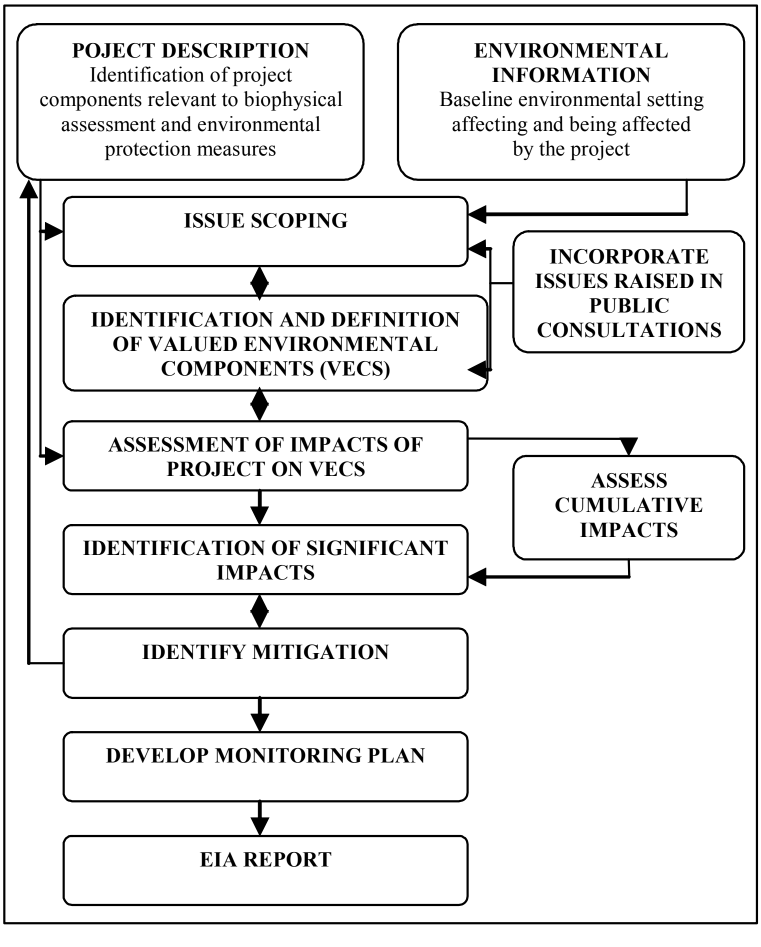

FIGURE 1: Typical Environmental Impact Assessment process (Bell et al., 2003)

Environmental Impact Assessment (EIA) is a comprehensive and systematic process designed to identify, analyze and evaluate the environmental effects of proposed projects. It should have the following main objectives:

- To involve the public in an open and participatory manner;
- To allow for the effective integration of environmental considerations and public concerns in decision-making;
- To be a powerful tool to help decision-makers achieve the goal of sustainable development" (Anderson, 2001).

Currently, most countries have set up their own EIA systems. The particular components, stages, and activities of an EIA process usually depend upon the requirements of the individual countries. However, most EIA processes have a common structure (Figure 1), and the application of the same main stages is a basic standard of good practice. In EIA systems there is a sequence of activities implemented in a project in a logical sequence termed an EIA process.

Project description and screening: In this section, one should provide a concise description of the project's geographic, ecological, social and temporal context, including any off-site investments that may be required by the project, to decide whether an Environmental Impact Assessment is required.

Scoping: It is used to identify the key issues of concern at an early stage in the planning process, and identify possible alternatives. It can also be used to aid site selection and to identify any possible alternatives. The scoping process should be carried out by interested parties such as the planning or environmental agencies, and members of the public. The results of scoping will determine the scope, depth and terms of reference to be addressed within the Environmental Impact Statement.

Environmental information: Baseline data describes the existing environmental status of the identified study area. The site-specific primary data should be monitored for the identified parameters and supplemented by secondary data if available.

Impact analysis: To identify and predict the likely environmental and social effects of the proposal and evaluate their significance. To describe the various types of environmental impacts of development projects both beneficial and negative.

Identification, mitigation and management: To review the action taken to prevent, avoid or minimise the actual or potential negative effects of a project. The measure could include the abandoning or modifying of a proposal, substitution of techniques using BATNEEC (Best Available Technology Not Entailing Excessive Costs).

Public consultation and participation: Public participation is a necessary component of the EIA. Consultation with affected communities is recognized as a key to identifying environmental impacts and designing mitigation measures. After the completion of an EIA report, the law requires that the public must be informed of and consulted on a proposed development.

Environmental monitoring plan: Environmental monitoring is the systematic observation of the state of the environment and of the factors influencing it. Its main purposes are to forecast changes in the state of the environment and to provide initial data for planning documents, programmes and projects. As one of the most important aspects of EIA, monitoring should be carried out during both construction and operation phases of a project. This is not only to ensure that the commitments made are complied with but also to observe whether the predictions made in the EIA reports were correct or not.

EIA report: contains the information obtained, analysed, interpreted and compiled in report form. The report should contain a non-technical summary, methods used, results, interpretation and conclusions.

Review: The EIA report must be submitted for review in order to assess whether or not all the possible issues have been adequately addressed and to facilitate the decision-making process.

Decision-making: With the help of information and conclusions given in EIA reports and the outcome of reviews, the decision makers determine whether or not the project should go ahead.

2.3 EIA in geothermal projects

Geothermal utilization can cause surface disturbances, physical effects due to fluid withdrawal, noise, thermal effects and emission of chemicals as well as affect the communities concerned socially and economically (Ármannsson and Kristmannsdóttir, 1992). Therefore, it is necessary that geothermal development is associated with a well-defined EIA system. At present, geothermal plans and projects that require an EIA are increasing in number. Some countries, for example, Iceland, Italy, USA, Philippines, and New Zealand have set up systematic regulations on geothermal utilization. With the continued development of geothermal resources, more countries have followed the USA and funding agencies, and adopted recommendations of EIA for geothermal development.

Geothermal utilization started much earlier than EIA work in Tianjin. Although the geothermal development and utilization have become more and more widespread, so far no complete geothermal EIA project has been carried out. However, some geological work which is related to an Environmental Impact Assessment was carried out when the developers applied for mining licences for geothermal utilization according to the law on mineral resources (e.g. reports of the feasibility of geothermal resource exploitation and utilization, schemes for geothermal utilization, etc.). These reports or schemes deal with environmental aspects, and although they are not real EIAs, they can be regarded as rudimentary EIA work in the geothermal field.

2.4 EIA in China

The Chinese Environmental Impact Assessment system was originally established in 1979. It is based on foreign experience, combined with its own situation, and has been developed in several steps. At present, a practical EIA system for construction projects has been formulated. However, there is still no regulation or law on EIA for geothermal development in China. The implementation of EIA in China started in the 1980s. In 1992, the Chinese government made it compulsory for construction projects.

China's new *Environmental Impact Assessment Law* was passed on October 28, 2002 and became effective on September 1, 2003 (Wang and Zhou, 2003). The purpose of this Act is to provide China with a sustainable development strategy, and prevent the implementation of planning and construction projects having negative impact on the environment. New laws establishing comprehensive regulations have begun to curb environmental damage. The EIA Law will strengthen trends towards higher technical standards and will require increased attention to compliance by investors, business operators, construction companies, technical consultants and government departments. The EIA Law also requires for the first time that government plans undergo varying types of EIA, some of which will be subject to comments by experts and by the public. Trends in public opinion and in government policy point towards continued tightening of standards and enforcement.

3. OVERVIEW OF TIANJIN

3.1 Geographical setting and climate

Tianjin is the largest open city by the sea of North China and one of the 4 municipalities directly under the Central Government of the People's Republic of China (Figure 2). It is located between latitudes 38°33' and 45°15' S; and longitudes 116°42' and 118°03' E. It is by the Bohai Gulf and in the eastern part of the North China Plain, north of the Yan Mountains. The distance from the centre of the city to Beijing, China's capital, is 120 km, and 50 km to the east is the Bohai Gulf. It takes one hour by train to reach Beijing. Five tributaries of the

FIGURE 2: Location map of Tianjin, China

Haihe River merge in the city and the mainstream, 72 km long runs south-eastward to the Bohai Bay.

Tianjin's total area is 11,305 km^2, 186 km from north to south and 101 km from east to west. Flatland covers 94.2% of the land area at between 2.2 and 50 m above sea level. The northwest part is a mountainous area (elevation 500-2882 m) and flatlands comprise the southeast part (elevation below 50 m). The coastline of the province is 133 km long.

Temperature in Tianjin is relatively high and it has a semi-humid continental monsoon climate with four clearly distinct seasons. It has cold winters and hot summers while spring and autumn are short and pleasant. The annual sunshine totals 2400-3100 hours. The annual frost-free period is 120-200 days. The annual precipitation varies with location from 300 to 800 mm, and the annual average temperature stands at 13°C in most areas except that it is below 4°C in the northwest highlands. Space heating is required for a minimum of four months a year.

3.2 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 Municipality is divided into 15 districts and 3 counties (Figure 3). By the end of 2003, the permanent municipal population was 10.11 million, the natural population growth being 1.10%. The striking feature of the municipal population distribution is the high density in the central districts with 2.01% of the total area accounting for 41% of the total population. Tianjin's educational, scientific and cultural causes 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.

FIGURE 3: Regional map of Tianjin

Tianjin is the economic and trading centre of northern China. In 2003, the Gross Domestic Product (GDP) of Tianjin was 238.7 billion Yuan, and the per capita gross domestic product was 25,874 Yuan. 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 engaging 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.

3.3 Natural resources

Tianjin is rich in natural resources. Over 30 kinds of metallic and non-metallic ores and fossil fuels have been found. Over 20 types are worth exploiting. The most important metallic ores include chambersite, manganese, gold, tungsten, molybdenum, copper, iron ore, lead, zinc etc, among which chambersite was discovered for the first time in China in Tianjin. The major non-metallic materials are: cement limestone, barite, dolomite, stromatolite, marble, natural oil stone, pottery clay, maifanshi porous stone etc. The principal fuel deposits are petroleum, natural gas, coal and coal gas. Both the Dagang and Bohai oilfields in the southeast of Tianjin are well known oil and gas fields in China.

Tianjin is also rich in geothermal resources covering an area of 2320 km^2. The total reserve is over 20 billion tons with a temperature between 30 and 105°C.

Tianjin produces a large quantity of salt, e.g. one-third of the country’s sea-salt. With a sodium chloride content as high as 96-98%, the salt is an important raw material for the marine chemical industry. There are over 270 km^2 of barren and silt land awaiting utilization. The Tianjin Auto Works produce 150,000 cars a year. In Tianjin, there are many species of plants (mostly re-vegetation) and animals and over 30 fish species. Aquatic Products Bohai Fishing covers 2100 km^2. The city has developed a major aquatic breeding and ocean fishery industry. The famous Bohai prawn is the major aquatic export product. 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 and operating costs than Beijing, Shanghai, and Guangdong.

3.4 History and tourism

Tianjin, also known as the diamond of the Bohai Gulf and the gateway to the capital of the People’s Republic of China, has a long and illustrious history, and the marks that the past has imprinted upon the place can still be seen today. Notable history of the city began with the excavation of the Grand Canal during the Sui Dynasty (581-618 AD). At this time, Tianjin was considered to be one of China's most important military fortresses. Any "aliens" would have to get through Tianjin for direct access to the capital, a mere 80 km to the west. The city, whose rise started during the mid-Tang dynasty (618-907 AD), also became known as a transportation route.

Tianjin is located at the lower end of nine tributaries merging into the Haihe River which flows through the city. Tianjin’s local culture is derived both from the warm and honest old inner city culture and that of the riverside, and it is full of life, vitality and vigour. Thanks to its historical experiences, Tianjin has encountered many European cultures, and their integration within a Chinese society has made Tianjin’s urban culture uniquely enchanting. Tianjin’s architecture is particularly unique. With a combination of traditional Chinese cultural architecture and a rich mixture of architectural culture from other parts of the world, it is known as the "World Museum of Architecture". In Tianjin, there are world-famous folk artefacts such as the coloured clay figures of Zhang, a famous culinary culture such as Gou Bu Li Bao-zi (steamed stuffed dumplings) and so on.

The geographical location makes Tianjin a good place for tourism. Tianjin is a rich tourist resource. The city scenery around Tianjin includes the Xikai church (built by French Catholics in 1916), Tianjin TV & Radio tower (built in 1991 rises 415.2 m above the ground), Dabei Zen temple (a famous temple built in l669 during the Qing Dynasty), Seaview tower (in fact a Catholic church built in l869), Haihe river (a symbol of Tianjin, spanning 70 km across the city proper), and some special streets, etc. There are many attractions in Tianjin's suburbs. Jixian county is a famous place with a rich culture and a beautiful landscape. There is natural scenery in Panshan, and the Great Wall can be approached at Huangyaguan Pass built during the Ming Dynasty. The wall and its watchtowers are on mountain ridges about 730 m a.s.l. The ancient stratum section is in the north of the county, there lies a stretch of a well-preserved stratum section. About 20 km long, the 9,197 m thick stratum occupies a land of 800 hectares. It is l.95 billion - 850 million years old. The new coastal district is also a famous tourist area.

4. GEOTHERMAL SYSTEMS OF TIANJIN

4.1 Introduction

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 in a sedimentary basin, and belong to the static storage type. There are 10 geothermally anomalous areas (Figure 4). The total area of geothermally anomalous areas with temperature gradients ≥3.5°C / 100 m is about 2320 km^2. The highest temperature gradient is 8.8°C / 100 m, the highest wellhead temperature 105°C.

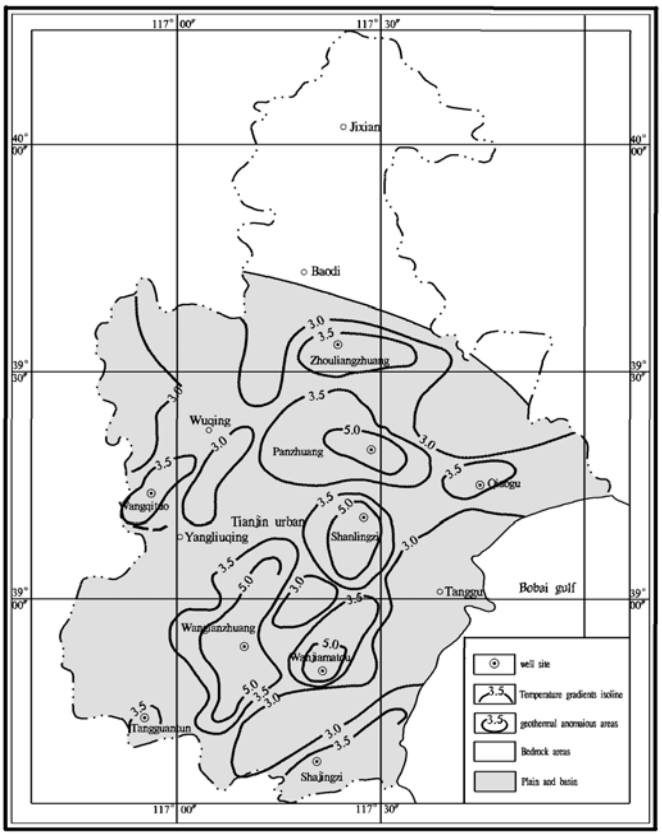

FIGURE 4: Distribution map of geothermal anomalies in Tianjin

The north-northeast structure in the Tianjin region was formed by many large structural movements, and 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.

A series of small uplifts and depressions has formed due to uplift or subsidence of the Mesozoic and Cenozoic rocks (Figure 5). The uplifts include the Wangcaozhuang lift, Ninghe lift, the Panzhuang lift, the Dacheng lift, the Shuangyao lift and the Xiaohanzhuang lift; while the depressions include the Wuqingbaxian depression, the Baitangkou depression, the Banqiao depression, and the Beitang depression. In general, the geothermal reservoir conditions in uplifts are better than in depressions.

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, north-easterly and easterly trend. The geothermal field is controlled by faults and the water quantity is large in the place near the water conducting fault belts.

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 distributed 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 Mingzhen (Nm) Group and the Guantao (Ng) Group from in the upper Tertiary. The fractured reservoirs in the bedrock include three groups and an Ordovician system, a Cambrian system and a Jixianian system.

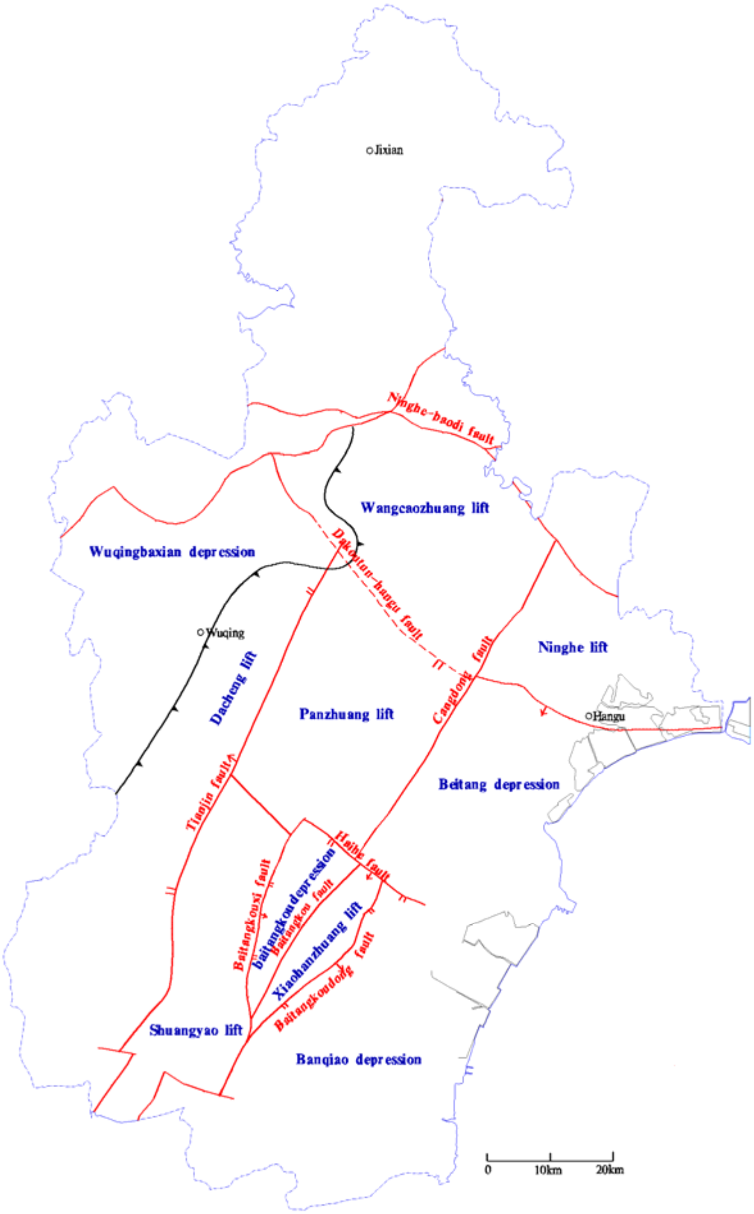

FIGURE 5: Distribution of uplifts and depressions in Tianjin

4.2 Characteristics of the major geothermal reservoirs

The Mingzhen (Nm) group extends over 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 m^3/h, wellhead temperature 50-80°C. The Guantao group is distributed over 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 corrosive.

The Jixianian 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 Jixianian 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 in the Baitangkou depression area, and is very difficult to exploit. 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 Jixianian 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, and the chemical composition of the waters of the explored geothermal reservoirs in Table 2.

TABLE 1: Main characteristics of explored geothermal reservoirs

Geothermal reservoir	**Aquifer roof depth (m)**	**Aquifer thickness (m)**	**Outflow temp. (°C)**	**Flow rate (m^3/h)**	**Water type**	**Water quality assessment**
Mingzhen	300-600	≥500	40-70	40-100	HCO_3-Na– Cl·SO_4-Na	Good
Guantao	1200-2200	<1000	50-80	60-130	HCO_3-Na Cl·HCO_3-Na	Good
Ordovician-Cambrian	800-5000	Variable	60-90	100-200	Cl ·HCO_3-Na Cl·HCO_3·SO_4·-Na SO_4·Cl –Na·Ca	Highly corrosive
Jixianian	1700-4000	1000	79-105	100-200	HCO_3·SO_4-Na – Cl-Na	Good

TABLE 2: Chemical composition (mg/l) of geothermal water
from explored geothermal reservoirs (Li, 2003)

	Mingzhen		**Guantao**		**Ordovician**		**Cambrian**	**Jixianian**		
Well no.	TG-13	WQ-06	WQ-08	DL-10	JN-02	NK-14	DL-11	BD-01	DL-28	JH-01
Na^+	243.6	364.8	232.7	512.6	545.2	747.5	460.0	205.1	445.4	553.6
Ca^{2+}	4.0	4.0	3.0	24.0	40.1	501.0	54.1	38.1	34.1	44.1
Mg^{2+}	0.6	1.2	0.6	5.5	7.9	97.3	8.5	7.3	11.6	17.0
HCO_3^-	524.8	634.6	476.0	549.2	518.7	195.3	427.1	366.1	436.3	360.0
SO_4^{2-}	48.0	9.6	28.8	251.7	275.7	2065.3	336.2	168.1	328.5	379.4
Cl^-	35.4	175.5	53.2	386.4	482.1	802.9	372.2	111.7	390.0	584.9
H_2SiO_3	34.58	52.13	66.95	41.34	53.3	43.94	80.08	110.5	82.55	68.25
F^-	4.28	6.38	5.8	7.85	8.45	3.6	7.8	8.6	11.0	8.15
pH	8.56	8.2	8.6	8.0	7.71	8.02	7.5	8.29	7.22	7.32
TDS	895.4	1237.5	866.4	1774.0	1946.1	4484.7	1793.5	1038.3	1774.5	2056.0

4.3 History of geothermal utilization and development 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, 3 of which have been thoroughly explored. So far, 8 fields have been explored and the greatest depth explored is about 4000 m. By the end of 2003, there was a total of about 255 geothermal wells in Tianjin, of which 169 produce from sedimentary reservoirs, 86 from bedrock reservoirs, and 13 are reinjection wells. In 2003, the total volume of geothermal water production was 2.3×10^7 m^3, the volume reinjected was 1.44×10^6 m^3 or 6% of the production. The Jixianian system is the largest producing thermal reservoir, the annual production is 8.59×10^4 m^3, or 37% of the total production volume, next in size are the Nm and Ng groups (Figure 6).

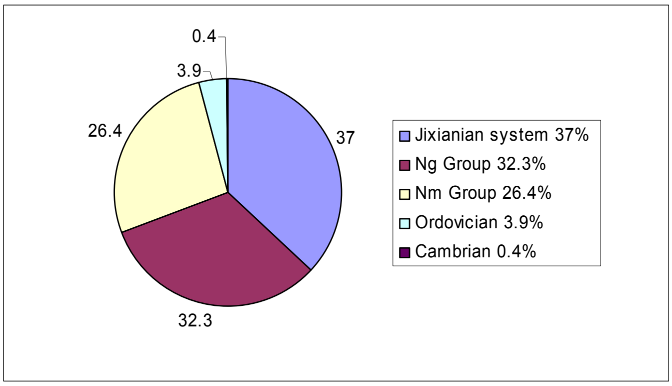

FIGURE 6: Production of geothermal water in Tianjin in 2003

Since geothermal exploration and development in Tianjin started, multiple benefits have been realised. 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 (Figure 7). The total area heated by geothermal energy is 8.60 million m^2 and accounts for 13.5% of Tianjin's total space heating area or 80% of total geothermal space heating area in the country. 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.

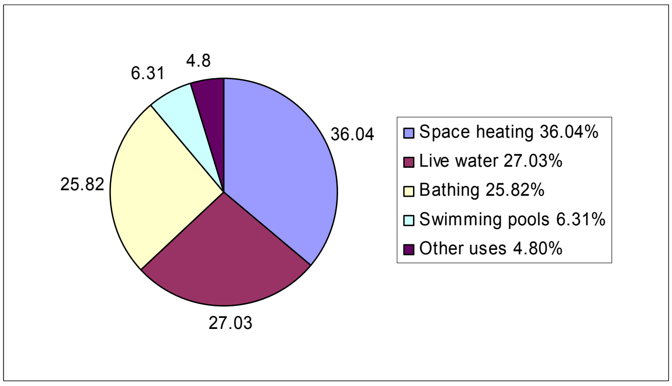

FIGURE 7: Geothermal utilization in Tianjin in 2003

4.4 Main characteristics of the geothermal fields

Tianjin's geothermal resources have a huge potential for utilization. According to a preliminary estimate, the attainable resource is over 7×10^9 m^3 ($\geq$25°C), mostly concentrated in 10 geothermal fields. The characteristics of the 10 geothermal fields are shown in Table 3.

The geothermal fields in Tianjin are very large, their areas range from 40 to 610 km^2. The WLZ and SLZ fields are mostly located within the city zone, where the scale of utilization is also the largest, therefore, there is a huge potential for utilization. So far, preliminary exploration has been completed in 8 fields.

TABLE 3: Main characteristics of the geothermal fields in Tianjin (Li and Li, 2004)

Geothermal fields	Conformation location	Depth of bedrock roof (m)	Area (km^2)	Avail. water volume ($10^6 m^3$)	Highest temp. gradient (°C/100m)
Wanglanzhuang	Shuangyao lift	1000	534	503.14	8.0
Shanlingzi	Dongzhuang lift	1200	315	283.1	8.3
Wanjiamatou	Xiaohanzhuang lift	1000	235	189.68	8.8
Panzhuang	Panzhuang lift	1300	610	111.42	6.9
Zhouliangzhuang	Wangcaozhuang lift	880	180	140.57	5.5
Qiaogu	Structural zone	1700	90	105.67	5.5
Wangqingtuo	Dacheng lift	1400	114	117.88	5.0
Shajingzi	Beidagang lift	1500	190	210.99	4.5
Tangguantun	Structural zone	1200	40	24.21	7.6
Kancaizhuang	Structural zone				4.5
Total			2328	2186.66	

5. ENERGY AND ENVIRONMENT

5.1 Current environmental status

Tianjin is not only one of the biggest economic and trading centres of northern 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.

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 hereby contaminated with raw sanitary wastes, industrial wastes 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 has taken place in many areas, and cones of depression are becoming larger. The wastewater discharge reached 463 million tons in 2003, of it 216 million tons are industrial and 247 million tons domestic wastewater. The industrial solid waste is 6.4 million tons (Data from Tianjin Environmental Protection Bureau, 2003).

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 pollution with an annual average of 0.133 mg/m^3, sulphur dioxide emission is 0.073 mg/m^3, and nitrogen dioxide annual average 0.051 mg/m^3. In 2003, sulphur dioxide discharge reached 0.26 million tons, of which 0.23 million tons are from industrial pollution. The soot discharge was 0.10 million tons. Sulphur dioxide pollution is especially severe from heating applications. The increase of automobiles, has led to exhaust gas from vehicles also becoming a major factor of air pollution.

To improve environmental conditions, Tianjin municipality has made dedicated efforts to raise people's awareness of environmental protection together with economic development. In 2003, Tianjin's investment in environmental improvement was 8.17 billion Yuan, an increase of 47% from the previous year.

Improvements on coalition networks for fossil coal fired burners using less than 10 tons/hour has been completed; 865 wastewater processing plants can now process 347 million tons of waste water annually. Wastewater processing has been increased to 9,894 tons/day and waste gas processing to 1.53 million m^3/h. Water protection has been effected and river ways renovated. The first domestic dangerous waste process centre has been established. In Tianjin, there are 9 ecological demonstration areas and 8 nature protection areas, the latter covering 0.15 ha. They form a part of Jixian county national geology parks which are currently being developed.

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. Tianjin has become one of the cleanest cities in China.

5.2 Energy consumption and air quality

Energy consumption in Tianjin has risen with economic growth, increasing by 114.6% from 1980 through 1995, the gross energy consumption being 25.77 million tons normal coal. Tianjin's main energy forms are electricity, coal and combustible gas. Tianjin depends on coal for 41.6% of its energy (in 1995) with coal widely used in industry, as well as for space heating (Bao, 2002). Compared to Japan, the USA, and India, where energy from coal accounts for 14%, 22%, and 53%, respectively, coal consumption in China including Tianjin is quite high (Hou, 2003). The coal consumption in Tianjin is still about 40 million tons per year, although an increase in electricity consumption has improved the energy structure. The high dependence on coal leads to severe air pollution from sulphur dioxide (SO_2), nitrogen oxides (NO_x), dust, and other pollutant emissions.

Problems arise from huge quantities of sulphur and nitrogen oxide emissions. In moist air, sulphuric and nitric acids are formed. The acids, which are spread by the wind and precipitated by rain cause damage to forests, affect aquatic ecosystems and corrode railway tracks, roads, and historic buildings. The high concentration of smoke and soot particles causes poor visibility and results in an increase in respiratory diseases. Hence in recent years, this situation prompted the Tianjin government to take measures against air pollution in its 10th five-year plan. Targets included 10% reductions in SO_2, NO_x, and TSP (Total Suspended Particles) emissions, compared to the year 2000 levels; and 20% reduction in SO_2, emissions in cities designated as SO_2 pollution control zones, in compliance with the National Atmospheric Environment Grade 2. The Tianjin government plans to pursue policies such as transition to clean energy, use of clean coal, closure of key pollution sources, and wider use of collective heating systems in order to meet its targets for improving the atmospheric environment. This work has been started and the district benefits are being reaped.

Changes in air environmental quality have been recorded since the 1980s. Despite the fact that the municipal energy consumption total has doubled, after 20 years of persistent effort, the TSP has gone down by over 50%, SO_2 down by over 2/3 and NO down close to the permitted level. According to the Tianjin Environmental Protection Bureau (2003), between 1981 and 1997, the air TSP has diminished on the whole, and in 2003 it reached a lower level attaining 0.2 mg/m^3. The SO_2 annual average is 0.073 mg/m^3 and has certainly been reduced. The concentration of NO has dwindled every year from 1981 to 1997.

It is becoming increasingly evident that air pollution is to a large extent correlated to the seasons and climatic changes etc. In winter, air pollution tends to be worse, being affected by coal heating, and special weather conditions like foggy days, zero wind days etc. Springs and autumns are dry with little rain, but in summer the air quality should be optimal. The main contribution to air pollution is still coal dust pollution, resulting in the remarkably heavier pollution during the heating period than non-heating period. The main pollutants are still dust particles and SO_2. The SO_2 pollution in the city centre is higher than elsewhere, and more serious during the winter heating period when average values are 4-6 fold those of the non-heating period.

With the fast and continuous development of the national economy and the further improvement of Tianjin's trunk road network, the number of vehicles has increased steadily to 405,000 (excl. motorcycles) to the end of 2000. Monitoring over recent years indicates that CO is the principal pollutant in the exhaust gas of vehicles.

5.3 Environmental economics

Tianjin municipality has undertaken an assessment of the environmental benefits of urban gardens and forests, and established models and methods of calculation for assessing and analysing ecological/environmental benefits of urban green areas. In Tianjin, it has also been studied how to reform the rule of pollution levies. Further efforts are being made to establish and improve the mechanism for decision-making for integrating environment with development, and to explore the operational models, technical specifications and operational methods for undertaking environmental impact assessments on major economic development policies and plans. Strategic environmental assessments will be gradually promoted. Strict approval procedures have been adopted for those projects that do not comply with the national industrial development policy, and do not fit into the overall municipal master plans. A rule of environmental veto has been adopted in approving procedures of those projects. Tianjin Municipality is disseminating the *Notification for Establishing National Environmental Model Cities* with the aim of turning the city into such a model, through implementing the strategy of sustainable development and strengthening environmental protection and ecological conservation.

Tianjin will continue to adjust its gas consumption mix so as to significantly improve air quality in the city. It will increase the use of natural gas for both the industrial sector and in residential and public buildings. Heating will mainly be provided by cogeneration, supplemented by large-scale boiler units so that gradually there will be no coal burning in the downtown area of the city. It gives priority to the use of wind power, solar energy, geothermal energy and bio-energy and efforts have been made to promote biogas in the rural areas. It has given subsidies and funding support to rural environmentally friendly energy construction projects, and continues to expand its demonstration projects on biogas utilization in large and medium-sized animal and poultry farms. It has conducted work on energy efficiency and conservation in all relevant sectors.

6. BENEFITS OF GEOTHERMAL DEVELOPMENT

6.1 Environmental benefits of geothermal compared to fossil energy

Combustion of fossil fuels such as coal, oil, and gas has negative effects, as burning of any of these resources leads to atmospheric pollution. Coal is by far the dirtiest of these non-renewable resources. The combustion of coal releases large amounts of carbon dioxide, nitrogen oxides, and sulphur dioxide, and small amounts of highly toxic uranium, lead, cadmium, mercury, rubidium, thallium, and zinc.

The use of oil for energy also releases carbon dioxide and nitrogen oxides. Emissions of both chemicals contribute to the formation of smog. Because of its restricted occurrences, much of the oil extracted from the ground must be transported by pipe to the main cities. Occasionally, transported oil is spilled into the environment where it takes its toll on wildlife. Natural gas is the cleanest fossil fuel to burn. Burning it produces an amount of carbon dioxide per unit of energy released that is 50% less than from coal and one-third less than from oil. In addition, burning natural gas does not cause sulphur dioxide emissions.

Tianjin's population is 10 million. Space heating is needed at least 120 days per year. In Tianjin, coal is used for over 80% of space heating every year, causing large emissions of carbon dioxide. The practice of space heating using low to medium-temperature geothermal resources has proved to be free of carbon dioxide emissions.

Compared to coal, oil, and natural gas, geothermal energy causes almost no pollution in terms of particulate matter, sulphur dioxide, nitrogen oxides or aromatic hydrocarbons. Moreover, geothermal energy provides an additional advantage stemming from the fact that it causes minor carbon dioxide emissions. Hence, geothermal energy is environmentally friendly, is called green energy, and is a renewable energy source. Proper utilization of geothermal energy can reduce the greenhouse effect and sustain global energy. Therefore, the city's energy consumption mix should be altered to include more geothermal as soon as possible (Table 4).

TABLE 4: Environmental benefit assessment of geothermal utilization in 2003 (Li, 2003)

Item	Unit	Space heating in winter	Comprehensive utilization	Total
Saving raw coal	tons/a	250,000	54,000	304,000
Reduced carbon dioxide	m^3	220,000	47,520	267,520
Reduced sulphur dioxide	tons/a	3,000	648	3649
Reduced nitrogen oxide	tons/a	2177	469	2646
Reduced fly ash	tons/a	5861	1266	7127
Reduced ash	tons/a	75,000	16,200	91,200
Reduced traffic volume	km/a	3,250,000	702,000	3,952,000

6.2 Comparison of economic benefits of the use of geothermal energy and fossil fuel energy

Four district heating system alternatives are evaluated, i.e., a heating system using coal, natural gas, fossil fuel and geothermal water, to demonstrate the capital cost of the four approaches. The capital cost takes into consideration the heat resource, transmission and distribution network, and consumer facilities. The practice proved that the capital costs of the heating systems using coal, natural gas and fossil fuel are fairly close, and are all lower than that of the geothermal system. However, based on the current market energy cost, the geothermal system has the lowest fuel/resource cost and lowest heating energy cost per unit – only 8.9% that of diesel fuel, 10.7% of natural gas and 45% of coal. The result of the comprehensive calculation reveals that the coal approach has the lowest capital cost – however, it is at a serious disadvantage because of the severe air pollution it causes. The approach of using geothermal water has the highest capital cost, yet the lowest operating cost and the best energy utilization efficiency (Zhang et al., 2000).

Great benefit is achieved for air quality improvement by geothermal development. Coal consumption has been reduced by 40,000 tons each year, carbon monoxide emissions by 835 tons/year, sulphur dioxide emissions by 620 tons/year and nitrogen oxide emissions by 147 tons/year.

Thus, the black smoke and bad air pollution in the city have been considerably reduced.

6.3 Health benefits for the public

Large-scale utilization of geothermal energy offers indirect benefits to the public by reducing the combustion of fossil fuels and local atmospheric pollution. Direct benefits are also numerous, particularly in bathing, swimming, mineral water consumption and recreational purposes. Tianjin's total volume of geothermal water production was 2.3×10^7 m^3 in 2003, and of that about 60.66% was used in these sectors. Exhaustive use of geothermal water associated with health and recreation, has led to the development of resorts with spas; not only contributing to the establishment of long-term tourism, but also therapeutic uses, notably balneology. Tianjin has become a famous “geothermal city”.

Compared to other energy sources, geothermal energy is extremely well suited to large baseload heating applications such as swimming pools. Moreover, the relative abundance of energy often allows spas to be heated to higher temperatures than other conventionally heated facilities, and this enhances their attraction for swimming and their suitability for clinical treatment of diseases.

6.4 Employment benefits

At present, urbanization has become a truly global phenomenon whose increase in rate and scale is catastrophic. The urban population of Tianjin has reached 10 million. The gigantic concentration of people will result in a multiple increase in the supply of water and energy to cities and a huge need for job creation.

At present, Tianjin’s geothermal development is sizeable and has been highly beneficial to the local economy and a tool for job creation. The number of individuals directly employed in geothermal energy utilization is difficult to quantify with any degree of accuracy. Firstly, many service and specialist development companies as well as consultancies operating in this field, also operate in related industries notably oil and gas exploration and groundwater management. The demand for specific services also tends to be cyclical. Equipment suppliers, such as turbine and pump manufacturers, pipe makers, and control hardware companies will also supply items for geothermal schemes, but only as a part of their product range. These estimates exclude people employed in recreation, tourism, spas, greenhouse horticulture, processing industries, and fish farming.

The analysis and evaluation of the use of the four energy resources indicates that a geothermal heating system is technically feasible, and financially reasonable. It is particularly environmentally friendly, and provides a substantial and easily achievable energy saving result. Geothermal energy has the following advantages: compactness of its heat supply station, low operating cost, effectiveness in its comprehensive utilization, fast capital cost return, and especially its limited contribution to air pollution. Up to today, the area of space heating by geothermal energy in Tianjin has reached 8,600,000 m^2 and the population has become more and more adept at using geothermal energy. In the future, geothermal energy will play a more important role in energy supply, alleviation of environmental pollution and improvement in resident life.

7. ENVIRONMENTAL IMPACTS AND PROPOSED MITIGATION

7.1 Impacts on groundwater systems

Tianjin is one of the cities in North China that lack water, most of its water consumption is concentrated in industry, agriculture and daily life. Not only are the water resources scarce but water pollution is also increasingly serious and causing additional damage to agri-eco systems like surface water, ground water, soil crops etc. For resolving this problem, the water diverted from the Luanhe River and the Yellow River has been basically well maintained as the only potable water source for Tianjin after 2000. For this reason, what needs to be considered first in the process of geothermal development is the groundwater system.

Severe contamination of surface water and over-exploitation of groundwater in some places has caused severe land subsidence and falling water levels. For the past years, intensive geothermal exploration has been carried out in most areas. Any unsuitable water development will intensify the groundwater imbalance. Therefore, it is quite important to treat all groundwater as one system and integrate the water use plan and combine the management and utilization of shallow groundwater and geothermal water. Utilization of the geothermal water reserves must not be treated in isolation, but in connection with the use of other water sources such as groundwater and river water etc., a much greater load on the water reserves.

At present, the main utilization of geothermal water is for space heating, bathing, industry, fish farming etc., and these uses will help to minimize withdrawal of potable water. The geothermal water is of good quality, with salinity in the range 0.4 to 5 g/l. The water's salinity is rather high only in fracture reservoirs in the bedrock. With respect to chemical composition, the water used for space heating can be reused for industry, drinking water, domestic water and city virescence etc. after disposal.

In order to build a clean tourist city in Tianjin, an integrated utilization plan has been put forward. Most of the geothermal water in Tianjin cannot be used as drinking water, but after disposal, it may be potable and used for production of mineral drinking water. Besides, utilizing warm wastewater for fish breeding has made it possible to achieve a faster and larger body mass growth than in natural conditions. The breeding season can be expanded from 150 to 300 days a year. The fluoride, copper, zinc, and chromium contents of the geothermal water in Tianjin are rather high, but after dilution it can be used in the fish industry.

7.2 Land subsidence, lowering of water level, depletion of groundwater

Land subsidence and lowering of water level can be caused by the overexploitation of geothermal water and cold groundwater. In Tianjin, geologists indicate that subsidence is mainly caused by the compression of a clay layer. Based on the observation of changes in different layers, they found that 77.6% of the subsidence is in the clay layer, and 22.4% in the sand layer. In Tianjin, the total land subsidence has reached 96 cm (Hou, 2003). A part of the land subsidence has been caused by geothermal production, and cannot be ignored in the total land subsidence. It has been observed in many geothermal fields, especially very clearly in Tanggu of Tianjin. So the production of geothermal water from the shallow deposit layers should be watched very carefully. Based on the experience in Tianjin, the utilization of deep formation geothermal water causes very little subsidence. The subsidence can directly or indirectly cause damage to homes, railroads, highways, and water drainage systems and may damage the pipelines through which the geothermal fluids are pumped from the wells to the users. It can also cause the formation of ponds and cracks in the ground, and further lead to instability in buildings.

In Tianjin, the geothermal resources are already developed to a high degree. Due to over-exploitation of groundwater and geothermal water in Tianjin, the water level keeps on being lowered in the primary producing reservoir. The analytical results from long-term development monitoring indicate that in the downtown and suburban production zone, the water level decreases annually by 6-13 m in the Jixianian system reservoir and over 4 m in the Ng group reservoir, and the cones of depression are becoming larger and larger. Continued production may lower the water level to a greater withdrawal depth for the hot water and result in pump damage. Usually, a cold groundwater zone overlies the geothermal systems. If exploitation of the system results in a large pressure drop in the reservoir, cold water may flow downward into the system, leading to a mixture of cold water and geothermal water. In the city centre of Tianjin, high nitrate concentrations are found in some geothermal water implying mixing of shallow and deep zone waters.

At present, most of these environmental problems can be avoided by means of reinjection of the spent thermal water into the aquifer. One of the purposes of reinjection is to maintain the pressure of the reservoir. Wastewater reinjection can help to reduce pressure drop and hence subsidence. It is important that reinjected water be similar in quality and properties to the subsurface water in the aquifers. An important restriction is that the biological material content should not exceed 1000 mg/l and the water should not be subject to bacteriological and biological contamination. So spent bath water cannot be used as reinjection water, unless it is purified. However, it is quite vital to choose the right location for a reinjection well at a safe distance to avoid lowering the temperature of the production well by cooler water. On the other hand, the distance should be short enough to maintain a pressure connection.

7.3 Thermal pollution

In order to meet the demand of space heating, the geothermal water needs to maintain a high temperature, the amount is large and being higher than that of the surroundings promotes biological processes. As a result of this warm water, the solubility of oxygen in water decreases. The oxygen dissolved in the warm water can become exhausted leading to the death of aquatic living organisms. The multiple use of the water is a way to solve the problem, for example, a hot water supply, water source heat pumps, hot water cultivation etc. Artificial fountains can be built to offer water cooling. The geothermal fluid production can be controlled to reduce thermal pollution during the non-heating season. At present, surface disposal, polluting the environment often takes place where there are no injection wells in Tianjin. In some places, surface soil was salted and natural hot springs spoilt. The water can be cooled in special storage ponds or tanks to avoid modifying the ecosystems in natural bodies of water as much as possible.

7.4 Chemical impact

Tianjin's geothermal water is of good quality. It can be divided into 9 types (Table 1). However, in some places, close to faults, e.g. in Jinghai county close to the Cangdong fault, the mineralization and especially the fluoride concentration are quite high. High mineralization may be hazardous for space heating, domestic and fish farming uses. In geothermal water with high salt content, the process of ion-exchange may be set off with calcium ions changing places with sodium ions. Because the sodium ions have a higher bond energy, this process is practically irreversible leading to soil solidification upon discharge. High fluoride concentration has been shown to be very toxic to humans. Too high concentrations can cause teeth and bone diseases. High fluoride water cannot be reused for fish farming or agriculture.

7.5 Gas emissions

High-temperature geothermal fluids typically contain various non-condensable gases (e.g. carbon dioxide and hydrogen sulphide) and other components (e.g. mercury, arsenic, boron), some of which can cause rather serious environmental problems for geothermal development. For example, CO_2 is a greenhouse gas, and hydrogen sulphide is toxic to humans. But in low- to medium- temperature geothermal fields, there are almost no gas problems. In Tianjin, the geothermal fluid contains very little boron, almost no gaseous CO_2, and no hydrogen sulphide, mercury or arsenic. So geothermal development will not affect air quality, or result in serious long-term environmental degradation.

7.6 Visual impact

Direct use installations for space heating have no visual impacts. Other uses of geothermal energy such as horticulture and fish farming tend to have relatively minor visual effects, depending on the scale of development and the nature of the terrain in which these activities take place. Visual impacts and land use will be most prevalent during drilling, testing and construction of geothermal installations, mostly in the form of traffic and dust. These effects are obviously temporary.

7.7 Noise

Tianjin is a populous city with economic development. Social noise originating in social life and traffic has been the biggest source of noise. The range of noise values is down to 55 dB, below the limit value of class 2 “Urban Area- Environmental Noise Standard”. During low- to medium-temperature geothermal development, noise is usually only a problem during well-drilling/testing activities adjacent to residential areas. The impacts from drilling and well testing are temporary and will disappear when all the wells have been drilled and tested.

The potential impact of noise depends not only on its level but also on the proximity of residential areas to the site. Noise is attenuated with distance (by about 6 dB every time the distance is doubled), although lower frequencies (e.g. noise from drill rigs) are attenuated to a smaller extent than higher frequencies (Brown, 1995). On the site itself, workers can be protected by wearing ear mufflers during drilling and testing. Therefore, the sound environment of Tianjin can be made satisfactory. The noise generated in direct heat applications is usually negligible.

7.8 Corrosion

In utilization of geothermal water, corrosion of installations is a potential problem. The salinity of the base rock reservoir geothermal water currently used is favourable to health. Excessive concentration of ions such as Cl^-, SO_4^{2-}, Fe^{2+}, F^- and H_2S can be harmful to production equipment. For example, the chloride ion causes breakdown of passive films that provide protection to substrate metals and often results in pitting corrosion. Chlorides also form relatively stable complex ions or coordination compounds that may causeaccelerated corrosion. Sulphate is the primary ion in some geothermal fluids. It is not, however, as aggressive as chloride. Oxygen present in low concentrations in geothermal fluids can be neglected. However, the intrusion of oxygen into hot geothermal fluids will lead to greatly accelerated corrosion. The combination of oxygen and chloride is especially bad and may lead to catastrophic failures if there is a danger of stress corrosion cracking.

In the design of geothermal comprehensive utilization systems, the quality of geothermal water must therefore be taken into account. Two solutions are put forward for district heating systems. One is adding corrosion inhibitor to the geothermal water and using it directly in the district heating system, the other is using geothermal water indirectly through heat exchangers. Years of the practice show that the indirect heating system with heat exchangers can serve as a foundation for the geothermal system from technical, economical, environmental, and energy utilization points of view, with fossil fuel energy used for peak loads. Therefore, indirect utilization systems have become popular in recent years.

8. RISK ASSESSMENT

8.1 The risk in well drilling

Financial risk in well drilling is substantial due to its large initial investment costs. Depending on the nature of the hydrological and geological data, the water output or temperature can deviate from the situation predicted during drilling or for the finished well. The risk is intensified for new geothermal fields being developed because of limited hydrological and geological data (Wang, 2000). In contrast, some places have more data from drilling for oil exploration. In these areas, the risk is relatively low.

At present, geothermal exploration and research in Tianjin is at a relatively advanced stage, so the risk in well drilling is low. For the present, the risk involved in well drilling is assessed in the feasibility study for drilling. It is considered as a potential disadvantage and dealt with by sensitivity analysis, thus the investment risk is reduced. The investor may ask the geothermal well's designer and the drilling company to take the risk. In today's China, the risk in most situations is shared between the investor and the drilling company. The details can be laid down in the contract.

8.2 The risk of declining production

This can be caused by several factors: The reservoir's permeability and recharge ability may be too highly evaluated. The discharge period of the new well may be too short or there may be misjudgement in the discharge estimations. Too many geothermal wells may be located in a certain area, the produced quantity becomes too large, and/or there are not enough injection wells. Cold groundwater may flood the system and cool the reservoir and thus create a reservoir pressure decline. So the utilization of a geothermal reservoir carries a significant risk in low- to medium-temperature geothermal development, and the assessment of resource size and production capacity is a critical part of any geothermal development project.

A complete understanding of the reservoir can only be obtained by withdrawing fluids from the reservoir over a sustained period, with subsequent computer modelling to assess the performance in the future. It can take several years of production before the reservoir performance can be gauged with confidence since the reservoir rate of decline is frequently exponential in nature with a high initial rate of decline. But because of a lack of long-term production data at the feasibility stage, resource assessments mainly rely on the extent of the reservoir as defined by drilling and geophysical anomalies, and knowledge of reservoir fluid temperatures. Such assessments may involve large errors.

Too fast resource depletion is the primary problem in Tianjin's geothermal fields. It has been shown that the risk could be reduced by improving management and intensifying the relevant law. The risk of pressure decline can be mitigated by conservatively estimating the rate of heat extraction in comparison to the estimated resource capacity. In the fields already developed, regular long-term monitoring of production data (engineering and scientific data) has been undertaken, accompanied by simulation studies to better predict the future behaviour of the reservoir in order to maximize production and minimize premature reservoir failure. The effect of reinjection has been considered too.

8.3 The risk of contaminating drinking water

The fresh water aquifers are located above the geothermal reservoirs, thus drilling operations may lead to groundwater contamination. Drilling fluids are usually the greatest potential threat to the environment. The drilling process damages the environment, as the deep well will unavoidably intersect some underground water aquifers and there is a possibility of contamination by the drilling fluids. For the purpose of protecting shallow groundwater, both production and injection wells should be cemented and lined with proper casing, and solid waste from the drilling operation should be deposited in suitably controlled landfills.

Moreover, the geothermal wastewater contains high concentrations of some undesirable chemical constituents. Therefore direct release may be the cause of chemical pollution in the shallow layer water.

8.4 The risk of management and market

The Tianjin municipality has paid great attention to geothermal management in recent years. Tianjin's drilling cost and well operation costs are fairly stable. A large number of residences are multi-users in a pipe network district heating system. The market situation is unlikely to change and the risk is very small. The thermal water sales price, management and regulatory, interest and inflation rate are relatively stable, and the risk is very small. Compared to district heating, the risk inherent in comprehensive utilization is quite big. The extent of the risk depends on the saleability of the products but is not geothermal in nature.

The risks from drilling investment and resources sustainability are considerable. Early stages of projects should be handled with great care and the administration of resources strengthened to cut down the risks. The heating industry employing deep low- to medium-temperature geothermal resources requires high investment since stable thermal value and market output may be high. Tianjin's requirements for district heating constitute a large market and a high rate of increase, so there is more investment opportunity. It is still possible to invest and get benefits from regions with geothermal anomalies, as has been proven by Tianjin practice. Surface disposal causes thermal pollution. To reduce disposal or injection temperature and raise geothermal utilization efficiency, the applied technology of giant water source heat pumps should be applied more extensively in the future. Reinjection is the best solution to disposal of excess heat, the injection wells should be gradually increased in number to cut down the risk of reservoir resource degradation in productive geothermal fields.

9. MONITORING

Careful and regular monitoring of geothermal reservoirs during production is an essential ingredient and an indispensable part of any successful management program. Data is obtained about production, water temperature, water chemistry of reservoirs and groundwater level through monitoring (Axelsson and Gunnlaugsson, 2000). If the understanding of a geothermal system is adequate, monitoring will enable changes in the reservoir to be seen in advance. Studies to better predict the future behaviour of the reservoir in order to maximize production and minimize premature reservoir decline should be carried out. Thus, it is important to establish a proper monitoring program for any geothermal reservoir being utilized.

9.1 Monitoring of groundwater changes

Monitoring of groundwater is significant for studies of the relationship between geothermal utilization and land subsidence. Direct discharge of effluent may cause chemical pollution in the shallow layer groundwater, exploitation of geothermal water in the shallow deposit layer and groundwater level will lead to a drop in groundwater level and therefore possibly cause land subsidence. By monitoring the groundwater level, temperature, and chemistry, the groundwater system changes can be detected and future problems avoided. There are several important chemical parameters that should be determined, such as pH, TDS, SO_4^{2-}, F^-, SiO_2 and nitrate. In addition, the determination of stable isotopes ^{18}O, d^2H, and tritium are also a must. Tianjin has already set up a fine monitoring network system for groundwater.

9.2 Monitoring of reservoir production, pressure, temperature and chemistry

Long-term monitoring of the geothermal reservoir is necessary for the sustainable development of a geothermal field. We can analyze its long-term production stability having obtained important data on a geothermal system's nature and properties. The main factors monitored in a reservoir are production, pressure, temperature and chemistry.

In Tianjin, monitoring data of the geothermal reservoir's dynamics has already been collected over 10 years and this data has provided the basis for scientific management. In 2003, a total of 200 geothermal wells (including reinjection wells) were monitored, with water level and temperature checked once to thrice monthly. Samples for chemical analysis were drawn from 93 typical wells covering all geothermal areas and reservoirs. Through the analysis of a large number of constituents, the reservoir response to long-term production has been established, and future trends have been predicted taking into account the effects of reinjection. Finally, annual reports have been prepared and used as a decision-making tool for geothermal administration.

9.3 Monitoring of land subsidence

Land subsidence is the lowering of the land-surface elevation due to changes that take place underground. Common causes of land subsidence from human activity are pumping water, oil, and gas from underground reservoirs. It has been observed in groundwater reservoirs and petroleum reservoirs in Tianjin. Subsidence has a number of implications for geothermal production and also other effects on the surrounding places. It is difficult to mitigate land subsidence, but it can be minimized by means of reinjection of the spent geothermal water back into the aquifer.

Ground subsidence can be gauged by repeated levelling using traditional optical survey techniques. Permanent survey marks (benchmarks) are installed on the ground or on permanent structures such as concrete pipeline supports. The elevation of these is then measured, relative to a base station outside the field, using standard 2nd or 3rd order techniques along closed loops. Temporary intermediate points are generally needed. In areas of a high subsidence rate (> 100 mm/yr), the levelling needs to be completed quickly to avoid introducing errors caused by ground movement between the start and closure of a loop. The frequency of surveys will depend on the rate of subsidence, the location of the subsidence area and gravity measurements.

10. PROMOTING GEOTHERMAL DEVELOPMENT

10.1 International financing

Lack of funds is one of the main barriers to geothermal development in Tianjin. It can be alleviated by the introduction of foreign capital. In fact, in the early 1980's, Tianjin municipal authority began to explore and develop geothermal energy with the help of the United Nations Development Programme (UNDP). The total investment for the geothermal exploration up to now is more than 8 million USD. In 1994, Tianjin obtained credits of about 2.78 million dollars from the Nordic Investment Bank (NIB) for use in Tanggu region geothermal projects.

Presently, fast macroeconomic development in China attracts foreign capital. Therefore, funding for environmental protection and geothermal projects can be obtained from host governments, international assistance agencies and foreign aid agencies, such as the World Bank Group, the United Nations Development Programme (UNDP), the Nordic Finance Group, the Global Environment Fund (GEF), the United Nations Environment Programme (UNEP), the Geothermal Energy Development Fund (GeoFund) and the Prototype Carbon Fund (PCF). These global funds currently seek to support initiatives in individual cities in China on urban environmental protection and management, "Clear Water, Blue Skies". Other studies include urban environmental management, the environmental impact of coal use, energy conservation, options in greenhouse gas emissions control, and biodiversity conservation, all of which have contributed to the development of geothermal projects and provided grants for them. Therefore, expanded international support for Tianjin's geothermal energy development is particularly important, as the government is beginning to adapt its economic development to a market system.

10.2 Advanced technologies and professional training

Although the technical development and the optimal use of the Tianjin geothermal resource make it a leader in China, there are still some problems to be solved, for example, in the fields of antisepsis, antiscale, heat reservoir system, reinjection technique, heat pumps, the management of geothermal fields and others. Tianjin should continue to strengthen geothermal development, cooperate with foreign countries, localities should seize the opportunity to attract domestic and foreign high technology, raise the geothermal utilization efficiency, and set up a geothermal heating industry to obtain environmental and economic benefits.

The largest potential use of geothermal energy is that of geothermal heat pumps (GHP). The GHP is the highest efficiency heating and cooling system in existence (Rybach, 2003). Although heat pump technology is already being applied, the scale and the scope are small. It should be more widely used by the geothermal community, and a service system set up.

The United Nations have participated in three geothermal training programmes (UNDP, UNESCO, UNU), located in New Zealand, Italy and Iceland. From 1979, many Chinese technicians, engineers and scientists have been trained and made contributions to geothermal development within China. By 2004, 58 graduates had taken part in specialized geothermal training in geological exploration, borehole geology, geophysical exploration, borehole geophysics, reservoir engineering, chemistry of thermal fluids, environmental studies, geothermal utilization, and drilling technology. It is important to continue to build up and strengthen groups of specialists for Chinese geothermal exploration and development.

10.3 Strengthening management

Though geothermal exploration has reached a high level in Tianjin, there are still many problems that need to be solved urgently. Because large profits can be made from developing geothermal energy, more and more companies have invested in drilling geothermal wells and producing geothermal water for space heating or other utilization. Most geothermal wells are concentrated in certain limited areas where space heating and potable water are in great demand. Some of the problems experienced are: the water level is receding too fast; the well owners produce geothermal water in the quantity they like with relatively low cost, discharging large quantities of waste, etc. There were about 255 geothermal wells in Tianjin by the end of 2003. Therefore, to mitigate this hazardous situation and achieve sustainable development of the geothermal resource, it is essential to strengthen management.

Tianjin's municipal government pays great attention to geothermal management and set up the Geothermal Management Division in 1994. As a special administrative agency dealing with geothermal resources, the division is responsible for the technical development and the optimal use scheme of geothermal resources in Tianjin (Dong, 2000). In recent years, projects have been carried out in the fields of geothermal utilization, reinjection, reservoir engineering, monitoring and digital systems of geothermal management, etc., under the supervision of the division. Meanwhile, the government has passed a series of laws and regulations, for the development and protection of geothermal resources, and rules and regulations were updated and put into force on July 1, 2004 (Li, 2004). Along with the strengthening of the geothermal industry, it is expected that some problems will be solved in the foreseeable future.

11. CONCLUSIONS

Environmental impact assessment (EIA) has become a fundamental instrument of policy in various countries around the world to achieve the objective of sustainable development. It is a truism that geothermal energy plays an important role in the development and environmental protection of the city. Therefore, it is desirable to attain sustainable development of the geothermal resources with the aid of EIA.

Tianjin is rich in low- to medium-temperature geothermal resources. The geothermal water is used for many purposes such as space heating. Compared to traditional energy resources, geothermal resources are competitive environmentally and economically. Environmental impacts of geothermal development in Tianjin include: impacts on groundwater systems, decline of water level, depletion of groundwater, land subsidence, thermal pollution, chemical contamination, gas emission, visual impact, noise, and corrosion. Negative impacts are minimal and temporary, and can be mitigated by effective methods.

In order to promote geothermal energy development and sustainable development in Tianjin, geothermal management should be strengthened and advanced technologies promoted. The geothermal resources should be protected from excessive exploitation and should be used and renewed rationally. Geothermal energy has great potential in Tianjin, and will play an important role in developing the local economy, enhancing environmental conditions, and serving the people with future energy.

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