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HOT SPRING INTERFERENCE STUDY FOR PREDICTING HOT SPRING CHANGES IN GEOTHERMAL FIELDs

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ABSTRACT

Avoiding hot spring interference by geothermal power development is strongly required for geothermal developments in Japan to avoid conflict with hot-spring owners and environmentalists. Since many hot springs in Japanese geothermal fields are used for bathing in the tourist industry, their opinions and those of the Environmental Agency cannot be ignored in geothermal power development. For predicting hot spring failures prior to committing to the construction of power plants, a method had been developed which is based on techniques used for geothermal resource exploration and reservoir engineering. In this study, verification of effectiveness of the method was conducted by comparing predicted results and monitoring data in various fields.

The prediction method consists of studies in three steps. The first step is performed to assist in understanding the relationship between geothermal reservoirs and hot spring aquifers using a geothermal model which includes both the geological structure and the thermal structure. The purpose of the second step is the construction of a geothermal fluid-flow model which considers the origin of hot spring water. At this step, the connection of the hot spring aquifer with the geothermal reservoir is investigated using mainly chemical and isotopic analyses of fluid. If the models on geological and geothermal structures can be prepared with relatively high precision and the flow model of geothermal fluid is considered reliable, then the prediction of future changes in hot springs caused by geothermal power development is performed as a third step study using a reservoir simulator, based on these models. Changes in temperature and pressure of hot spring aquifers are calculated at this step, and, in some cases, changes in the concentration of non-reactive chemical components such as chloride ion etc. are also calculated. With consideration of the results from the above three steps and their errors, changes to hot springs are predicted all-inclusively and adequate monitoring methods for the hot springs are proposed.

The method developed has been applied to several geothermal fields such as Beppu, Kirishima, Wairakei, Palinpinon and so on for the purpose of verifying its effectiveness. The Wairakei and Beppu fields are well-known as typical geothermal fields where significant changes to hot springs near geothermal development have been reported. Predictions using the above method were done using mainly existing data available prior to power plant operation. Predicted results agreed generally with the observed changes of the hot springs after commissioning the power plants in these fields. Consequently, the method was verified to be effective and useful. The method was also applied to the Kirishima field where the operation of geothermal power plant has not influenced the hot springs in and around the power plant. In this field, reasonable agreement between the predicted changes and measured ones were obtained, and the effectiveness of the method was also confirmed.

1. INTRODUCTION

The preservation of hot springs in and around geothermal fields where geothermal power development is planned is indispensable in Japan, as one of environmental conservation measures. Fumaroles and steaming ground ("Jigoku" in Japanese) are sightseeing spots and hot springs ("Onsen" in Japanese) are used for bathing in the Japanese tourist industry. Visiting "Onsen" and bathing in natural hot-spring water are Japanese customs from old times and the tourist industry related to "Onsen" has been prosperous. Since hot spring failure caused by geothermal power development is regarded as a serious problem, people who make their living with "Onsen" are anxious about it and have opposing opinions to development near their hot springs. Construction of a cooperative relationship between geothermal power developers and "Onsen" owner groups (and environmentalists) is necessary before proceeding with geothermal development in Japan.

Aiming at the mitigation of their anxiety, the New Energy Foundation, NEF, has been entrusted to develop a method for clarifying hot spring interference and forecasting hot spring failures by geothermal power development (Matsuda et al., 1994). The method developed had been made by using techniques developed and data used for geothermal resource explorations. The methods effectiveness was verified in this study (Inuyama et al., 1999) and some of the results are introduced in this paper.

2. PROPOSED METHOD FOR PREDICTING HOT SPRING INTERFERENCE BY POWER DEVELOPMENT

2.1 Procedure of Hot Spring Interference Study

The hot spring interference study consists of geoscientific studies in three steps. The structural relationship between a hot spring aquifer and a geothermal reservoir is clarified geologically and geothermally at the first step. The study results are summarized in a geothermal model. The relationship between hot spring water and geothermal fluid is investigated and a connection between the hot spring aquifer and the geothermal reservoir is assumed at the second step. The study results of this step are summarized in a geothermal fluid flow model. At the end of these steps, the potential for hot spring interference by geothermal power development can be judged qualitatively. In cases where hot spring water is a mixture of geothermal water, ground water and secondarily heated water, the proportion of geothermal water in the hot spring water can be calculated using chemical and isotopic data.

At the third step, numerical calculation using reservoir simulators is used for predicting physical and chemical changes in hot-spring aquifers. A numerical block model is constructed on the basis of the geothermal model (including geological model) and the geothermal fluid flow model.
Specifications for the planned power plant are then considered in this calculation. Any change to the physical and chemical characteristics of the hot spring aquifer, which may be caused by geothermal power development is predicted at this step.

Informed judgment on hot springs interference is performed at Stages 1 and 2, taking into account the models developed at the first and second steps and the reliability of the models i.e. estimation error. In this judgment, the hot springs which may be effected by geothermal power operation are selected and the time-course of changes to the hot spring aquifer is predicted.

Data for these studies are the same as those used for geothermal resource exploration. If necessary, complementary studies are performed. The procedure for the interference study is shown in Figure 1.

2.2 Geothermal Model

The structural relationship between hot spring aquifers and geothermal reservoirs is evaluated for assessing the potential for hot spring interference by power development, using a geothermal model. Geological and thermal structures together with the distribution and behavior of geothermal fluid are described in the geothermal model. Their structural relationship is revealed during the evaluation and interpretation for the modeling.

The evaluation and interpretation are performed using existing data for geothermal resource exploration and by complimentary studies on hot spring aquifers. These data are normally collected by geological study, geophysical survey (gravity survey and resistivity survey), geochemical study (fluid-geochemistry and soil/soil-air survey) and exploratory well study (well log, well discharge test and interference test) for geothermal development. Data from several exploratory wells and a strategy of resource development are necessary for study at this step.

The following geological and geothermal information needs to be known:

i) Geological structure
  a) Basement structure
  b) Faults (or fractures)
  c) Geological characteristics of formations
  d) Permeability
ii) Geothermal structure
  a) Heat sources
  b) Formation mechanism of hot spring aquifer and geothermal reservoir
  c) Distribution and extent of hot spring aquifer and geothermal reservoir
  d) Cap rocks (low permeability zone)
  e) Temperature of hot spring aquifer and geothermal reservoir
  f) Thermal structure

The reliability and errors of the above information and data have to be determined for a proper judgment on the hot spring interference. Also checking the quality of data and the methods of data-processing and interpretation.

The potential for hot spring interference is judged on the basis of the following factors at this step.

a)The structural connection of the hot spring aquifers with the geothermal reservoir through high permeability zones along faults and/or formations
b)The role of cap rocks (separability between hot spring aquifer and geothermal reservoir)
c)The distance between the hot spring aquifer and geothermal reservoir

In the judgment, a) the structural connection and b) the role of cap rocks are considered to be more important than c) the distance.

2.3 Geothermal Fluid Flow Model

The formation mechanisms of hot springs and the relationship between the chemical and isotopic characteristics of hot spring water fluid and geothermal reservoir fluid are evaluated for the purpose of judging the potential of hot spring interference by power station development, using a geothermal fluid flow model. Additionally, the temperature and geology of the deep hot-spring aquifer and the geothermal reservoir, which supplies high temperature fluid to the hot spring are investigated. Geothermal fluid behaviors such as fluid flow, mixing (and dilution), separation (evaporation) and connection between hot spring aquifer and geothermal reservoir are described in the geothermal fluid flow model. Their inter-connection is assessed from geochemical analysis and interpretation of the modeling.

The discussion and interpretation are performed using existing data from geothermal resource development investigations and complimentary study data on hot spring aquifers. These data are normally collected by fluid-geochemistry and exploratory well study (well discharge test and interference test) for power development. Data from several exploration wells and a strategy of resource development are necessary for investigations at this step.

The following geochemical information needs to be known.

i) Formation mechanism
  a) Hot spring water
  b) Geothermal reservoir water
ii)Grouping hot spring aquifers and geothermal reservoirs by

hydrothermal system
iii)Behavior of subsurface geothermal fluid
 a) Mixing
 b) Dilution
 c) Evaporation
 d) Flow
iv) Similarity in origin of fluid between hot spring aquifer and geothermal reservoir
 a) Origin of fluid
 b) Geology of reservoir (and aquifer)
 c) Fluid temperature
v) Geothermal fluid flow model

The reliability of the above information and data errors need to be known for a proper judgment on hot spring interference.

The potential for hot spring interference is judged on the basis of the following factors at this step.
a) Formation mechanism of hot spring water, i.e. possibility of in-flow of geothermal fluid from the reservoir, which is planned to be tapped by production or reinjection wells.
b) Grouping of hot spring aquifers and geothermal reservoirs based on characteristics of each hydrothermal system.
c) Similarity of original hot spring water with the geothermal water which discharges from the geothermal wells to be used for power development.

2.4 Numerical Estimation of Hot Spring Interference

Provided that a reliable geothermal model and a geothermal fluid flow model are prepared during the previous steps, a numerical block model based on permeability and rock properties can be constructed for predicting quantitative changes in fluid characteristics of hot-spring aquifers. The fundamental procedure and reservoir simulators are the same as those used for geothermal resource evaluation. However, the setup of initial conditions at shallow levels and the modeling of the unsaturated shallow groundwater zone for this study need to be paid particular attention, compared with those for geothermal resource evaluation. The hot spring formation mechanism, which is assessed in the geothermal fluid flow model cannot be neglected either and needs to be reflected in the numerical model. Assumptions made on power plant capacity and the location of production zones and reinjection zones is indispensable information needed for adequate prediction.

Prediction of hot spring interference by the power development is determined from the discrepancy between hot aquifer characteristics (pressure, temperature and chemistry) in the calculated natural-state and the calculated state after starting steam production and water reinjection. The reliability of the calculated results is checked with the geothermal fluid flow model and measured values of pressure and temperature of geothermal and hot-spring wells.

In this study, the simulators of TOUGH 2 (EOS 3 code) and SING-II were used for modeling a few thousands blocks. The reliability of the obtained results was increased with sensitivity studies.

The possibility of hot spring interference is judged on the basis of the following factors at this step.
a) Temperature of the hot spring aquifer
b) Pressure of the hot spring aquifer
c) Chemical content (chloride ion) in the hot spring aquifer

2.5 Judgment on Possibility of Hot Spring Interference

After studies at the steps 1 and 2, the possibility of the hot spring interference by power development is judged qualitatively and is classified into one of the following three classes, with consideration of errors in the study results.
a) No or very low possibility of the hot spring interference.
b) Some possibility of the hot spring interference.
c) High possibility of the hot spring interference.

In cases b) and c) quantitative numerical estimation is strongly recommended for improving the prediction. The hot springs, which are predicted to be influenced by power development are selected for monitoring and measures adopted to avoid failure.

3. APPLICATION OF THE METHOD TO VARIOUS FIELDS - EXAMPLES OF CASE STUDIES

3.1 Geothermal Model

Fracture Type Geothermal-Field

The prediction method developed has been applied to several geothermal fields, where changes to hot springs after power plant operation are already known. In geothermal fields where geothermal fluid flow is believed to be controlled by permeability of fractures along faults, the fault characteristics and their fluid flow behavior were based on geoscientific surface studies. Referring to hot spring formation mechanisms, the faults across which the hot spring aquifer and the geothermal reservoir extend, were evaluated to determine the structural relationship between the hot spring aquifer and the geothermal reservoir.

For a proper judgment on interference, the role of alteration (as low permeability) zones situated between hot spring aquifers and geothermal reservoirs, was evaluated using resistivity survey data, temperature logs and the geology of exploration wells.

Figure.2 shows an example of the study results in the Kirishima field in Japan. This model was constructed using exploratory stage data. According to this model, the hot spring aquifer is considered to be controlled by faults different from those of the geothermal reservoir tapped by power plant production and reinjection wells. Alteration zones seem to play the role of cap rocks of the geothermal reservoirs. The hot spring aquifer was judged not to be related to the geothermal reservoir supplying the power plant.

In the Kirishima field, operation of the power plant (PP) started in 1994 and changes to the hot springs have been monitored before and after start-up. Since changes to the hot springs have not been observed until recently, the structural judgment is regarded to be reasonable in this field.

Similar applications of the method to other fracture type fields such as Beppu in Japan and Palinpinon in the Philippines were performed. In these fields, where some hot springs had been influenced by geothermal power development the effectiveness of the method was also verified.

Horizontal Permeability Type Geothermal Field

The failure of hot springs and fumaroles in the Wairakei geothermal field was investigated from the viewpoints of geological and geothermal models in this study. The results in this field were quite different from those for other fracture type fields. The behavior and distribution of geothermal fluid in the vast Wairakei field (including the Tauhara field, 6 kilometers away from the steam production field) is believed to be controlled not only by fractures along deep faults, but also by horizontal high-permeability zones such as the Waiora Formation at relatively shallow depths. The shallow Huka Falls Formation is considered to play the role of a cap rock for the deeper reservoir.

The hot springs and fumaroles at Geyser Valley, near the geothermal reservoir tapped by the production wells, are thought to be influenced directly by steam production for the PP as shown by the geothermal model in Figure 3. The hot spring aquifer must be considered to extend across the faults related to the deep geothermal reservoir at Geyser Valley. The hot springs and fumaroles failed due mainly to steam production through the production wells.

In this field, hot springs and fumaroles in the Tauhara area, were also affected by power generation at Wairakei. This interference is caused by propagation of the pressure decline within the geothermal reservoir to the shallow aquifer through the horizontal permeability zone. The Huka Fall Formation is considered to be incomplete as a cap rock in some areas. In this kind of field different approaches, from those used for fracture type fields, are necessary to reveal the relationship between the geothermal reservoir and the hot spring aquifer.

3.2 Geothermal Fluid Flow Model

In spite of the many kinds of geothermal field structure, known geochemical methods and interpretation can be applied to clarify the formation mechanism and origin of hot spring water and geothermal fluid used for power generation. At this step, the origin of hot spring water is compared with that of the geothermal reservoir fluid using chemical and isotopic data. Consideration is then given to the mixing and flow of subsurface fluid, and the geothermal model and then the hot spring is assessed as to whether it will be interfered with by steam production from the geothermal reservoir.

As an example, Figure 4 shows the geothermal fluid flow model in Beppu, which was constructed based on fluid geochemical interpretation (Yahara et al., 1994). Almost all hot springs in this field are understood to originate from the geothermal reservoir in the western part from this figure. However, steam production for the power station in the southwestern part influenced the characteristics of the hot springs in the eastern part.

In the case of the Wairakei field, since two types of geothermal fluids supplying shallow hot spring aquifers in one hydrothermal system spreading over the vast Wairakei field do not mix with each other, adequate interference prediction on hot springs other than those at Geyser Valley could not be performed. The hot spring aquifers of high enthalpy at Tauhara are considered to originate from the deep geothermal reservoir, which is located far from the steam production field for the Wairakei PP. According to geochemical interpretation of the geothermal fluid flow modeling, the deep geothermal reservoir in Tauhara did not seem to be connected with that in the steam production field. Therefore, the hot spring aquifer at Tauhara was judged not to be influenced by steam production for the PP. However, changes in geothermal manifestations at Tauhara, such as thermal eruption, hot-spring failure etc. occurred with steam production. Geochemical approaches were however successfully applied to several other fields for modeling geothermal fluid flow and understanding the connection between hot spring aquifers and geothermal reservoirs.

The mixing ratio of deep geothermal fluid in hot spring water is calculated using the self-consistent least square method at this step. The calculated results before starting steam production in Wairakei are shown in Figure 5. The mixing ratio of Cl type water A as seen in the geothermal water for power generation was remarkably similar to the failed hot-springs at Geyser Valley in Wairakei.

3.3 Numerical Estimation of Hot Spring Interference

Quantitative prediction of characteristic changes in hot spring aquifers caused by the steam production for the Wairakei PP was performed using a numerical block model of seven vertical layers from 500 to -2000 meters above sea level as shown in Figure 6. Both calculated and measured results at Geyser Valley are shown in Figure 7. In this case, the calculated values were not in perfect agreement with the measured ones, but the potential for interference of hot springs from steam production could be recognized.

In the calculations performed on other fields such as Beppu, Kirishima, Palinpinon etc., changes in hot spring aquifers were predicted well with this calculation. Figure 8 shows the results for the Palinpinon PP.

3.4 Judgment on Possibility of Hot Spring Interference

As previously mentioned, interference judgments are carried out in two stages. Judgments made at the first stage are qualitative and based on information on geothermal structure at the first step and geothermal fluid flow at the second step as shown in Figure 1. The possibility of hot spring interference by the power development could be determined in most of the cases such as Geyser Valley in Wairakei, Kirishima, Palinpinon (the Palinpinon and Cambcal hot-springs) and Beppu (hot springs in the southern part). The predicted results from the first stage are useful for considering countermeasures against hot springs failure. Namely, the relocation of production and reinjection wells and/or the reduction in generating capacity of power plant might be adopted as mitigation measures.

In some cases such as Wairakei & Tauhara, steam-heated hot-springs in Palinpinon and some parts in Beppu, reliable conclusions could not obtained in the first stage studies. In these cases, numerical evaluation using reservoir simulators at the third step in Figure 1 was quite effective in predicting changes. As part of the second stage judgments, the hot springs whose characteristics are possibly changed by the power development were separated from the hot springs which had not been clear in the interference at the first stage judgment. Not only could prediction of the future changes to the hot springs be seen but also improved reliability of the study results can be expected by performing all the studies from the first to the third step.

4. APPLICATION TO JAPANESE GEOTHERMAL POWER DEVELOPMENT PROCEDURE

In geothermal development in Japan, utmost attention is paid to the interference to or impact on surrounding hot springs. The prediction method developed, having been verified to be effective during these studies, is recommended to be included in any programme of geothermal development before committing to power plant construction. The results of the forecasting study provide information useful for mutual understanding between hot spring owners and geothermal power developers.

For the advancement of geothermal power development in Japan, carrying out the prediction study during the Promotion Survey for geothermal power development, sponsored by the Japanese Government is most desirable. Investigating the influence of geothermal development on hot springs during the pre-feasibility study, such as the promotion surveys, must be effective for developing a trust-worthy relationship between power developers and hot spring owners (and/or environmentalists). At present, the prediction method is being modified for use in Promotion Studies.

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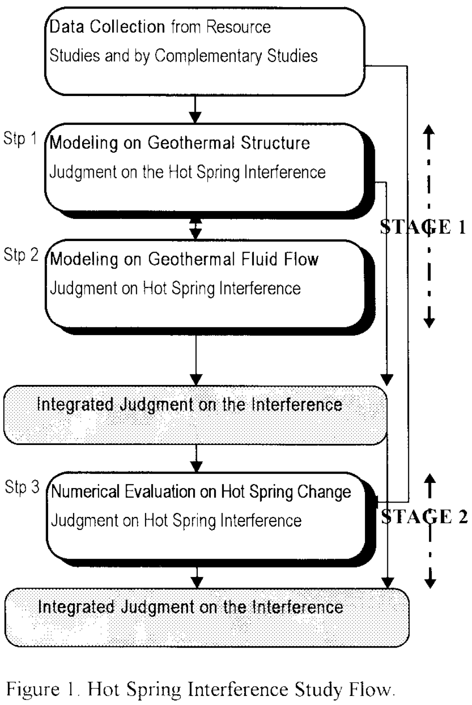

Figure 1. Hot Spring Interference Study Flow.

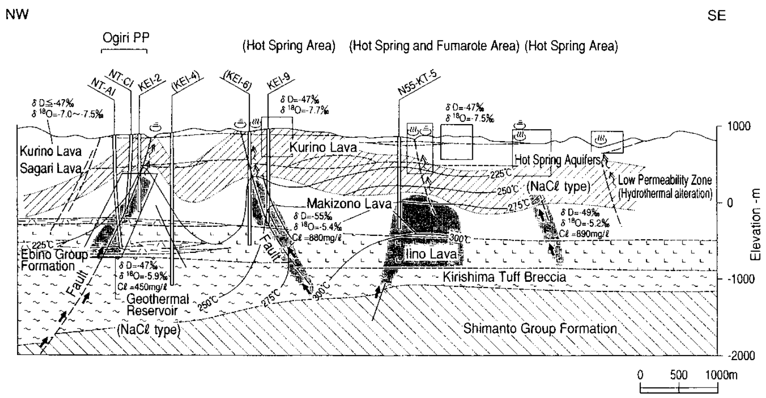

Figure 2. Geothermal Model of the Kirishima Field for Understanding the Relationship between Hot Spring Aquifers and Geothermal Reservoir

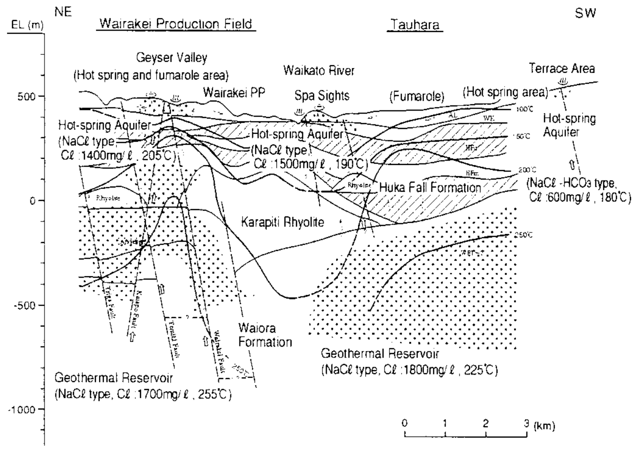

Figure 3. Geothermal Model of the Wairakei Geothermal Field

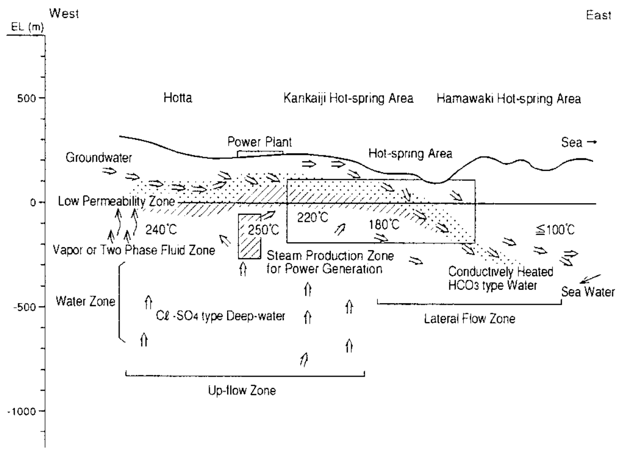

Figure 4. Geothermal Fluid Flow Model of the Beppu Field

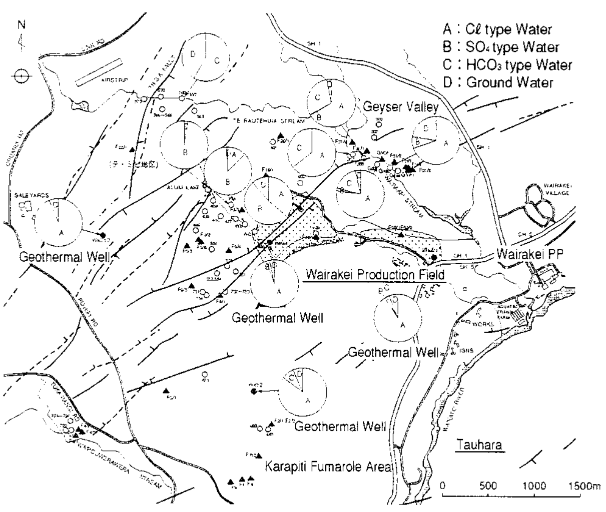

Figure 5. Mixing Ratio of Geothermal Water in Hot Spring Water in the Wairakei Field

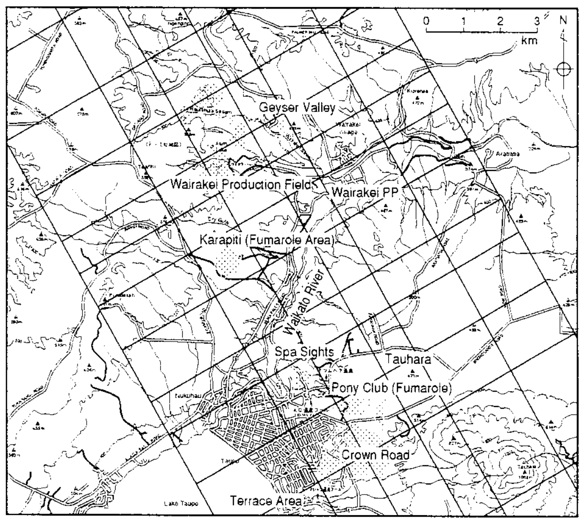

Figure 6. Block Model for Quantitative Estimation of the Wairakei Field

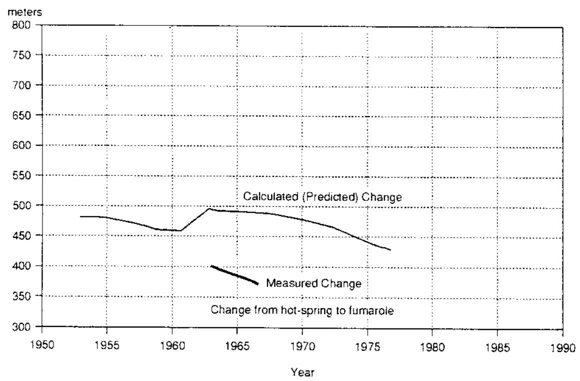

Figure 7. Change of Water Level of Hot Spring Aquifer in Wairakei

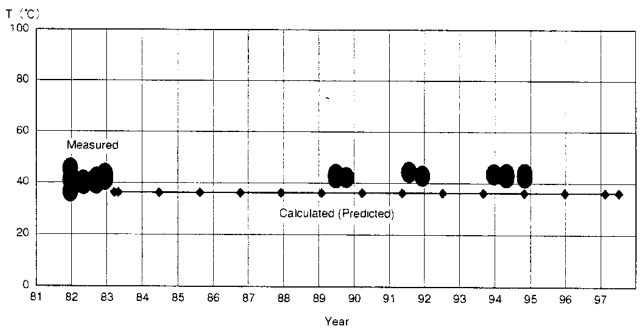

Figure 8. Change of Temperature of Hot Spring Aquifer in Palinpinon