

## Evaluation and analysis of underground brine resources in the southern coastal area of Laizhou Bay

M Tian<sup>1</sup>, H T Zhu<sup>2</sup>, J Feng<sup>1,3</sup> and Q S Zhao<sup>1</sup>

<sup>1</sup>Department of Environmental Science and Engineering, Qingdao University, Qingdao 266000, China

<sup>2</sup>Qingdao No.2 High School, Qingdao 266000, China

E-mail: qdufengjuan@126.com

**Abstract.** The southern coastal districts of Laizhou Bay are some of the most important areas for underground brine exploitation in Shandong Province. Recently, these areas have been gradually developed by the underground brine mining industry. Such economic interest has led to brine exploitation so that underground brine resources are running out. Based on this phenomenon, this study describes the supply, runoff and draining conditions of the area by collecting and organizing the background information of the studied area. Hydrogeological parameters are then calculated according to pumping tests, and the amount of sustainable resources in the coastal areas of the Southern Bank of Laizhou Bay are then calculated based on the uniform distribution of wells. Under the circumstances of underground brine mining, the exploitation potential of the underground brine is evaluated in accordance with the calculation results of exploitation quantum. Finally, suggestions are provided for the sustainable exploitation of underground brine in the area.

### 1. Introduction

Underground brine, one of the most accessible and exploited underground water resources, contains high-concentrations of Na and Cl ions and varying amounts of elements such as Br, I, K, Li, Mg, Ca, Sr, and Ba, with a mineralization exceeding 50 g/L. Underground brine has been widely-used in the salt, chemical, aerospace, and nuclear industries [1]. Its formation is primarily determined by natural geographical conditions and climatic characteristics.

Underground brine in the study area was formed in the late quaternary period and has become a massive metallogenic belt distributed along the contemporary coastal line [2]. The general mineralization varies from 50g/L to 150g/L, with the highest reaching 217g/L. Generally, the buried depth of the underground brine varies from 0m to 60m while the deepest ranges from 70 to 80m, including approximately four brine layer groups, which can be categorized as latent underground brine and pressurized underground brine. According to incomplete statistics, there are 228 mining enterprises which produce crude salt and bromine, more than 70 of which are located in Shouguang City and Hanting District, Weifang City. The gross area covers 189.79 km<sup>2</sup> with 7084 brine-producing wells, and the annual exploitation quantity is approximately equal to 2 9489.7 million m<sup>3</sup>/a, in addition to an annual crude-salt production of approximately 8.099 million tons and bromide production of 31.5 thousand tons. The overall production quantity of Shouguang City is ranked the highest in the world, producing enormous economic profits.



However, while environment-unfriendly development has brought considerable economic profit, over-exploitation leads to great disparity in exploitation quantity and recharge rate of underground brine. The amount of mined underground brine has increased in recent years, despite a simultaneous decrease in groundwater level which has forced underground brine production into a depression, resulting in huge impact to the geological and ecological environment of the area. Therefore, evaluating and analyzing the underground brine resources in the southern coastal area of Laizhou Bay can contribute to the protection and rational utilization of brine resources [3-5].

## 2. Hydrological and geological conditions of underground brine resources

### 2.1. The division of underground brine layers

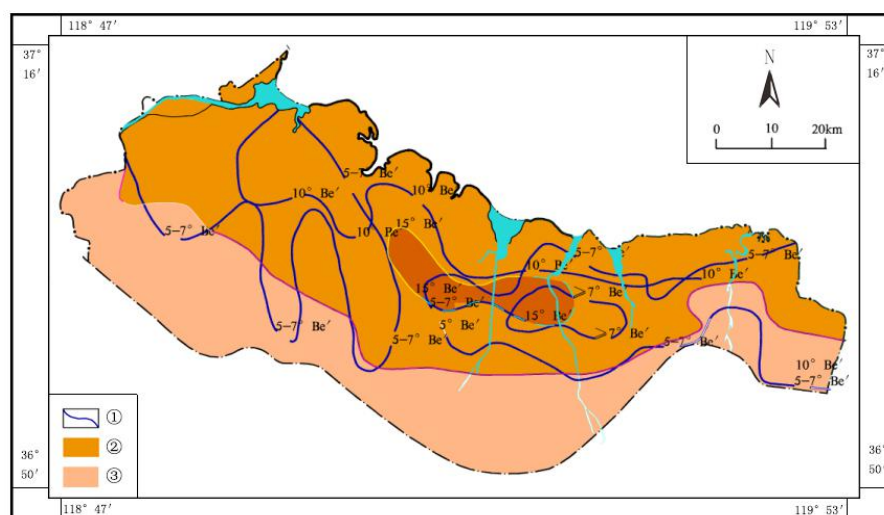
The phreatic and faint confined brine layer, as well as the unconfined and faint confined aquifer, is located in the Holocene marine sedimentary strata in the quaternary region. Due to the constant mining of underground brine, this aquifer only exists in areas with a buried groundwater depth less than 10 m.

Confined brine layers, located in the Pleistocene marine sedimentary strata in the Quaternary, are separately distributed throughout the entire area, as well as an impermeable layer of certain thickness located between the aquifer and the unconfined and faint confined aquifer above. In this region, the confined aquifer is the main brine layer, composed of two to four fairly stable brine layers in the coastal area north of Weifang and three fairly stable brine layers in Tushan, Laizhou. The buried depth of the confined brine layers in the north coastal district of Weifang is the shallowest and thinnest.

There is a compact aquifuge with a stable horizon located between the phreatic and faint confined brine layer and the unconfined and confined aquifer; the permeability coefficient of the aquifuge varies from  $2.5 \times 10^{-7}$  to  $6.7 \times 10^{-7}$  cm/s, and exhibits good water isolating properties.

### 2.2. Distribution of underground brine layers

The underground brine resources in the study area are of particular zonation. To the west of Yangzi Town, Hanting District, the concentration of brine is low-high-low from the coast to inland, which indicates lower brine concentrations both near shore and far off-bank, and higher brine concentration in the middle region. To the east of Yangzi Town, Hanting District, the concentration of brine is high-low going from the coast to inland [6], which indicates a higher brine concentration near shore and lower brine concentrations far off-bank.



① Isoline of brine concentration ② Brine area ③ Salt-water area

**Figure 1.** Brine concentration distribution.

Lower brine concentration near shore is frequently affected by tidal action. This area is approximately 10km wide, and the brine concentration varies from approximately  $5^{\circ}\text{Be}'$  ( $^{\circ}\text{Be}'$  is used

to denote the concentration of solution) to  $10^\circ\text{Be}'$ . The higher concentration area in the middle is roughly equivalent to the position of the 2.5m above sea level and varies from 10km to 20km in width. This area is generally unaffected by tidal action except for the equinoctial circle spring tide every month or year. Brine in this area exhibits a high and stable concentration, which generally ranges from  $10^\circ\text{Be}'$  to  $15^\circ\text{Be}'$  with a maximum value of  $17.5^\circ\text{Be}'$ . The area of lower brine concentration far off-bank is farther away from the coast, and ranges from 5km to 10km in width. This area is mostly unaffected by seawater but is affected fresh water coming from land and meteoric water. The brine concentration ranges from  $5^\circ\text{Be}'$  to  $10^\circ\text{Be}'$  and gradually changes into saltwater with a concentration less than  $5^\circ\text{Be}'$ . Underground brine in the studied areas is distributed along the Xiaoqing River and Sha River. This area is parallel to the coast and distributed in a northwest-to-southeast direction, and is located 75km to 90km EW-trending, and from 6km to 20km NS-trending. The total area is approximately  $1348.48\text{km}^2$ .

### 2.3. Hydrological and geological characteristics

**2.3.1. Recharge, runoff and drainage.** The recharge of the brine in this area is accomplished by artificial recharge. Seawater flows through artificial saving pools and is poured vertically into the shallow brine layer. The runoff of natural brine is primarily caused by production activities. In the brine extraction area, when a large amount of mined brine changes the brine level and forms a cone of depression, brine around the mining area or peripheral brine will runoff into the mining area. Brine, seawater and the surrounding saltwater is basically in dynamic equilibrium with slow runoff in areas where brine is conserved, such as Wudi, the Jiaozhou Bay coast, etc. [7, 8]. The main drainage route natural brine is artificial exploitation, followed by evaporation discharge, which concentrate the brine concentrated allow infiltration of atmospheric precipitation to contribute to the dilution of natural brine.

**2.3.2. Water abundance.** Experimental pumping tests were conducted on mining wells in salt fields. Results indicate that when drawdown ranges from approximately 3.3m to 15.0m, water outflow from one certain well varies from  $11.72\text{m}^3/\text{d.m}$  to  $255.68\text{m}^3/\text{d.m}$ , indicating that water abundance is medium to good. The results also indicate that the coefficient of permeability ranges from 0.85m/d to 13.94m/d, and that the radius of influence ranges from 31.85m to 172.49m. Units-inflow of the brine layer increases, and the water abundance improves from west to east.

**2.3.3. Characteristics of water level dynamic.** According to underground brine statistics released by the geological environment monitoring station in Weifang, the level of brine gradually decreased as the exploitation quantity of brine increased. Overall, the trend decreased annually. From 1991 to 2005, the water level of the brine decreased slowly with a rate of 0.13m/a. After 2005, due to increased prices of crude salt and bromine, a substantial increase of the exploitation quantity of brine resources occurred which, combined with the influence of brine exploitation in other regions, resulted in a water level decrease of 1.39m/a. This indicates that brine resources are limited and lack the ability to recharge. Therefore, long-term exploitation will certainly cause the brine weater level to decrease [9].

## 3. Evaluation of underground brine resources

### 3.1. Exploitable amount of underground brine resources

Assuming that the group well pumps do not impact a single well, the exploitable amount of underground brine in the study area can be estimated using the method of uniform distribution of wells [10] and the exploitable amount of underground brine in the entire area can be calculated based on the theory of unsteady flow, according to the following equation (1), (2), (3), (4), (5), we could calculated the exploitable amount of underground brine resource [11, 12].

$$Q_z = NQ_d t \quad (1)$$

$$N = \frac{F}{D^2} \quad (2)$$

$$Q_d = \frac{Ts}{0.183 \lg \frac{2.25at}{r_0^2}} \quad (3)$$

$$s = H_0 - H \quad (4)$$

$$a = \frac{T}{\mu} \quad (5)$$

where  $Q_z$  is the exploitable amount of underground brine ( $\text{m}^3/\text{d}$ ),  $N$  is the well spacing,  $Q_d$  is the water yield of a single well ( $\text{m}^3/\text{d}$ ),  $t$  is the time elapsed since pumping began ( $\text{d}$ ),  $F$  is the division area ( $\text{m}^2$ ),  $T$  is the transmissibility coefficient ( $\text{m}^2/\text{d}$ ),  $s$  is the drawdown in a piezometer measured ( $\text{m}$ ),  $a$  is the hydraulic conductivity coefficient ( $\text{m}^2/\text{d}$ ),  $r_0$  is the distance from the axis of the piezometer wells ( $\text{m}$ ),  $\mu$  is the specific yield,  $H_0$  is the initial head, and  $H$  is the hydraulic head;

The calculated parameters are substituted into the equation to obtain different beneficial components in brine; the results ranking from highest to lowest are as follows: NaCl,  $\text{MgCl}_2$ ,  $\text{MgSO}_4$ ,  $\text{CaSO}_4$ , KCl, and Br, and their respective exploitable amounts are  $1653.6 \times 10^4 \text{t/a}$ ,  $285.7 \times 10^4 \text{t/a}$ ,  $126.6 \times 10^4 \text{t/a}$ ,  $80 \times 10^4 \text{t/a}$ ,  $16.6 \times 10^4 \text{t/a}$  and  $4.254 \times 10^4 \text{t/a}$ . According to the brine concentration partition data, the largest exploitable amount of brine resources is greater than  $10^\circ \text{Be}'$ , which also contains the largest useful set of components. The results are shown in table 1 and table 2. In addition, the exploitation quantity and the extraction of useful components in Shouguang based on the division of administration are much greater than those indicated in the other three cities, followed by Changyi, Hanting and laizhou. Laizhou has the smallest exploitation quantity among the studied cities.

**Table 1.** Exploitable amount of resources in different concentrations.

Concentration	Brine $10^4 \text{m}^3/\text{a}$	NaCl $10^4 \text{t/a}$	Br $10^4 \text{t/a}$	$\text{MgCl}_2$ $10^4 \text{t/a}$	$\text{MgSO}_4$ $10^4 \text{t/a}$	$\text{CaSO}_4$ $10^4 \text{t/a}$	KCl $10^4 \text{t/a}$
$5 \sim \leq 7^\circ \text{Be}'$	5243.5	239.2	0.8	49	17.2	15	3.2
$7 \sim 10^\circ \text{Be}'$	7518.4	561.2	1.2	91.3	41.6	29.6	8.2
$\geq 10^\circ \text{Be}'$	8357.7	853.2	2.2	145.4	67.8	35.4	16.6
Sum	21118.8	1653.6	4.2	285.7	126.6	80	28

**Table 2.** Exploitable amount of resources at different distances.

Exploitation amount ( $10^4 \text{t}$ )	NaCl	Br	$\text{MgCl}_2$	$\text{MgSO}_4$	$\text{CaSO}_4$	KCl
Shouguang	874.0	2.3	157.3	66.4	51.2	12.7
Hanting	255.6	0.6	43.0	18.6	8.6	4.6
Changyi	444.7	1.1	71.1	35.9	16.6	8.7
Laizhou	79.3	0.2	14.3	5.7	3.6	2.0

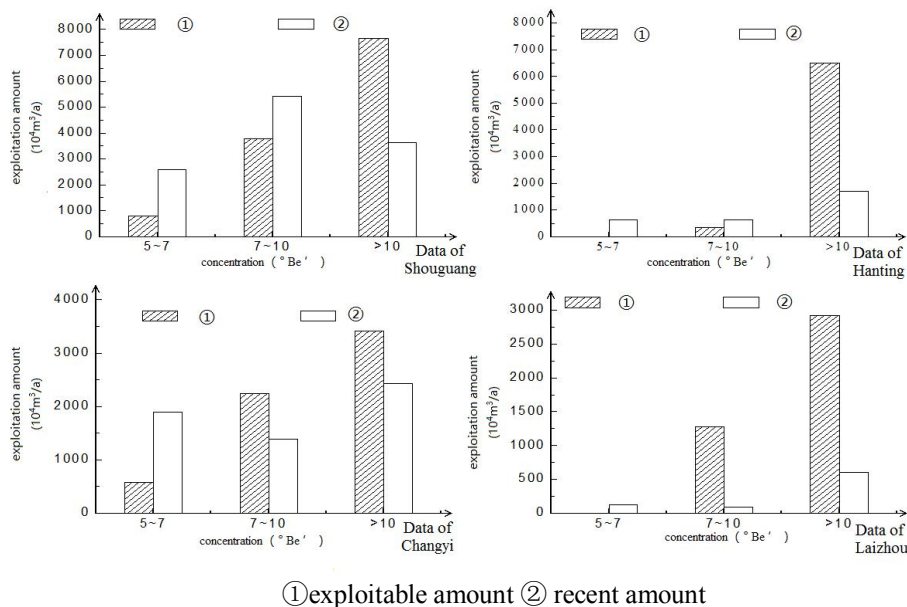
### 3.2. Exploitation potential of underground brine resources

The present study indicated a number of factors in brine exploitation including the over exploitation of brine so that the underground brine level decreases at an unexpected speed. It is necessary to protect the environment and sustain resources evaluate the potential of underground brine. Brine resources are evaluated by analyzing the exploitation potential coefficient, calculated as equation (6):

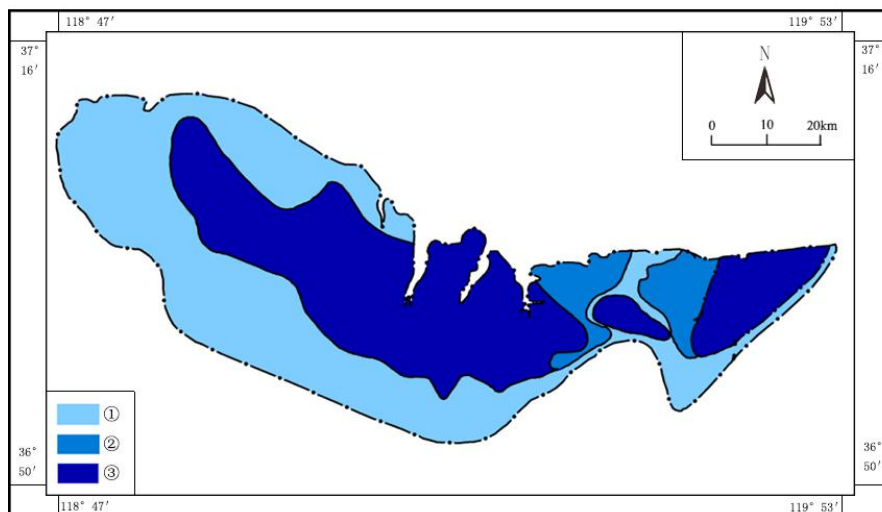
$$P = \frac{Q_z}{Q_k} \quad (6)$$

where  $P$  is the exploitation potential coefficient,  $Q_z$  is the exploitable amount of underground brine ( $10^4\text{m}^3/\text{a}$ ), and  $Q_k$  is present amount of underground brine ( $10^4\text{m}^3/\text{a}$ ).

According to the present level of brine resource exploitation, the exploitation potential coefficient in each division is calculated and compared to the standard value. The results are shown in figure 2. The exploitable amount of brine resources is  $21118.8 \times 10^4\text{m}^3$ , and the present amount is  $29489.7 \times 10^4\text{m}^3/\text{a}$ , with an average exploitation potential coefficient of 0.91.



**Figure 2.** Exploitable amount and present exploited amount in each area.



①Potential region( $P \geq 1.2$ ) ②Equilibrium region of exploitation and recharge( $0.8 < P < 1.2$ ) ③Over-exploitation region( $P < 0.8$ )

**Figure 3.** Distribution of exploitation potential.

However, the different exploitation situation result in over-exploitation region in some areas, especially the regions brine concentrations exceeding  $10^\circ\text{Be}'$ . The over-exploitation is  $14501.9 \times 10^4\text{m}^3/\text{a}$ . Due to over-exploitation, regional underground brine areas have formed a cone of depression. Based on the exploitation potential coefficient of underground water, the study area can be divided into a potential region, an equilibrium region of exploitation and recharge, and an over-exploited region. The results are shown in Figure 3.

#### 4. Summary

Results indicate that underground brine resources in the study area are being exploited on a large scale with some minor areas of overexploitation, based on calculation and analysis, but the area as a whole maintains the balance of discharge and recharge, indicating that the area still possesses comparatively tremendous exploitable capacity. Results indicate that mining enterprises around the study area are implementing an irrational mining policy and potential resources in some areas that have not been fully utilized. Some suggestions are described below.

According to the evaluation of the exploitation potential of underground brine resources in the studied area, mining enterprises should adjust exploitation areas reasonably, e.g., by lowering the upper limit of brine extraction in over-mined areas and enlarging the mining capacity in the regions with abundant mining potential.

Comprehensive dynamic e-systems for the monitoring of underground brine are required to monitor the long-term water level, exploitation quantity, and water quality of underground brine, and more accurate calculations should be performed to study hydrogeology parameters, which are necessary to provide more scientific support for the exploration and development of underground brine in this region.

Appropriate funds should be invested to improve current exploitation and extraction technology in order to conduct the production mode so that mining enterprises reap greater profits by increasing exploitation quantity and utilizing the efficiency of brine resources, thus reducing the cost to utilize the limited resources fully and sustainably, especially for  $\text{MgCl}_2$ ,  $\text{MgSO}_4$ ,  $\text{CaSO}_4$  and  $\text{KCl}$ .

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