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Sustainable Yield of Hot Springs in Shandong Peninsula, China

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ABSTRACT

Shandong Peninsula, located on the eastern coast of China between Beijing and Shanghai, is one of the regions rich in natural hot springs. Most of the hot springs are distributed in the Jiaobei uplift and Jiaonan-Weihai orogenic belt, with fractured geothermal reservoirs controlled by the deep and large faults, as well as convective heat sources. Fifteen natural hot springs were found and of which the temperatures range from 49.7 to 90 °C, TDS range from 0.41 to 16.62 g/L and natural flow rates range from 1.79 to 41.42 m^3/h. Their total production is about 2.11 million in 2008. Due to large-scale exploitation of geothermal water; the water levels have been declining in the last 20 years. Most of the hot springs dry up when exploitation is increased during winter seasons, and only part of them can return to being artesian during the rainy season when the exploitation is decreased.

Corresponding to the geothermal water level decrease, the colder surface water and shallow groundwater infiltrate and recharge the the geothermal water, which causes the drop in geothermal water temperature.

Yujiatang, one of the 15 hot springs is taken as an example in this paper to explore the sustainable yield. Based on the geological and hydrogeological conditions, the geothermal reservoir conceptual model of Yujiatang geothermal field is formulated, and the numerical model is developed. Finally, the sustainable yield of the Yujiatang geothermal field is evaluated with the prerequisites of its water level being higher than the minimum allowable water level and the water temperature higher than the minimum allowable temperature.

1. INTRODUCTION

Shandong Peninsula is one of the regions rich in geothermal resources in East China, with fractured geothermal reservoirs controlled by the deep and large faults, as well as convective heat sources. So far, 15 natural hot springs, accounting for 78% of the total in Shandong Province, were found with a total production of 2.11 million m^3 in 2008. These springs are distributed over 8 cities, including Qingdao, Weihai and Yantai. Due to the large-scale exploitation of geothermal water, a decrease in water levels and temperatures has occurred. In order to solve these problems, it is inevitable to investigate the sustainable yield of hot springs.

2. GENERAL SITUATION OF THE HOT SPRING IN SHANDONG PENINSULA

2.1 Distribution and Outlet

The strata of Shandong Peninsula are intrusive rocks, metamorphic rocks, cretaceous sediments, volcanic accumulation and loose deposits of the Quaternary period. This area, with a complex structure, is located in the Ludong uplift. Structures with different properties formed in various geologic periods. The mutual superposition, mutual cut and mutual restriction of them caused the formation of a tectonic framework in Shandong Peninsula with NNE trending, NE trending and EW trending.

As shown in Figure 1, geothermal resources in Shandong Peninsula are mainly distributed on the east side of the Qingdao-Laizhou line. The natural hot springs occur in the middle-east part of the Jiaobei uplift and Jiaonan-Weihai orogenic belt (Weihai uplift and east margin of Jiaolai depression).

All the hot springs flow out in points formed at the cross positions of the structures in which the fracture belt provides runoff passages from water infiltration towards the outlet. The strikes of faults that controlled the formation of hot springs occur in four types: NE, NW, NNE and NNW.

Without providing runoff channels, tectonism also leads to low terrain, in which the hot springs can easily flow out. It can be seen from Table 1 that hot springs appear at the low-lying discharge areas, nearby rivers, valleys and coasts. The Quaternary deposition thicknesses are no more than 20m at the hot spring locations. Under natural conditions, the water level of geothermal water is higher than the elevation of the ground surface, the hot water rises through the Quaternary aquifer and then overflows.

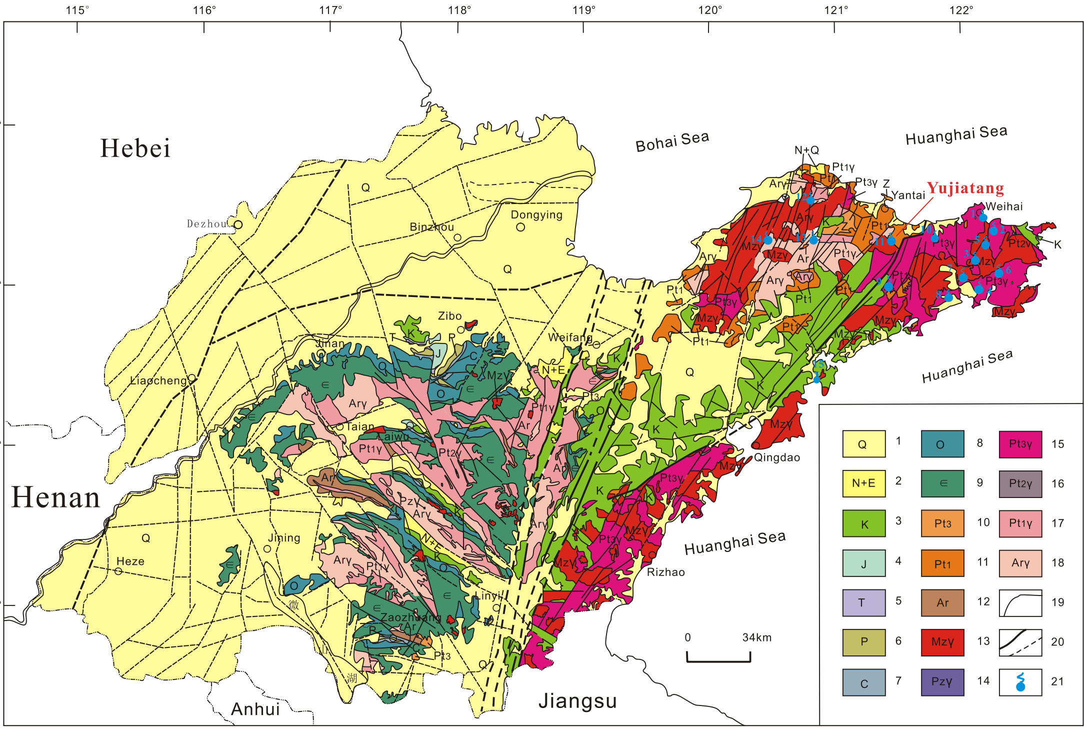

Figure 1: Hot springs Distribution in Shandong Peninsula

(1-Quaternary, 2-Paleogene+Neogene, 3-Cretaceous, 4-Jurassic, 5-Triassic, 6-Permian, 7-Carboniferous, 8-Ordovician, 9-Cambrian, 10-Neoproterozoic, 11-Palaeoproterozoic, 12-Archaean, 13-Mesozoic intrusive rock, 14-Paleozoic intrusive rock, 15- Neoproterozoic intrusive rock, 16- Mesoproterozoic intrusive rock, 17- Paleoproterozoic intrusive rock, 18-Archaean intrusive rock, 19- Geological boundaries, 20-Faults, 21-Hot springs)

Table1: General Situation of hot springs in Shandong Peninsula

No.	Name	Location	Landform	Bedrock and fault strike	Temperature(°C)	Elevation(m)
1	Baoquantang	Donghai coast	coastal beach	Granite; NW,EW,NE	69	2.6
2	Wenquantang	west of Wenquantang village, Wenquan town	riverbed	Granite; NE,EW	52	25
3	Qilitang	Qilitang village, Wencheng town	river terraces	Granite; NE,NW,EW	66	28
4	Tangcuntang	Southwest of Tangcundianzicun village, Zhengjiachan town	river terraces	Granite; NE,NW	55	13
5	Hongshuilantang	west of Yangquan village, Caomiaozi town	floodplain	Granite; NE,NW	72	66.83
6	Huleitang	Beitangxi village,Gaocun town	river terraces	Gneiss; NE,EW	66	15.48
7	Dayingtang	northeast of Daying village, Puji town	riverbed	Granite; NW,NE	69	15.3
8	Xiaotang	Xiaotang village, Fengjia town	river terraces	Granite; NW,NE	65	27
9	Xingcuntang	Xing village, Yazi town	river terraces	Granite; NW,NE	29.5	52
10	Longquantang	Longquantang village, Longquan town	river terraces	Monzonite granite; NE,NW	62	20
11	Yujiatang	north of Yujiatang village, Gaoling town	floodplain	Granite; EW,NW	65.4	42
12	Wenshitang	Wenshitang village, cunLiji town	river terraces	monzonite granite; NNE,NWW	61.8	10
13	Aishantang	Aishantang village, Songshan town	gully	Granodiorite; NNE,NNW	49.7	148
14	Tangdong	Tanghou village, Chengguan town	river terraces	Granite; NNE,NNW,EW	87.7	40
15	Jimodong	East of Wenquan village, Wenquan town	river terraces	The Mesozoic sandstone and intrusive rock; NE,NNW	90.0	25

2.2 Geothermal Reservoir Characters

The fractured geothermal reservoirs of Shandong Peninsula are all in a belt shape and the reservoir rocks are Mesozoic granitic rock and Early Cambrian Metamorphic felsic rock. The conceptual model of these fractured geothermal reservoirs is shown in Figure 2. Precipitation infiltrates and is heated up when it penetrates deep into the system, then flows up to shallow aquifer and flows out as a hot spring from a suitable place at the ground surface.

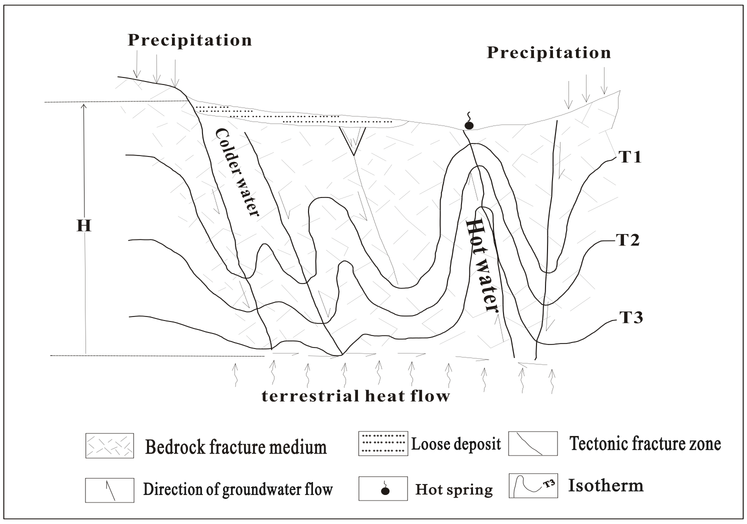

Figure 2: Geothermal reservoir conceptual model of Shandong Peninsula (Suo LT., 2014)

Table 2: Geothermal reservoir characters of Hot springs in Shandong Peninsula

Spring name	flow rate(L/s)	geothermal reservoir area (km^2)	geothermal reservoir thickness(m)
Baoquantang	2.00	0.14	100
Wenquantang	2.56	0.43	61.4
Hongshuilantang	0.87	0.22	47
Qilitang	11.50	0.090	40
Huleitang	0.57	0.046	74
Dayingtang	0.50	0.049	90
Tangcuntang	1.90	0.051	100
Xiaotang	0.68	0.040	66
Xingcuntang	1.81	0.043	75
Longquantang	1.50	0.25	250
Yujiatang	1.16	0.25	250
Wenshitang	4.63	0.15	200
Aishantang	5.21	0.20	380
Tangdong	3.18	0.36	220
Jimodong	3.18	0.50	200

The temperatures of the hot springs range from 49.7℃ to 90℃, except for Xingcuntang with a temperature of 29.5℃ (Table 1). The geothermal reservoir areas have been determined with shallow geothermal gradient measurements (1m), as well as with tectonic characters, geophysical prospecting and existing hot and cold water wells distribution. The geothermal reservoir thicknesses have been determined by drilling and geophysical prospecting together with interpreting geological settings and geochemical data obtained earlier. The details of the geothermal reservoir characteristics of the hot springs are shown in Table 2. The geothermal fields, with distribution areas all less than $1km^2$, are mostly in shapes of belts or ellipses. Their long axes are coincident with strikes of geothermal controlling faults, with the reservoir thicknesses varying from 40m to 380m. The 15 geothermal water systems, without obvious hydraulic connections, are in different hydrogeological settings and independent from each other. The natural flow rates of hot springs have large differences, with a maximum of 11.50 L/s for Qilitang and a minimum of 0.50 L/s for Dayingtang.

2.3 Water Geochemistry

Table 3 shows the chemical compositions of the hot spring water, which could be categorized into two types by TDS. One is of lower TDS (less than 1g/L) and higher pH around 8. The other kind is of higher TDS and the pH ranges from 6 to 7. The ion contents with lower TDS is rich in Na^+ as cation and HCO_3^- as anion, as well as having obviously a higher content of SO_4^{2-} (Figure 3). Some ions such as Cl^-, Na^+ and Ca^{2+} have a remarkable relationship with TDS. The higher the TDS the larger the concentration of these ions. Otherwise, ions like HCO_3^-, SO_4^{2-}, and Mg^{2+} have no close relationships with TDS (Figures 4 and 5).

From the water geothermal property of the hot spring waters, we can derive that the recharging of geothermal water in Shandong Peninsula is diversified, not only from sea water although most of the hot springs are located very close to the sea.

Table 3: The chemical compositions of hot spring water (Ji MR., 2014)

No.	name	main component content (mg/L)									pH	TDS(g/L)	Hydrochemistry type
		K	Na	Ca	Mg	Cl	SO_4	HCO_3	SiO_2	F			
1	Baoquantang	260	4450	1508	193	9925	360	70	88	2.6	7.4	16.62	Cl-Na·Ca
2	Wenquantang	27	458	58	12	499	87	197	79	7.3	7.9	1.24	Cl-Na
3	Qilitang	10	160	17	1.97	48	170	210	81	19	7.2	0.58	SO_4·HCO_3-Na
4	Tangcuntang	20	1480	879	8.7	3918	275	22	60	2.4	6.5	6.46	Cl-Na·Ca
5	Hongshuilantang	19	222	24	2.4	56	230	329	97	4	7.5	0.67	HCO_3·SO_4-Na
6	Huleitang	19	236	37	0.9	170	325	75	86	3.6	6.7	0.90	SO_4·CI-Na
7	Dayingtang	20	424	254	1.6	956	280	40	69	2.64	6.8	2.01	Cl-Na·Ca
8	Xiaotang	32	643	278	5.3	1368	210	55	63	2.56	6.9	2.61	Cl-Na·Ca
9	Xingcuntang	5.5	167	5.5	0.9	78	170	91	20	4.24	6.5	0.52	SO_4·CI-Na
10	Longquantang	3.9	131	7.9	0.8	33	88	169	69	12	8.4	0.41	HCO_3·SO_4-Na
11	Yujiatang	4.8	123	9.8	3.45	56	87	135	106	15.5	8.3	0.42	HCO_3·SO_4·Cl-Na
12	Wenshitang	13	377	38	6.37	92	335	574	118	4.4	7.8	1.21	HCO_3·SO_4-Na
13	Aishantang	6	205	15	0.65	77	122	305	72	2.4	8.1	0.62	HCO_3·SO_4-Na
14	Tangdong	75	1163	143	8.14	1999	127	144	104	4.8	7.6	3.68	Cl-Na
15	Jimodong	123	2255	921	13.7	4838	101	25	94	3.22		10.74	Cl-Na·Ca

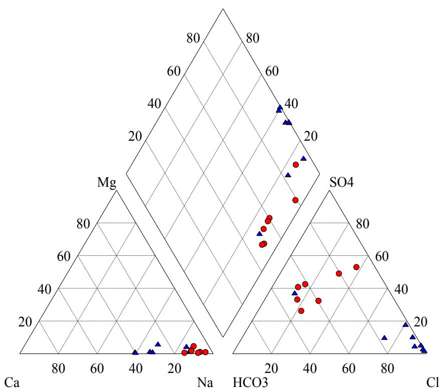

Figure 3: Piper diagram of water samples

(Red Symbol-TDS>1g/L, Blue Symbol-TDS<1g/L)

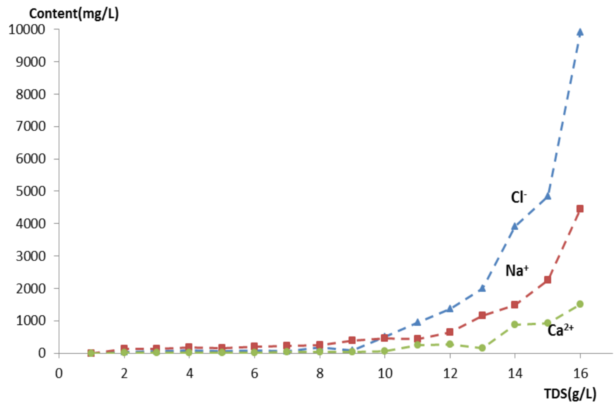

Figure 4: The relative diagram of Cl^-, Na^+, Ca^{2+} and TDS

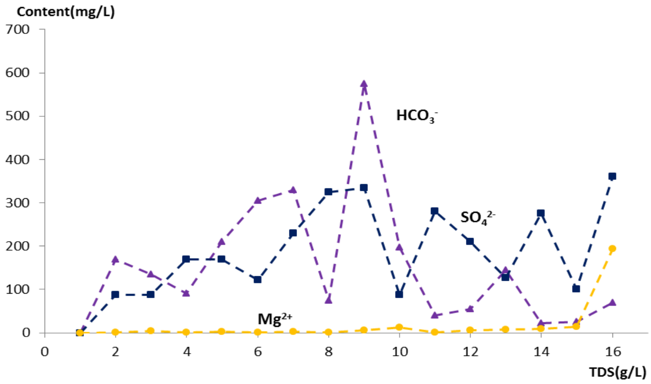

Figure 5: The relative diagram of HCO_3^-, SO_4^{2-}, Mg^{2+} and TDS

2.4 Natural Hot Water Level Dynamics

Initially, the 15 hot springs were artesian. However, due to the increase of artificial production over the last 20 years, geothermal water levels decreased significantly. Besides Xingcuntang, most of the hot springs became artesian seasonally, with only artesian flow during rainy seasons or periods with lower production.

For Yujiatang as an example, the relationship between water levels and temperatures is shown in Figures 6-7. The long-term observation data shows that the water level of Yujiatang is higher in warm seasons and lower during cold days, which was affected by precipitation and production. The water temperature is affected by water level changes. When water level drops, the water temperature decreases accordingly. The fitted equation between Temperature (T) and Water level depth (D) is evaluated as (Kang, 2013):

$$T = \exp(-0.035628 \times D) \times 58.33 \quad \text{(Regression coefficient, R-squared = 0.84)} \tag{1}$$

The maximum allowable drawdown can be calculated for a constraint temperature. Accordingly, geothermal sustainable yield should consider the allowable drawdown and use the geothermal resource reasonably.

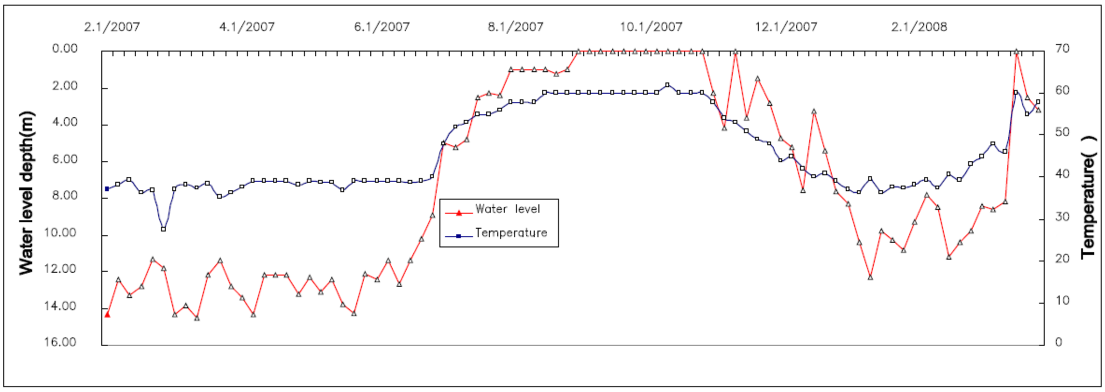

Figure 6: Effects of water level changes on temperatures in Yujiatang geothermal reservoir, Shandong Peninsula.

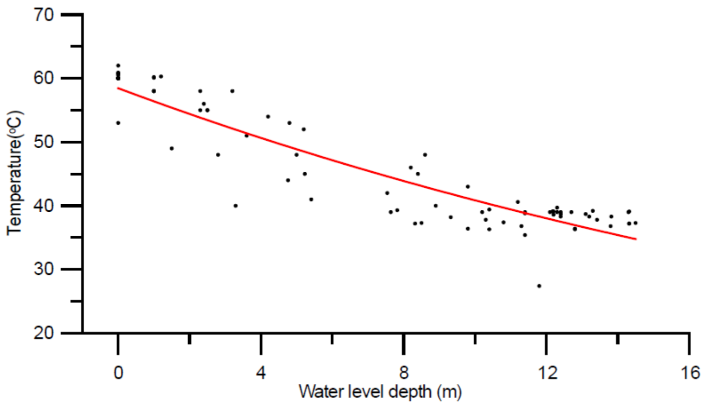

Figure 7: Correlation of temperatures with water levels in Yujiatang geothermal reservoir, Shandong Peninsula.

3. SUSTAINABLE YIELD EVALUATION OF HOT SPRINGS: A CASE STUDY OF YUJIATANG

3.1 Geothermal Reservoir Conceptual Model of Yujiatang

The Yujiatang hot spring flows out at the first river terrace west from Yujiatang village, Gaoling Twon, Muping District of Yantai City (Figure 1). Its outlet elevation is 42m. As shown in Figure 8, there are three decisive geothermal controlling faults. The main influencing faults are the F1 fault with the strike of 97°, and its secondary fault is F2. Both of them dips towards the South and their width are about 20m and 10m. The two faults are both water conducting and lead to water-rich areas to be formed. The F3 fault is water-resisting, and was cut off by F1. The reservoir medium is a structural fracture belt in granites of late Yanshan period in the Mesozoic. The geothermal field area is determined to be 0.25km^2 based on shallow geothermal gradient measurements (1m), and considering the geological settings.

The geothermal reservoir conceptual model of Yujiatang is shown in Figure 9. Precipitation infiltrates and is heated up, then flows up through the F1 fault to a shallow aquifer, mixing with colder water and then flowing out as hot spring.

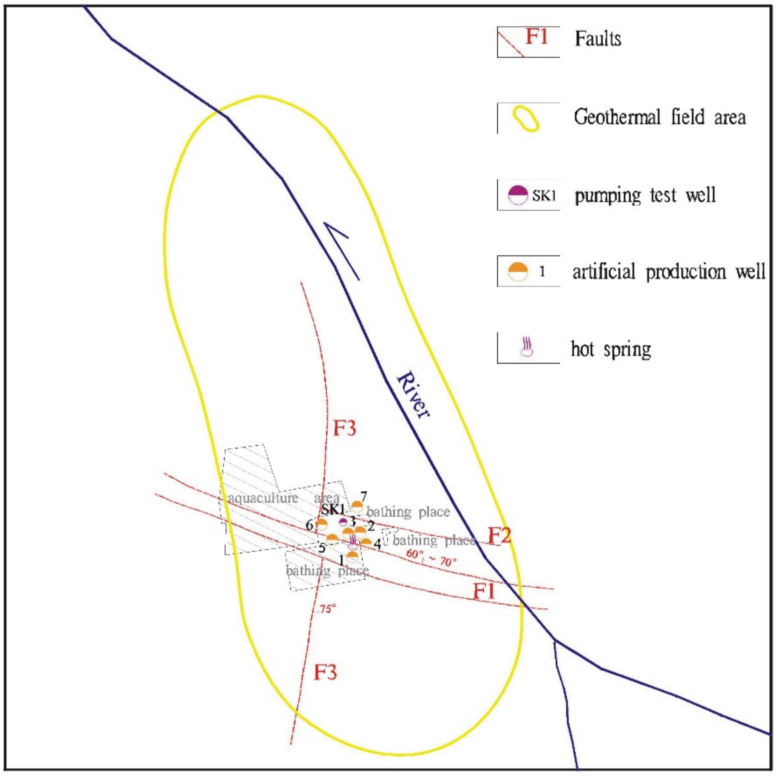

Figure 8: Situation of Yujiatang geothermal field (Figure extent is the model area determined to be 1×1 km^2)

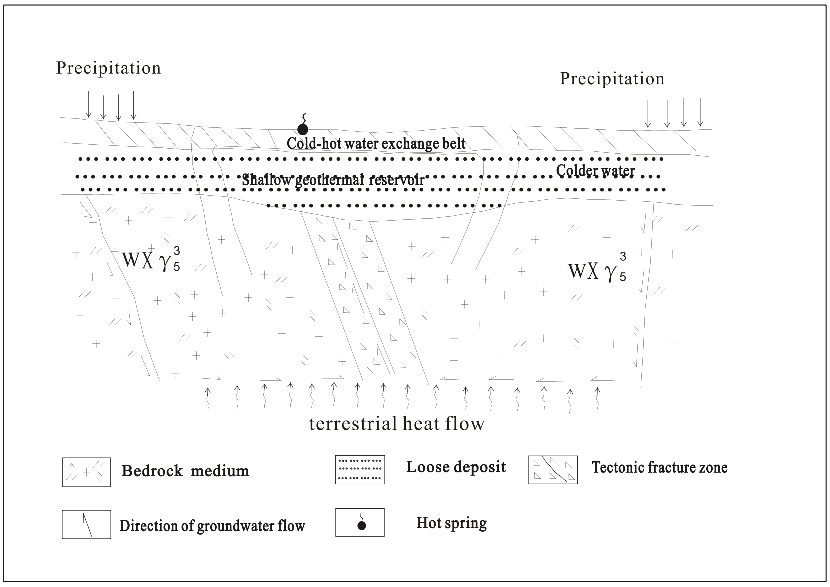

Figure 9: Geothermal reservoir conceptual model of Yujiatang

3.2 Numerical Model of Yujiatang Geothermal Field

3.2.1 Mathematical Model

Groundwater flow system can be described by the definite solution of the flowing differential equation:

$$\begin{cases} S\dfrac{\partial h}{\partial t} = \dfrac{\partial}{\partial x}\left(K_x\dfrac{\partial h}{\partial x}\right) + \dfrac{\partial}{\partial y}\left(K_y\dfrac{\partial h}{\partial y}\right) + \dfrac{\partial}{\partial z}\left(K_z\dfrac{\partial h}{\partial z}\right) + \varepsilon & x, y, z \in \Omega, t \geq 0 \\ \mu\dfrac{\partial h}{\partial t} = K_x\left(\dfrac{\partial h}{\partial x}\right)^2 + K_y\left(\dfrac{\partial h}{\partial y}\right)^2 + K_z\left(\dfrac{\partial h}{\partial z}\right)^2 - \dfrac{\partial h}{\partial z}\left(K_2 + p\right) & x, y, z \in \Gamma_0, t \geq 0 \\ h(x, y, z, t)\big|_{t=0} = h_0 & x, y, z \in \Omega, t \geq 0 \\ K_n\dfrac{\partial h}{\partial \vec{n}}\big|_{\Gamma_2} = q(x, y, t) & x, y, z \in \Gamma_1, t \geq 0 \end{cases} \quad (2)$$

In which: Ω-seepage area; h-water level(m); K_x, K_y, K_z -values of hydraulic conductivity(m/d) along the x, y, and z axis; K_n-values of hydraulic conductivity vertical the boundary(m/d); S-storage coefficient; μ- gravitational specific yield; ε-source term; h_0-initial water level(m); Γ_0-upper boundary; Γ_1-second kind boundary; *p*-recharge and evaporation(1/d); q- unit width discharge.

3.2.2 Numerical Model

The numerical simulation method is taken here to solve sustainable problems. A three-dimensional finite difference numerical model is developed and the discretization is shown in Figure 10. The recharge areas of the geothermal field are at a far distance and the ways of water transport are uncertain. In order to simplify and improve the precision of the model, the simulation area is set at 1km^2, with the Yujiatang geothermal field in the center. The model volume is 0.25 km^3 (1×1×0.25 km^3).

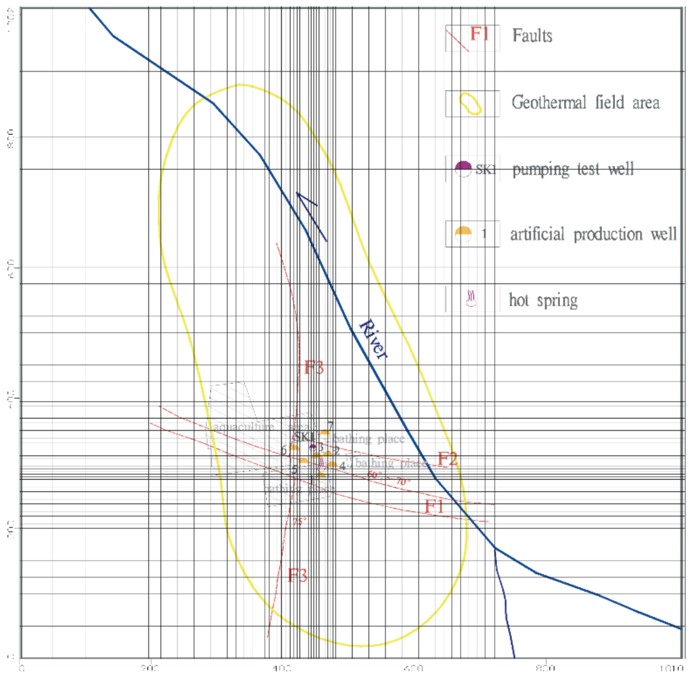

Figure 10: Plane discretization of the finite difference numerical model

The simulation time is about 76 hours, and observation data from pumping tests of well SK1 during this time period is taken for model identification.

The model is a one-layer structure. Geothermal water flows through fault passages from deep up into the shallow aquifer. The depth of the model is set at 250m, similar to the geothermal reservoir thickness.

Only the deep geothermal water is considered for recharge in the model; precipitation and rivers have less of an impact. Based on the principle of water balance, the annual average natural discharge rate of the hot spring avoiding the effect of artificial production is equal to the total recharge rate. The recharge rate is about 9.14L/s, obtained from a geothermal resources survey in Shandong Peninsula, 2008.

The discharge of the model is artificial production with a discharge rate of 9.20L/s. The hot spring is also discharged during the model period, with a rate of 1.16L/s and uses the Drain module to characterize.

3.2.3 Model Identification

We ran the model after entering the data required for constructing it. According to the pumping test data, we adjusted the hydrogeology parameter. When the calculated water level regime of SK1 is close to the observed water level, the model succeeded in computing the level of the well at each time step. The final calculated water level of SK1 compared with the observed one is shown in Figure 11. The model is considered to be calibrated and can be used by forecasting. After model identification, the hydraulic conductivity of the bedrock is 3.24×10^{-7} m/s and for the water conducting fault it is 5.21×10^{-6} m/s.

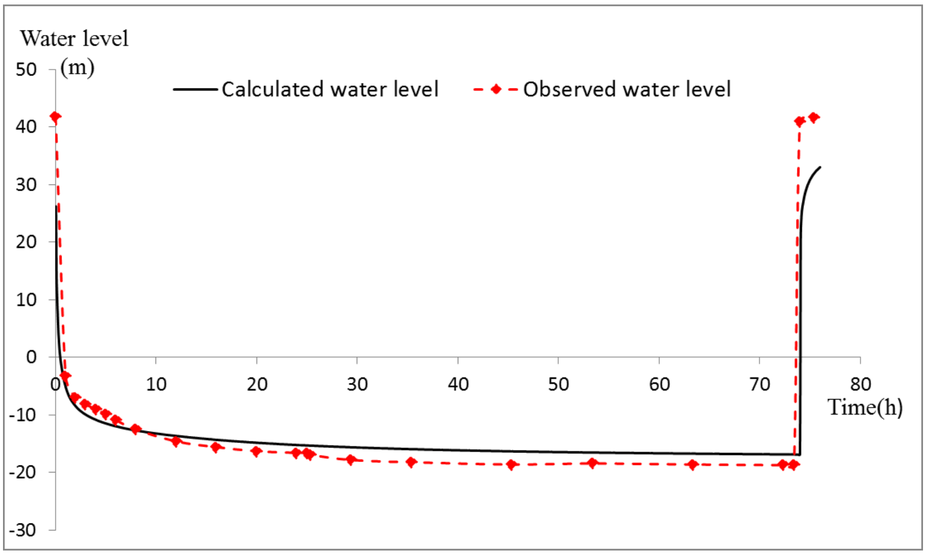

Figure 11: Comparison of calculated and measured water level elevation hydrographs in the SK1 observation well in the Yujiatang geothermal field

4. SUSTAINABLE YIELD FORECAST

In order to develop and utilize geothermal energy rationally, geothermal depletion caused by rapid water level drawdown should be avoided.

Considering the main restrictions for a sustainable yield in the Yujiatang geothermal field, the following requirements should be reached:

1. The water level should not decrease continuously but kept in dynamic balances.

2. Based on long-term observation data, the relationship between water level and temperature has been shown in Figures 6-7 and Equation 1. When the water level depth is deeper than 12 m, the water temperature is lower than 38°C, which decreases the utilization value remarkably. Accordingly, the maximum allowable water level depth is determined to be less than 12m.

4.1 The Forecast of Keeping Existing Production

The forecast time is set at two hydrological years (730 days). Recharge conditions and every hydrogeological parameter are the same as in the identified model above. There are two kinds of discharge ways. One is hot spring discharge which is determined as a Drain in the model, with a 42m discharge elevation. The other is artificial production through wells. The rates of production in the Yujiatang geothermal field change seasonally, because the main use locally of the geothermal water is bathing in winter days. The production rate is 9.84 L/s from December to March, 4.05 L/s from April to June and zero from July to November.

There are seven pumping areas locally and the lowest water level is shown by the observed well SK1 in the model. The elevation of the top of the SK1 well is 41.76m, so the allowable water level here should be higher than 29.76m.

The calculated water level changes of SK1 is shown in Figure 12. The water level changes with the production rate, and is kept in dynamic balance for two years. However, the minimum water level is about 23.8m which is lower than the allowable water level. That means the production rate from December to March (9.84 L/s) is overexploited, so it is necessary to decrease production rate.

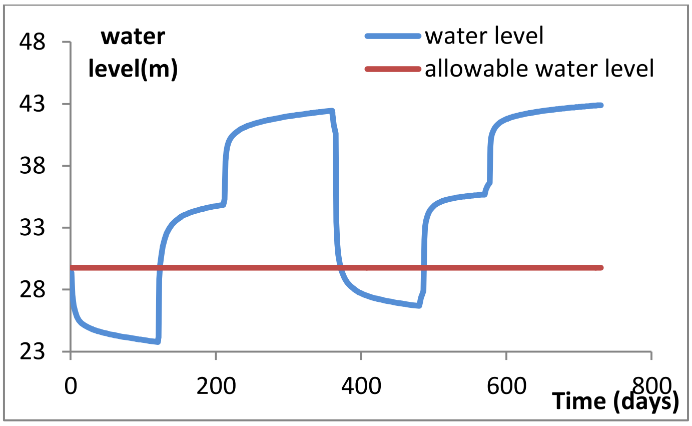

Figure 12: Forecast of water level changes of SK1 when keeping existing production (9.84 L/s)

4.2 The Forecast of Reducing Production

When decreasing the production to 7.41 L/s during the winter period from December to March and keeping the production unchanged in other months, the minimum water level of SK1 is about 29.87m, which is above the lowest allowable water level. Meanwhile, the water level keeps a dynamic balance during the two years, so the corresponding sustainable yield is evaluated to be 7.41 L/s (Figure 13).

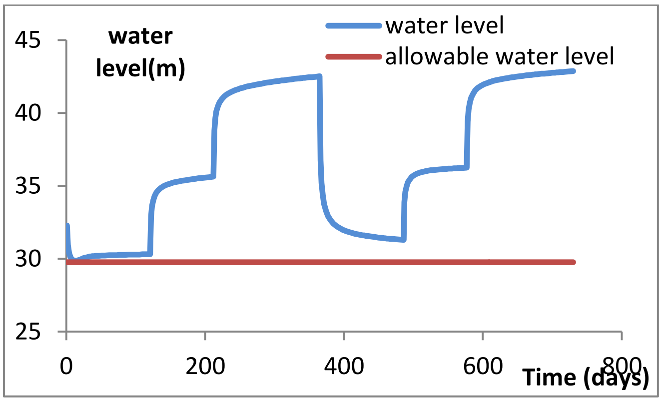

Figure 13: Prediction of water level variations of SK1 in response to the pumping rate of 7.41 L/s during the winter period

5. CONCLUSIONS

Hot springs in Shandong Peninsula are typical fractured geothermal reservoirs springs. Their generic temperature ranges from 49.7°C to 90°C, with the geothermal reservoir thickness ranging from 40 to 380m.

Based on properties of the hot spring water, we can derive that the resources of the geothermal water in Shandong Peninsula are diversified, not just from the sea water although most of the springs are located very close to the sea.

Due to the large-scale exploitation of geothermal water; the water levels have been declining in the last 20 years. Most of the hot springs dry up when exploitation is increased in winter seasons, only part of them can return to be artesian during the rainy season when the exploitation is decreased.

Corresponding to a geothermal water level decrease, the colder surface water and shallow groundwater infiltrate and recharge the geothermal water, which causes the drop in geothermal water temperature.

Yujiatang, one of the 15 hot springs is taken as an example in this paper to explore the sustainable yield. Based on the geological and hydrogeological settings, the geothermal reservoir conceptual model of Yujiatang geothermal field is formulated, and the numerical model is built up. Finally, the sustainable yield of the Yujiatang geothermal field is evaluated to be 7.41L/s with the prerequisites of its water level depth less than 12m and water temperature higher than 38°C.

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