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DEVELOPMENT AND VERIFICATION OF A METHOD TO FORECAST HOT SPRINGS INTERFERENCE DUE TO GEOTHERMAL POWER EXPLOITATION

Hiroyuki Tokita[1], Hiroshi Takagi[1], Yumi Kiyota[1], Koji. Matsuda[1], Hideki Hatanaka[1], Kanichi Shimada [2], Hirofumi Inuyama [3], Roger Young [4], Larry F. Bayrante[5], Oliver T. Jordan[5], Jesus Reymundo M. Salera[5] and Francis Edward B Bayon [5]
[1] West Japan Engineering Consultants, Inc. , 1-82, 2-Chome, Watanabe-dori, Chuo-ku, Fukuoka 810-0004, Japan
[2] New Energy and Industrial Technology Development Organization (NEDO), 1-1, 3-Chome, Higashi-Ikebukuro, Toshima-ku, Tokyo 170-6028, Japan
[3] New Energy Foundation (NEF), 3-6, Kioi-Cho, Chiyoda-ku, Tokyo 102-0094, Japan
[4] Industrial Research Limited (IRL), Gracefield Rd PO Box 31-310, Lower Hutt, New Zealand
[5] Philippine National Oil Company – Energy Development Corporation (PNOC-EDC), Merritt Road, Fort Bonifacio 1200, Makati City, the Philippines

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ABSTRACT

When proposing a geothermal power development, it is extremely important in terms of environmental conservation to forecast the possible influence of geothermal power exploitation on the surrounding hot springs. For mutual understanding, cooperation, and agreement between developers and hot spring owners as well as environmentalists, the environmental measures to conserve hot springs based on scientific study are particularly required in Japan, where hot springs represent important sightseeing resources. As such, The New Energy Foundation (NEF) has endeavored to develop a method to predict the influence of geothermal exploitation on the surrounding hot springs, by applying and modifying a method taken from geological, geochemical and reservoir engineering approaches. The procedure consists of two steps. First, based on a large scale conceptual model, the possibility of interference on hot springs is qualitatively assessed from the view points of the structural setting of the model and of the fluid flow connection between the geothermal reservoir and hot springs. The former is evaluated from geological analysis and the latter is derived from the similarity of origin and mixing of fluids, which are determined by geochemical analysis. Then, a quantitative estimation of the influence on hot springs is calculated by numerical simulation taking the exploitation scenarios into account.

In order to assure the reliability of the forecasting method, verification studies were conducted using two model fields: the Wairakei geothermal field in New Zealand and the Palinpinon geothermal field in the Philippines. Both fields had experienced decline of water tables and changes in the concentration of chemical components of thermal water at some surrounding hot springs after the exploitation commenced. In these verification studies, we made conceptual and numerical reservoir models, including hot springs, using limited data obtained only during the investigation stage. Then, we attempt to predict the above changes in surrounding hot springs after the geothermal exploitation. We succeeded in both qualitatively and quantitatively predicting the tendency of actual changes in the hot springs, which means that the forecasting method is effective. Based on the verification studies, we distinguished the differences between affected and unaffected types of hot spring aquifers. It is expected that the forecasting method will contribute to environmental conservation in geothermal exploitation.

1. INTRODUCTION

According to the 1998 annual report issued by the Japan Geothermal Energy Association, the total number of geothermal power stations, including those for non-commercial use, has reached 19, and their combined power output is 533MW in Japan. Although no influences on surrounding hot springs have been found since the first geothermal power plant in Japan was commissioned in 1966, we believe that the forecasting survey of the possible influences by geothermal development on hot springs should be carried out before exploitation. The survey is useful not only for environmental measures but also for the mutual understanding, regarding the development, between developers and hot spring owners as well as environmentalists. However, so far a method to forecast the interference between geothermal reservoirs and hot spring aquifers has not been systematically developed, due to some reasons, such as: 1) technical constraint in integrating shallow ground water and deep geothermal reservoir models, 2) lack of clear understanding on the interference between geothermal development and changes in hot springs and other thermal features, and 3) lack of budget or interests on need for such study. The New Energy Foundation, therefore, has been developing a forecasting method since 1989. The results of methodology studies suggest that the method commonly used for geothermal resource evaluation can be applied as a forecasting method by expanding the scale of conceptual and numerical reservoir models in such a way that both models include geothermal reservoirs and surrounding hot springs. We integrated and arranged the existing technologies of geology, geochemistry and reservoir engineering to elaborate the forecasting method. Then, we conducted verification studies between 1994-1998 in two model fields: the Wairakei geothermal field in New Zealand and the Palinpinon geothermal field in the Philippines. The former was chosen as a representative geothermal reservoir controlled by horizontally distributed permeable layers, and the latter as one highly controlled by a fault structural system. For the purpose of expanding and improving the method, we made a comprehensive manual in which the forecasting procedure and results of verification studies are described. The manual is expected to be utilized as a comprehensive guide in preparing future forecasting survey. In this paper, we introduce and discuss the method and results of the verification study.

2. FORECASTING METHOD

The forecasting method consists of two kinds of prediction: 1) a qualitative prediction based on a large-scale conceptual model with geothermal fluid flow model, and 2) a quantitative prediction by numerical simulation. Both models will usually cover an area of more than 100km^2, because the models should include surrounding hot spring aquifers as well as geothermal reservoirs. The conceptual model shows the inferred geothermal fluid flow and relationship between geothermal reservoirs and hot spring aquifers. This is based on interpretation of geological structure, fluid flow paths, fluid behavior, and the similarity of fluid mixing, which was derived from geochemical interpretation.

In general, hot spring water is formed by the mixing of hot waters in which various kinds of chemical components are dissolved. Accordingly, if geothermal fluids tapped by production wells from reservoirs are found to be mixed in hot spring waters, we can predict that geothermal exploitation in such a case will probably affect the surrounding hot springs. It means that the mixing model is very useful for forecasting influence of geothermal exploitation on hot springs. In order to clarify the mixing condition, we recommend conducting mixing analysis by the self-consistent least-squares method as well as interpretation of the relationship between silica or Cl ion concentration and enthalpy, Cl ion concentration and B/Cl ratios. In addition, a numerical simulation is also highly recommended, because the degree of influences on hot springs depends on the amount of production and reinjection rates of geothermal wells in the exploitation area. Even if the influences on hot springs are qualitatively predicted from the conceptual model with geothermal fluid flow model, any changes in the hot spring aquifer might not appear in the case of a small scale geothermal development. A quantitative prediction therefore is required to forecast the degree of influences by numerical simulation, taking the development scenario into account. The simulation procedure is almost the same as an ordinary reservoir simulation for geothermal resource evaluation, which consists of two steps, a natural state and a development stage simulation. For the natural state simulation, we should construct a three dimensional numerical model, which is capable of representing not only geophysical and geochemical characteristics of geothermal reservoir fluids such as pressure, temperature and Cl distribution but also surface geothermal manifestations such as natural discharge of heat, steam, and water, at hot springs and ground surface in a natural state. Once we obtain a model satisfying the above natural features observed at geothermal reservoirs, surrounding hot springs and ground surface, we can quantitatively predict change in hot spring aquifers by simulating the development stage. Throughout the simulation work, sensitivity studies are necessary for evaluating the uniqueness of the numerical model and also finding acceptable ranges of prediction results. Because we cannot expect to have sufficient measured data covering a large study area, to confirm the uniqueness of the model, we should construct several reasonable models and then conduct sensitivity studies to determine possible prediction results.

Table 1 shows the comparison of methods between geothermal resource evaluation and the prediction of hot spring influences. The conspicuous differences in the latter are summarized as follows.
1) The study area should generally be large; for instance, more than 100km^2.
2) Topography is an important factor for representing natural discharge at hot springs in the numerical model (Yang, 1993). Accordingly, a reservoir simulator is desirable to be able to consider atmospheric conditions at the surface, which means that the reservoir simulator should be capable of calculating both the behavior of air and water.
3) In order to compensate for the uncertainty of the numerical model caused by insufficient measured data, we need to prepare several acceptable models and then conduct sensitivity studies to evaluate the uniqueness of the models and decide acceptable prediction results.

3. CONTROL FACTORS OF INFLUENCES

Control factors of influences are shown in Table 2. Considering the following factors, we can generally forecast the possibility of influences on hot springs due to geothermal development on the basis of a conceptual model.
1) Horizontal distance and elevation difference between geothermal reservoirs and surrounding hot spring aquifers
2) Structural connection and the existence of cap rocks between geothermal reservoirs and surrounding hot spring aquifers
3) Formation mechanism of hot spring aquifers
Regarding the horizontal distance between geothermal reservoirs and hot spring aquifers, it is difficult to calculate the distance required to avoid interference between them because of the dependence on the structural connection and scale of geothermal development. However, as far as a geothermal development of up to 200MW, a distance of more than 8km seems to be sufficient to avoid interference between them, based on the verification studies conducted in the Wairakei and Palinpinon geothermal fields. In both fields, we have not observed any influences from the development, on hot springs located more than 8km away from the exploitation area, while some changes were found within a range of 5 to 6 km. Results of the simulation for both fields also suggest that pressure changes that occur due to geothermal development gradually reduce with distance, and completely disappear 8km from the exploitation area.

It is also difficult to determine the acceptable difference in elevations between geothermal reservoirs and hot spring aquifers required to avoid interference. However, we think that a difference of elevation of more than 1000m should be maintained, to avoid interference, because changes in hot springs due to geothermal development are mostly observed in elevation differences of less than 1000m.

Although we usually pay attention to areas where the reservoir pressure is remarkably changed, due to geothermal power development, it should be noted that when production or reinjection wells are connected by faults, pressure changes occur at hot springs along fault lines. The control factor of influences on hot springs will therefore be the structural connection rather than the distance between geothermal reservoirs and hot spring aquifers. In addition, the distribution of cap rocks is also important, because stiff cap rocks separate geothermal reservoirs and hot spring aquifers, and therefore reduce the possibility of interference between them.

Focusing on the formation mechanism, hot spring aquifers can be classified into three types: 1) deep hot-water type (Cl-type); 2) steam-heated type; and; 3) conductive-heated type depending on major anion of hot spring water. Among these types, the deep hot-water type, which is the thermal water with similar chemical characteristics to geothermal fluids in reservoirs tapped by production wells, is expected to be most influenced by geothermal exploitation because of the contribution of hot water derived from geothermal reservoirs. On the other hand, the possibility of influences for the conductive-heated type is expected to be the least, because it is formed only by the heating of shallow groundwater with conductive heat depths.

4. VERIFICATION STUDY AT WAIRAKEI

The Wairakei geothermal power plant (192.5MW), located on North Island in New Zealand, commenced operations in 1952. Geothermal reservoirs of a water-dominate type are formed in the highly permeable layer of the Waiora Formation which horizontally expands in the field. There are now 51 production wells producing around 1,500kg/sec in total. The production rate has been stable within the range of 1,390 kg/sec to 1,620kg/sec since 1973, while the maximum production rate was 2,326 kg/sec in 1964. The surface heat flow at the Wairakei geothermal field increased, reflecting the expansion of the two phase region (steam and liquid) around production zones after the power plant started operations. Surface heat flow of a maximum value of 750MW was observed around 1962. It continued to decline thereafter and fell to 600MW in 1979 (Allis, 1979). According to water level measurement at Champagne Cauldron at Geyser Valley located 1km to the north of the main production area of the Wairakei geothermal field, the water level had fallen by 21m by June 1996 when further measurement became impossible. In addition, a decline of the natural discharge rate of hot spring water, the decrease of Cl ion concentration and also a temperature decrease of 40℃ in the hot spring aquifers, were observed at Champagne Cauldron. Consequently, the natural discharge ceased in what was previously noted as the largest spring in Geyser Valley. Furthermore, pressure changes which occurred in the Wairakei area spread to the Tauhara area located about 6 km to the south of the main production area in Wairakei. A study of pressure changes in deep wells of the Tauhara field suggests that a decline of around 18 bars has occurred at more than 400m depth, due to exploitation at Wairakei (Allis, 1982). Surface heat flow increased and natural discharge of hot springs decreased at Spa Sights in the Tauhara area after the commissioning of the Wairakei power plant.

To verify the forecasting method, we attempted to predict the above changes in the Wairakei field and the Tauhara area by applying our proposed method, using the data obtained at the initial stage of development. Figure 1 shows the conceptual model of the Wairakei geothermal field including the Tauhara area. The conceptual model suggests that the development at Wairakei may influence the surrounding hot springs at Geyser Valley and Waiora Valley located 1 or 2 km away from the main production area of Wairakei, because the Wairakei geothermal reservoirs are connected with these hot spring aquifers in terms of geological structure and fluid mixing mechanism. According to the results of water analysis, by means of self-consistent least squares method using chemical and isotope data of hot springs and geothermal wells, four kinds of source waters were obtained: Cl type deep water, SO_4 type water, HCO_3 type water and groundwater. Hot water discharged from hot springs at both Geyser Valley and Waiora Valley contained a maximum of 80-90% Cl type water derived from the Wairakei reservoir tapped by production wells. The hot water of high Cl ion concentration seems not to have been diluted by ground water. It also indicates that acidic SO_4 type hot water has been formed by ground water heated with steam, separated from a Cl type aquifer beneath this area and acidic Cl-SO_4 type water was formed by the mixing of up-flowing Cl type water and SO_4 type water. All hot springs at Geyser Valley and Waiora Valley, therefore, can be judged to be related to the Wairakei geothermal reservoirs, which means that we can predict the possibility of influences such as decrease of natural discharge, temperature decrease and changes in the concentration of chemical components of hot spring aquifers in all of the hot springs in these areas. These changes were actually observed in hot springs in both valleys, showing the validity of the forecasting method. As a next step, in order to quantitatively forecast by simulation the influences on surrounding hot springs and natural heat discharge on the ground, we constructed a three dimensional numerical model based on the conceptual model. We adopted the reservoir simulator TOUGH2 (Pruess,1991) for the study, because it has the function of treating the unsaturated zone as being under atmospheric conditions at ground surfaces of the model. The numerical model covers an area of 187 km^2 (11km ×17km) including the Wairakei and Tauhara areas. We assumed two recharge zones of geothermal fluids from the deeper ports of the Wairakei and Tauhara areas existed, because the origins of source geothermal waters of both areas are considered to be different, based on the relationships between Cl and B ion concentrations as shown in Fig. 2. Considering the highest temperature of 268ºC℃ measured at the WK212 well and the ground surface heat flow of about 400MW, including that of the Tauhara area before the geothermal development, the temperature and inflow rate of fluids at both recharge zones was estimated to be 280 ºC and 330kg/sec, respectively, at a depth of 2,000m below sea level of the model.

The recharge zones are considered to be about 4km^2 in the Wairakei area and 2km^2 in the Tauhara area taking each reservoir extension into account. Assuming that the Upper Huka Formation has a low permeability and acts as a cap rock of the reservoir, while Waiora Formation below forms production zones with a high permeability, we finally decided the permeability distribution by trial and error. The model was repeatedly improved until we obtained satisfactory calculation results corresponding with the measured values collected at the initial stage of geothermal development, such as ground surface heat flow, pressure, temperature profile of exploration wells and so on. Fig. 3 through Fig. 5 show by simulation the comparison between observed and predicted changes of surface heat flow, water level at Champagne Cauldron and reservoir pressure of the TH1 well at the Tauhara area, respectively. As shown by these figures, we generally succeeded in forecasting the influences on the surrounding hot springs such as the decline of water table and the increase of heat discharge on the ground, reflecting the expansion of the pressure decrease region and steam-liquid two phase region due to the geothermal exploitation at the Wairakei field. In particular, we should note that the pressure decrease in the Tauhara area was also successfully predicted by simulation, although it was difficult to predict the changes at the Tauhara area from the geochemical interpretation only. This is because the results of fluid geochemical interpretation give the impression that the Wairakei and the Tauhara areas have individual hydrothermal systems.

5. VERIFICATION STUDY AT PALINPINON

The Palinpinon geothermal power plant, located on Negros Island in the Philippines, has operated Unit-1 (112.5MW) since 1983, and Unit-2 (80MW) since 1995. In total, 74 active wells (production and reinjection wells) had been drilled by 1997. The total production and reinjection rates are 972kg/sec and 278 kg/sec, respectively. The geothermal reservoirs are of the water-dominated type and are strongly controlled by fault. The distinctive features influencing the hot springs in this geothermal field are summarized as follows: decreases in natural discharge and temperature as well as changes in concentration of the chemical component of thermal waters were found at the Cambucal and Palinpinon hot springs located 5 or 6 km away from the exploitation area. No changes were found in other hot springs located relatively close to the exploitation area (Alincastre, 1995). Fig. 6 and Fig. 7 show the conceptual model and the cross section of the three dimensional numerical model of the Palinpinon geothermal field, respectively. The conceptual model indicates that the Cambucal and Palinpinon hot springs are formed beneath the altered Southern Negros Layer which plays the role of cap rocks. Both hot spring aquifers are thought to structurally connect with the Puhagan Fault, Ticala Fault, Mag-Aso Fault and the Palipinon Fault. These faults are related to the formation of the Palinpinon geothermal reservoirs. The geothermal fluids stored in the reservoirs are believed to directly contribute to the formation of the Cambucal and Palinpinon hot spring waters on the basis of geochemical characteristics such as isotope ratio, Cl ion concentration, B/Cl ratio and so on. Results of water analysis by the self-consistent least-squares method show that the hot spring waters at both Cambucal and Palinpinon, which have high Cl concentration, contain 23-90% of the deep hot water derived from geothermal reservoirs. As such, we can forecast from the conceptual model that these hot springs, at Cambucal and Palipinon, will be directly affected by geothermal development in spite of the relatively long distances of 5 or 6 km from the geothermal exploitation area. If a significant pressure decline is caused in the Palinpinon reservoirs after geothermal development, both a reduction of natural discharge and a decrease in temperature of the thermal water are also predicted at the Cambucal and Palinpinon hot springs due to a decreased supply of high temperature water and increased inflow of low temperature shallow-water. On the other hand, other hot springs which have low salinity and are located above the cap rocks, are predicted to be unaffected since they are thought to be mainly formed by steam heat or conductive heat. From the geochemical interpretation, we believe that the origin of the hot spring waters is meteoric water from a shallow depth which has not mixed with deep water from the geothermal reservoir. Accordingly, we can judge that these hot springs would not be affected by geothermal development. Even if the reservoir pressure significantly decreases due to geothermal development, the model predicts that the temperature of hot springs which are of the steam-heated or conductive-heated type will not decrease, because of the expansion of the steam phase around the reservoirs.

The results of the numerical simulation conducted using the numerical model, which has an area of 266 km^2 (19km × 14km), also show that most hot springs, except the Cambucal and the Palinpinon springs, should be unaffected by geothermal development. However, the Cambucal and Palinpinon hot springs are predicted to reduce natural discharge of thermal water after geothermal development due to a decrease of deep water supply. Fig. 8 shows the effective range of predicted mass flow rates at the Cambucal hot spring obtained by sensitivity studies. Results of the sensitivity studies suggest that the natural discharge at the Cambucal hot spring would cease, after geothermal development, in the period between 1985 and 1994. In fact the discharge of hot spring water actually ceased in 1994, confirming the validity of the prediction method.

6. CONCLUSIONS

1) As one of the environmental conservation measures for geothermal development, we constructed a method to predict influences on surrounding hot springs due to geothermal development by integrating geological, geochemical and reservoir engineering methods which are commonly used for geothermal resource evaluation. The forecasting method consists of a qualitative evaluation based on the conceptual model and quantitative prediction by numerical simulation.
2) Pressure changes due to geothermal development are partially transferred to surrounding hot spring aquifers through faults, although the area where reservoir pressure is remarkably changed is extremely limited around geothermal wells. Therefore, the most important factor is structural connection rather than distance between geothermal reservoirs and hot spring aquifers.
3) Focusing on the forming mechanism of hot spring aquifers, the deep hot-water type, in which the thermal water of similar chemical characteristics to geothermal fluids in reservoirs tapped by production wells is formed, is expected to be the most highly affected because of the contribution of hot water derived from geothermal reservoirs. On the other hand, the possibility of influences in the conductive heated type is expected to be least, because it is formed only by the heating of shallow groundwater with conductive heat from a deeper level. The possibility of influence for steam heated type springs is intermediate between the two.
4) The numerical model should have ground surface blocks, because the topography is important in allowing the natural discharge of hot spring waters. Accordingly, the simulator applied for the forecasting method is required to have a function for the treatment of unsaturated zones by calculating the behavior of air and water simultaneously. A sensitivity study is also necessary to compensate for insufficient data and to ascertain the uniqueness and reliability of the model.
5) Results of the verification studies of the forecasting method conducted in the Wairakei and the Palinpinon geothermal field show that the method can be used to predict hot spring interference due to geothermal power development. The forecasting method is expected to contribute to environmental conservation of hot springs as well as to the enhancement of geothermal power development. Also, hot spring monitoring before and after geothermal exploitation is highly recommended.

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Table 1 Comparison of methods between geothermal resource evaluation and hot spring influence prediction

Method	Geothermal Resource Evaluation	Hot spring Influence Prediction
Area	generally less than $100 km^2$	generally more than $100 km^2$
Topography modeling	Not always necessary	Necessary for hot spring modeling
Unsaturated calculation at ground surface	Not always necessary	Necessary for calculating the surface condition of air and water
Sensitivity Study	Desirable to evaluate the uniqueness of the model	Necessary to compensate for insufficient data and evaluate the model uniqueness

Table 2 Control factors of influences on hot springs

Factor	Remarks
Horizontal distance	8km appears to be sufficient to avoid the influence on hot springs.
Vertical distance	More than 1000m is required to avoid influence on hot springs.
Fault structural connection	Structural connection controlled by fault distribution is believed to control the influence on hot springs.
Cap rocks	Stiff cap rocks are expected to reduce the possibility of influence on hot springs.
Hot spring type	The deep water type (Cℓ type) is most possibly influenced, while the conductive heated type is least. The steam heated type is between the two.

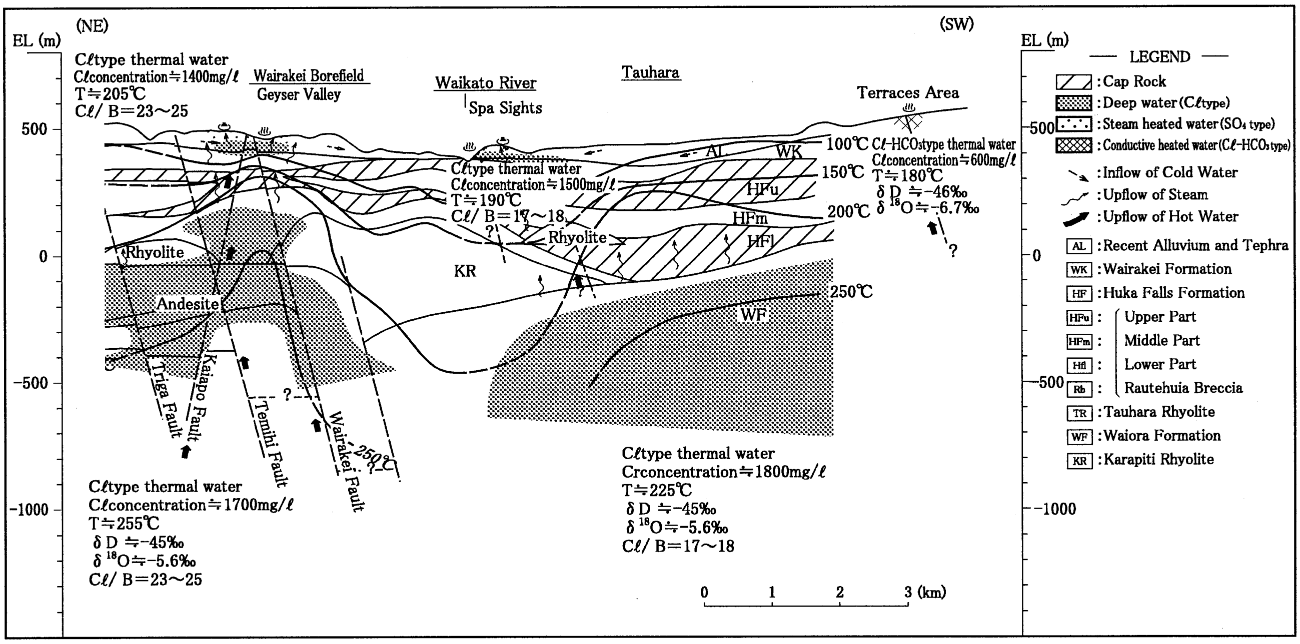

Figure 1 Conceptual model of the Wairakei–Tauhara area in New Zealand

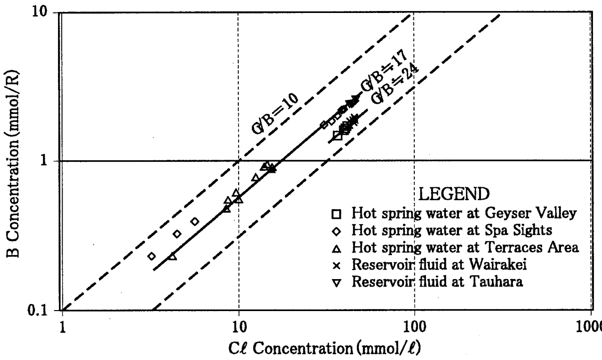

Figure 2 Relationship between Cℓ and B Concentrations of Thermal Waters at Wairakei–Tauhara

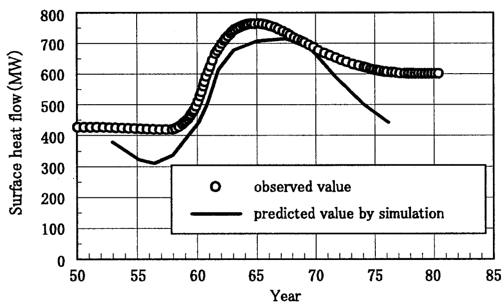

Figure 3 Comparison between observed and predicted change of surface heat flow at Wairakei and Tauhara

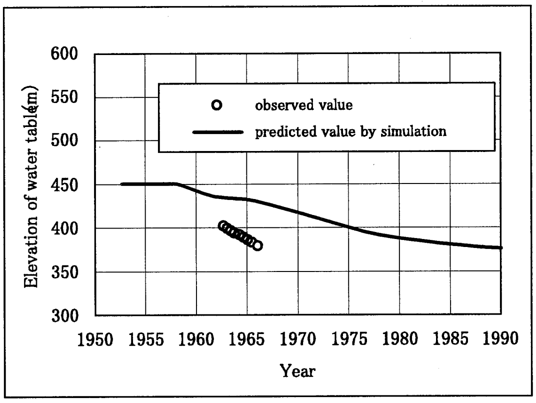

Figure 4 Comparison between observed and predicted changes of water level at Champagne Cauldron

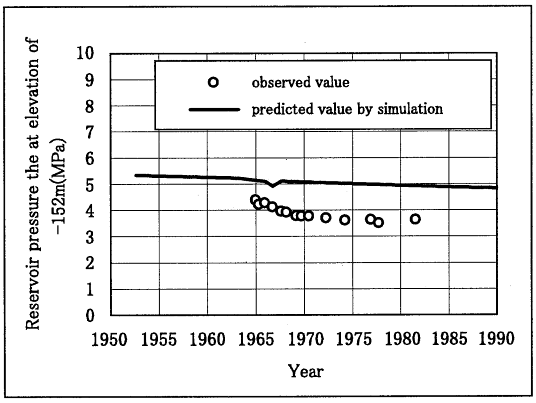

Figure 5 Comparison between observed and predicted changes of reservoir pressure of the TH1 well at Tauhara

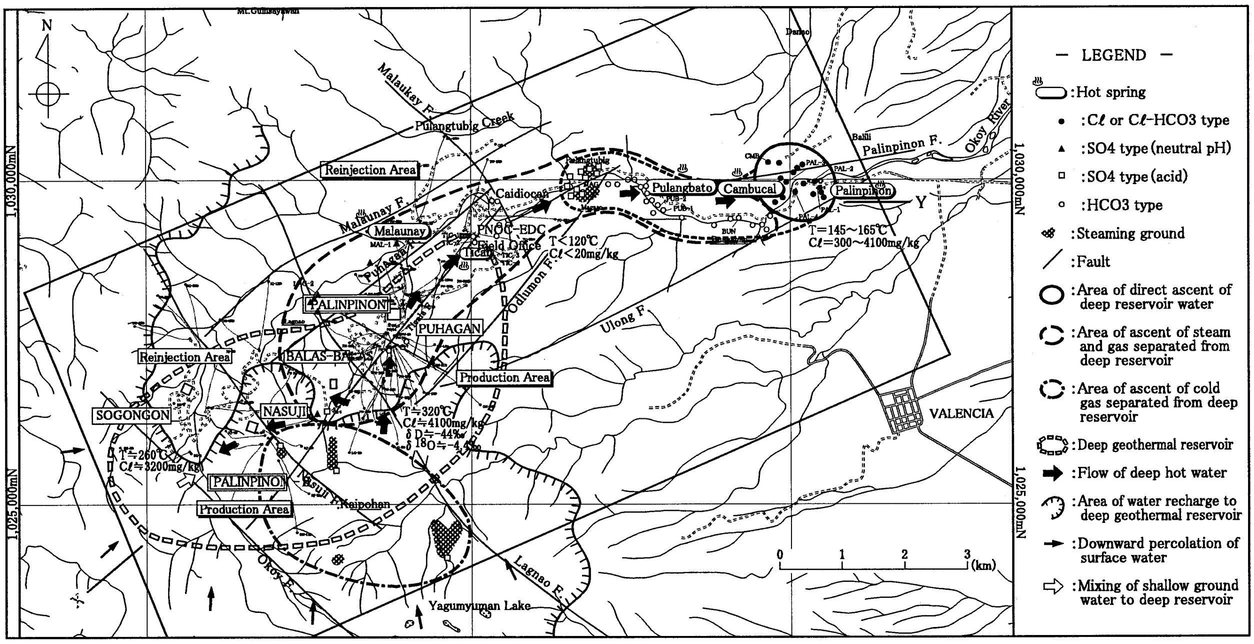

Figure 6 Conceptual model of the Palinpinon geothermal field

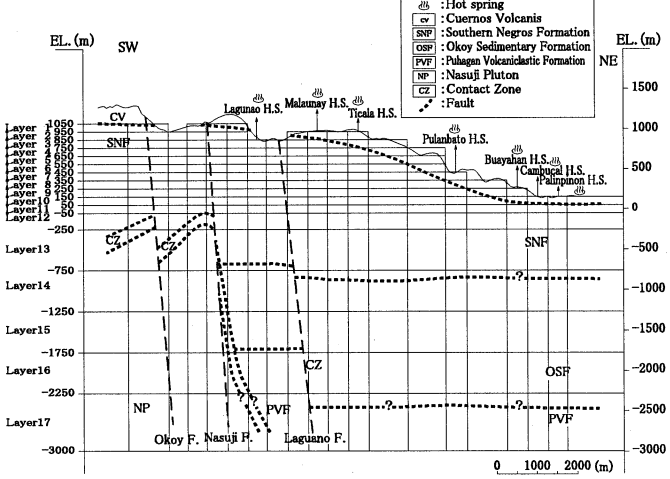

Figure 7 Cross section of the three dimensional numerical model of the Palinpinon geothermal field

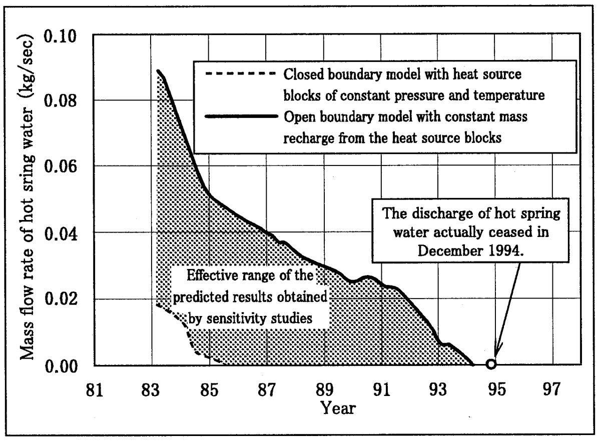

Figure 8 Effective range of the predicted mass flow rate at the Cambucal hot spring