NUMERICAL SIMULATION OF THE RUCHENG BASIN GEOTHERMAL SYSTEM, HUNAN PROVINCE, SOUTHERN CHINA

CHEN SONG
Geothermal Institute, University of Auckland, Auckland, N.Z.

ROBERT MCKIBBIN
Department of Engineering Science, University of Auckland, Private Bag, Auckland, N.Z.

SUMMARY - The intermediate-temperature Reshuiwei (Rucheng) Geothermal System was simulated numerically using the MULKOM program. Owing to the complexity of the geological Setting, which is controlled by the permeability structure, the simulation was started using 2-D and 3-D models of the natural steady state, followed by a simulation model for prediction of future developments.

The Reshuiwei (Rucheng) Geothermal System was simulated numerically using an extended model based on that of the Reshuiwei (Rucheng) Geothermal Reservoir (Chen, 1990). The simulation attempts to go a step further in demonstrating how to form and evolve this kind of geothermal model of a reservoir with specially appointed geological conditions fiom a macroscopic point of view. In addition, the paper recounts the simulation processes of setting up and modifying the model. The 3-D numerical natural steady-state simulation model was successfully obtained. It gave a good match to the previous simulation of Reshuiwei (Rucheng) Geothermal Reservoir and revealed the contributing factors of the system.

1 INTRODUCTION

The Reshuiwei Basin Geothermal System in Rucheng, Hunan Province, P. R. CHINA (see Figure 1.1) is a prospect with an intermediate-temperature system at shallow depth discovered in the mountainous region of South-East China. Over 750 years ago, the hot spring history of Reshuiwei (Rucheng) was recorded in writing in a geographical features book of China All the springs are found in the river-bed and on the banks of the Reshui river in the Reshuiwei Basin (Rucheng), where the natural flow rate of springs was about 36.3 kg/s; the area of the indication was about 0.017 km^2 and the temperature of a few major hot springs was about 91.5 ^0C. By drilling exploration wells since 1980, the maximum temperature of 92 ^0C was encountered at 30 m to 100 m depth, in wells ZK1 and ZK4, for example. The total discharge of hot water from these wells is approximately 60 kg/s (at a wellhead temperature between 40 ^0C to 92 ^0C), but only 3.5 kg/s of hot water (92 ^0C) has so far been utilized for supplying a 3000 m^2 heating area of geothermal greenhouses.

The Reshuiwei Basin is controlled by a series of transverse faults which extend across a few kilometres width and which are more than 10 km long (NNE-SW, see Figure 2). The basement is Mesozoic granodiorite with a thin layer (maximum thickness 5 m) of Quaternary sediments on top. The thermal area is composed mainly of subrounded granite boulders. The basic characteristics of this reservoir were established by a combination of methods such as geological, geophysical and geochemical surveys, heat and mass discharge assessments and drilling information.

These interpretations, and also some literature about low- and intermediate-temperature geothermal systems, were used to set up a new conceptual model. The intermediate-temperature Reshuiwei (Rucheng) Geothermal Reservoir was simulated numerically using the MULKOM Program (Chen, 1990). The study pointed out the detail of the permeability structure distribution within the active region of surface manifestations, and resulted in a 3-D simulation model of the natural steady state where the reservoir was extended to 4 km depth, and area of simulation was about 9.2 km^2. A good match to the geological and drilling information and all parameters for this area was obtained. The model suggested that the Rucheng Basin was controlled by a series of transverse faults (Chen, 1990). This led to the further step of explaining the heat redistribution. There is probably no heat source, such as a magma intrusion, which formed the original basis of the fist 3-D simulation model for the natural steady state. There were two assumptions for the natural-state model:

- the heat source was a hot liquid flow (17.0 kg/s, specific enthalpy 600 kJ/kg) at the bottom of simulation model;
- the simulation model only included the middle region of the Rucheng Basin which was at almost uniform elevation above sea level, but in fact did not consider the effect of the surrounding mountainous region.

It is therefore preferred to remove these artificial assumptions in order to improve the conceptual model. The methods of the new simulation model consider how to remove the two limitations so that the simulation area is increased (see Figure 3) and the depth of simulation is increased also. By deleting the assumption about input heat flow, and using natural heat flow only, the simulation results are mare convincing.

This is the first simulation model for this area, and is intended to assist in future developments.

---

[1] Permanent address:
Tianjin Geothermal Research & Training Centre
Tianjin University, Tianjin, P.R. China



Figure 1. Map of P.R. China showing the position of the Rucheng area.

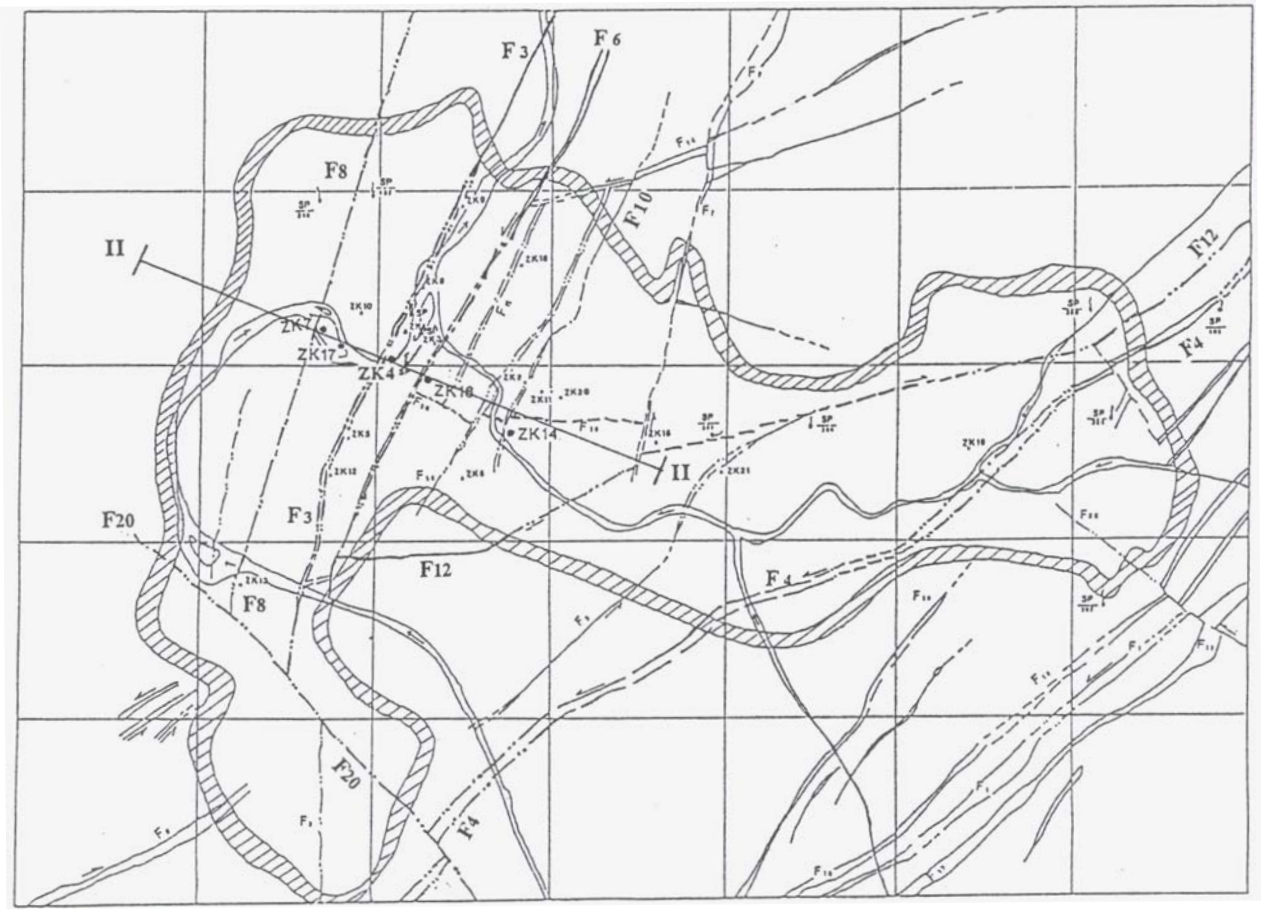

Figure 2. Map of the Reshuiwei Geothermal System showing faults, the resistivity boundary and wells.

2. GENERAL BACKGROUND

2.1 Geological Setting

Reshuiwei Geothermal Area is situated in a very complex fault-controlled small valley, at an elevation averaging 350 m above msl, bounded by Quaternary loose sediments originating from less than 5 m thick above Mesozoic granodiorite. Most of the basin area lies where the rock sequences were subsequently intruded by stress-granite (DGH, 1981a). The structural geology is distributed in the intense region of metamorphism. So far, more than three groups of fault systems have been delineated in the area, these trend ENE-WSW, NNE-SSW, NNE-SW. Among them, two groups of the fault systems, namely NNE-SSW, NNE-SW, are the most important contributing factors to the Reshuiwei (Rucheng) Geothermal System. The NNE-SW group fault system is younger than the other two groups, and some faults of another group have developed along this NNW-SW trending fault direction (See Figure 2). However, the area of the older NNE-SSW fault system is the position of the deep heat source area (DGH, 1981c).

The hot springs area is located along the major transverse F3 fault (deep angle 80^0) in the NNE-SW direction. Also, the Reshui river is near this F3 fault with the hot springs showing along this river-bed and its banks. The F3 fault band of gneiss and schist is generally about 30 m wide and delineates the boundary of the Reshuiwei geothermal field. It is also the major structural control for water storage and recharge for the geothermal system. The other transverse faults in the NNE-SSW direction strictly control the permeability structure of the thermal system. This point was supported by later drill holes situated in each fault region (see Figure 2).

2.2 Geophysical Survey

In 1981, the Department of Geology of Hunan (DGH) conducted a traversing Schlumberger resistivity survey at AB/2 spacing of 25, 65, 150 and 340 m, covering an area of 2.5 km^2. From the results of the survey, shown in Figure 2, it can be concluded that there are four zones of low resistivity (from 20-250 Ω-m). The first major low resistivity zone, which includes all of the hot springs area, forms a "T" shape and a 290^0 NNE direction which is the same direction as that of NNE-SW group fault. Four results of a traversing Schlumberger resistivity survey with different AB/2 spacing were used for checking by information from drill holes ZK16, ZK15, ZK19 and ZK18.

The major conclusions of the geophysical survey (DGH, 1981b) are:

- Reshuiwei Geothermal System is controlled by two major faults; one is the F3 fault on the western boundary and the other is the F1 fault on the eastern boundary.

  According to the geophysical survey and drilling measurement information, the thermal area is about 3 km^2 in extent.

  The thermal area is divided into three parts according to basic geological and geophysical analysis:
  - Reshuiwei Geothermal Field;
  - Danwan Geothermal Field;
  - Dongqishu Geothermal Field.

  [Note: the authors believe all three fields belong to one geothermal system for simulation, called the "Reshuiwei (Rucheng) Geothermal system" throughout this paper.]

2.3 Geothermal Characteristics

The surface manifestations at Reshuiwei geothermal area are predominantly water-dominated bubbling and boiling springs. The discharge temperature of the hot water discharge ranges normally between 88.0 ^{0}C and 91.5 ^{0}C (with a maximum of 98 ^{0}C). The discharge water of the springs is usually clear and colourless with a slightly higher content of sulphur (H_2S) than would make it potable, and the pH ranges from 7.2-8.8 at 25 ^{0}C. According to chemical analysis of the natural thermal discharges, the thermal fluid is characterized by an appreciably high concentration of silica, sodium and bicarbonate, whereas the concentration of calcium, potassium and chloride is rather low (DGH, 1981e).

This thermal system is controlled by faults which also control the distribution of hot water, the chemical characteristics of each giving a "confusion" distribution, suggesting that hot water of the springs of this system could be classified as sodium-bicarbonate type. More than six types of geothermometers were selected to try to get a "feeling" for reservoir deep temperature; they include a K-Mg-Ca geothermometer (Giggenbach, 1986), a SiO_2 geothermometer (Ellis and Mahon, 1977), a Na-K geothermometer and a Na-K-Ca geothermometer. The one thought to give the best result is the Na-K-Ca geothermometer (Hochstein and Caldwell, 1986), because of the comparatively low potassium. Calculated results show the deep reservoir temperature of the Reshuiwei Geothermal System to be between 140 to 170^0C. This result was supported by the results of the simulations.

2.4 Drilling Information

In 1980, twenty-one shallow holes (depths less than 400 m) were drilled (see Figure 2), and some well testing was carried out. The selection of each drill hole depended on the theory of fault-control of this thermal area. The wells ZK1, ZK4 and ZK3 certify F3 fault as a major controlling band of the Reshuiwei Geothermal System, and that it is also the major storage band. In Figure 3, one set of temperature-depth curves (vertical section II-II) is presented to show the changes along the central part of Reshuiwei Geothermal System in the WNW-ESE direction.

3. CONCEPTUAL MODEL

All geological, geochemical, geophysical, drilling information and heat loss analyses were used to establish a conceptual model for the simulations.

3.1 Heat Redistribution

Because of the long geological history of the Reshuiwei (Rucheng) Geothermal System, the heat source is not likely to be due to magma intrusion. The reason for the apparent

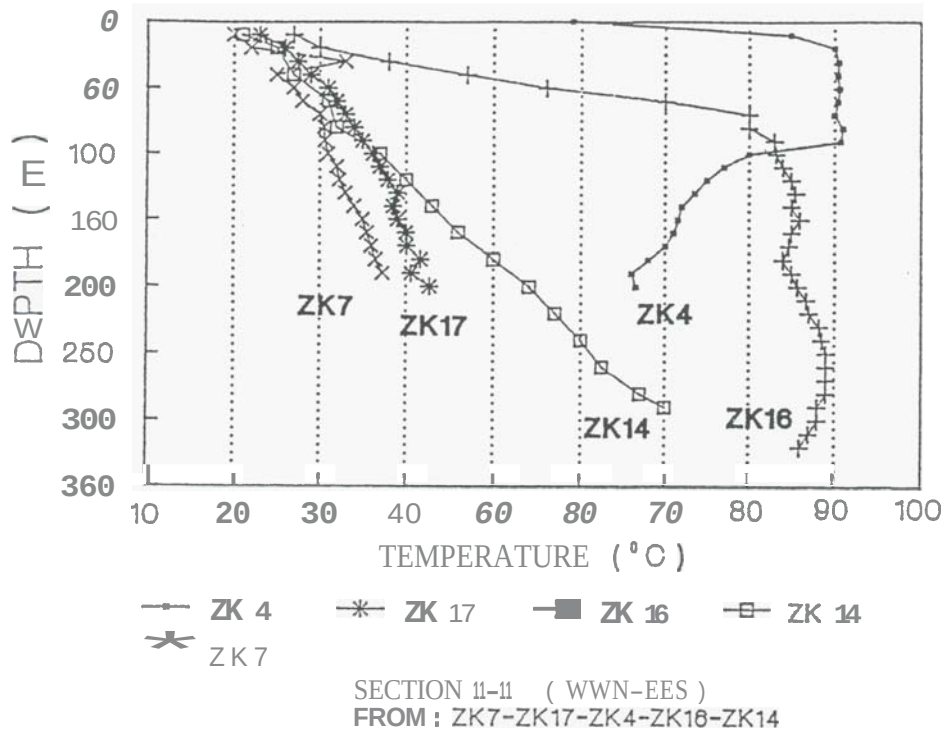

Figure 3. Temperature profiles in drill-holes within the Reshuiwei (Rucheng) thermal area.

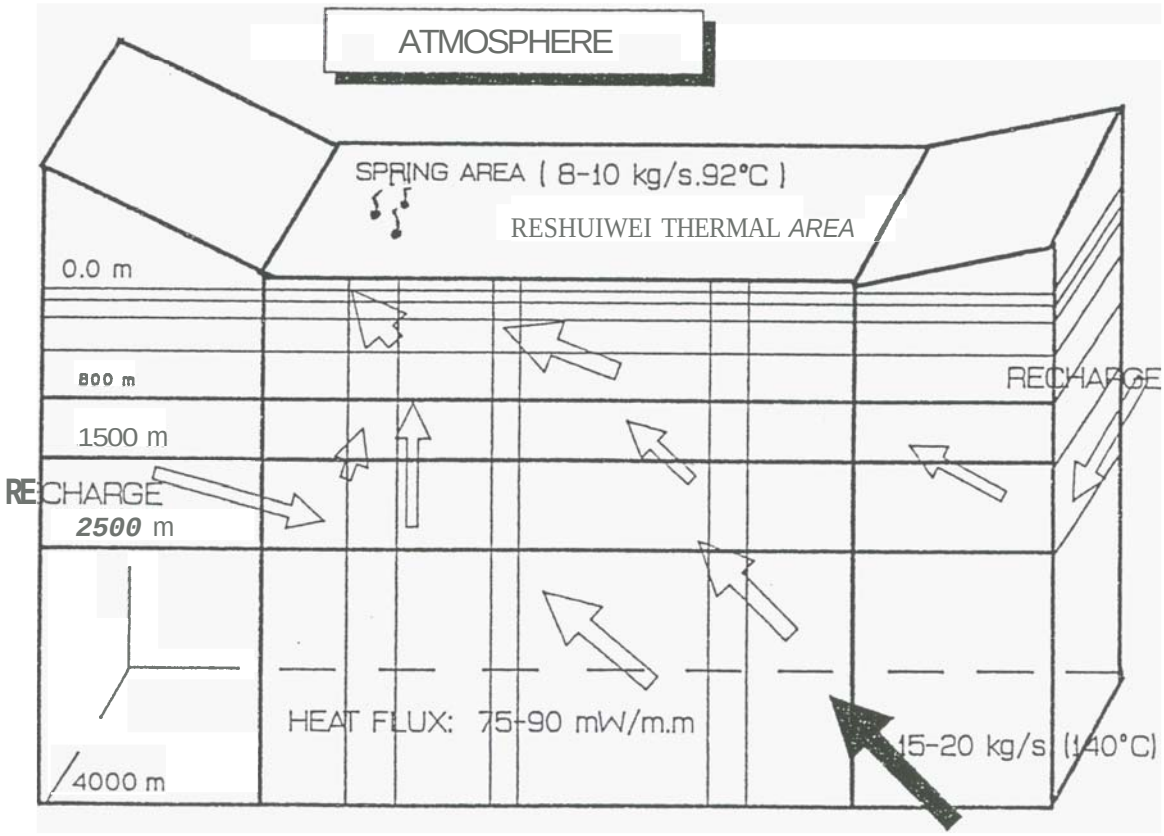

Figure 4. Conceptual model of the Reshuiwei Geothermal System.

formation of the "heat source" is tectonic movement which brings about terrestrial heat flux redistribution. It is suggested that the enhanced heat flow within the granites is the most likely heat source for the Reshuiwei (Rucheng) system which is associated with high temperature (about 140 ^{0}C at 4 km depth) and a high heat-generating capacity extending to 7 km depth. Temperature ranges are indicated by the Na-K-Ca geothermometer. The deep mass flow to be redistributed is about 15-20 kg/s at a depth of 4-7 km. Stated in another way, the heat flux of the area surrounding the thermal system (normally 60 -70 mW/m^2) is collected in the centre basin area (75-90 mW/m^2) to form what is called a "redistributed heat source" (Hochstein, 1986).

3.2 Fault Control of the System

Reshuiwei (Rucheng) Geothermal System contains very complicated faults. This is one of the reasons for the creation of a concentration of heat distribution. However, it also controls the permeability structure distribution by the various boundary faults forming pathways for the underground fluid flow resulting in a very "sensitive" area for the surface manifestations. The faults also create non-continuous, major water storage zones which accompany the faults. The main F3 and F1 faults also control Reshuiwei Geothermal System's boundary.

3.3 Creation of Conceptual Model

All drilling measurement data were synthesized in order to plot the isotherm pattern at 200 m depth and the vertical temperature gradient pattern at 95-200 m depth over the Reshuiwei fault zone, so that they also help to establish the conceptual model to give a "feeling" of the subground flow pattern. A conceptual model of the Reshuiwei Geothermal System was thereby created; this is shown in Figure 4.

3.4 General Model Analysis Methods

The conceptual model is important for the simulation of a geothermal system. According to fluid chemistry, natural heat loss and the reservoir structure of Reshuiwei Geothermal System, it had been classified as an intermediate temperature reservoir (Chen, 1990). However, one of the Reshuiwei (Rucheng) Geothermal System's major features is due to the complexity of the geological setting. This means that it is more sensitive to the permeability structure. Because of this, establishing the conceptual model correctly is important for the input of the initial simulation data for the 3-D natural-state model. Normally, developing the conceptual model requires several steps, which are as follows:

- identification of the prospect; hydrological, geological setting and surface manifestations;
- assessment of the structure and volume of reservoir, fluid characteristics and classification of the system;
- stored energy and power potential estimates;
- net heat loss (renewable resource estimate);
- drilling information.

Using this information to get a first small- or middle-size simulation model, the simulated *pressure* and temperature data of the reservoir model (natural steady-state model) are compared with *observed* data to check whether the original conceptual model is correct. If so, then the large-geological-size simulation modelling can be started. So far, verification of the basic conceptual model has been successful.

3.5 Creating the Large-size Model of the Geothermal System.

On completion of the above-listed stages, it was necessary to establish the fit to the geological condition. The heat some for the Reshuiwei (Rucheng) Geothermal System is most likely the anomalous heat flux in the deep granites, and this heat is transferred by convection, involving also flow in a deeper reservoir in the *granites.* The following were considered:

- increasing the simulation area *(see* Figure *5)* to include all of the Rucheng Basin region (simulation area 136km^2), and increasing the depth of the simulation model (6km);
- heat flux at the bottom of the Reshuiwei (Rucheng) Geothermal System is uniform (80-90 mW/m^2);
- the shape of the simulation model is cylindrical, the aim being to increase stability of the simulation modelling.

4. SIMULATION PROCESSES

4.1 Setting up the Model

Many items for the simulation model were considered, as follows:

- there are six main sets of faults trending NNE-SW, and on one of them (F3-fault) occurs the spring area (see Figure.2);
- the fluid flow is likely to merge and move upwards and along the F3 and F6 faults towards the North-West where the hot spring area occurs; the South-East area is locally sealed by mineral (mostly SiO_2) &position;
- the cold recharge comes from outside the basin to be redistributed; this is a major underground fluid some to be supplied;
- the permeability of rocks in the area varies from low to high depending on the type of the associated fractures;
- the thermal area (resistivity) boundary is shown in Figure 2 and the 3-D simulation's boundary in Figure 5.

For the numerical parameters, see Table 1, Table 2 and Figure 6.

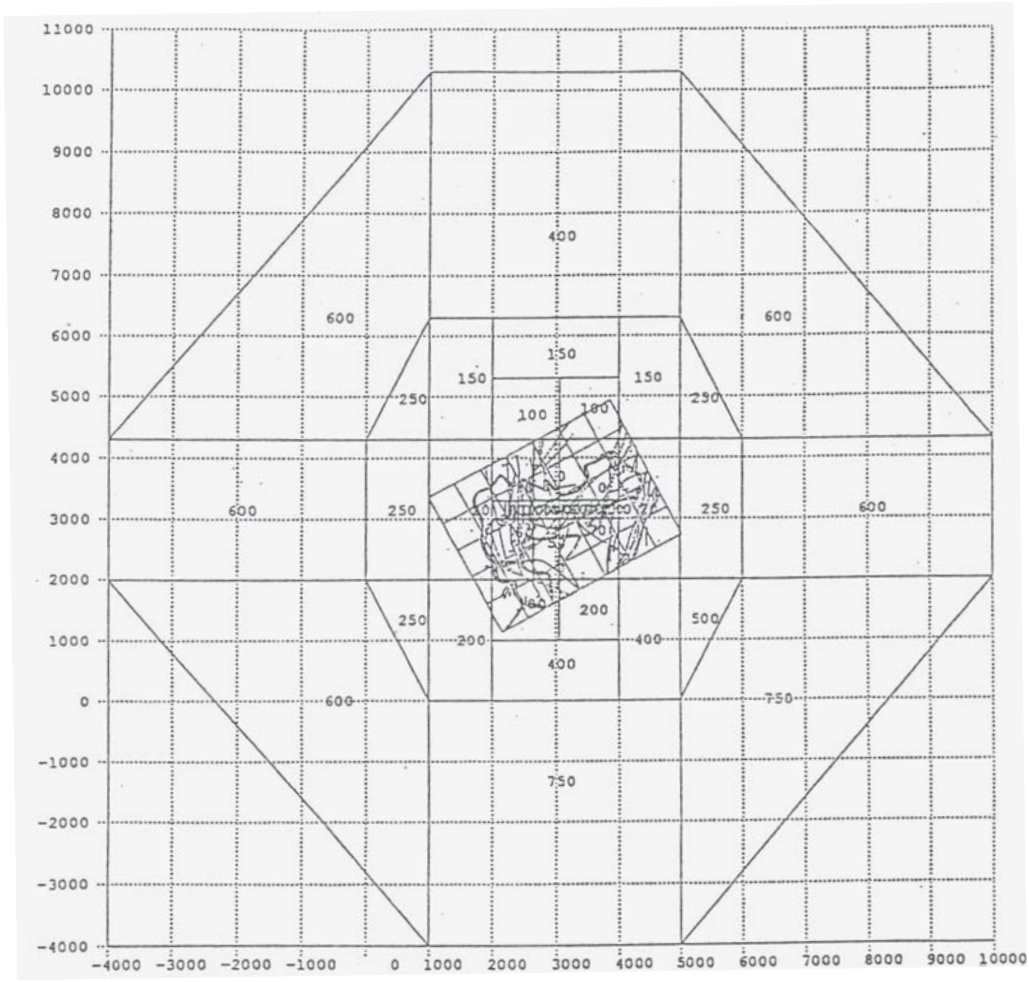

Figure 5. Plan view of the block layout for the large-scale 3-D simulation of the Reshuiwei Geothermal System. The map of Figure 2 is overlaid for reference. Surface elevations of blocks are given in metres above msl.

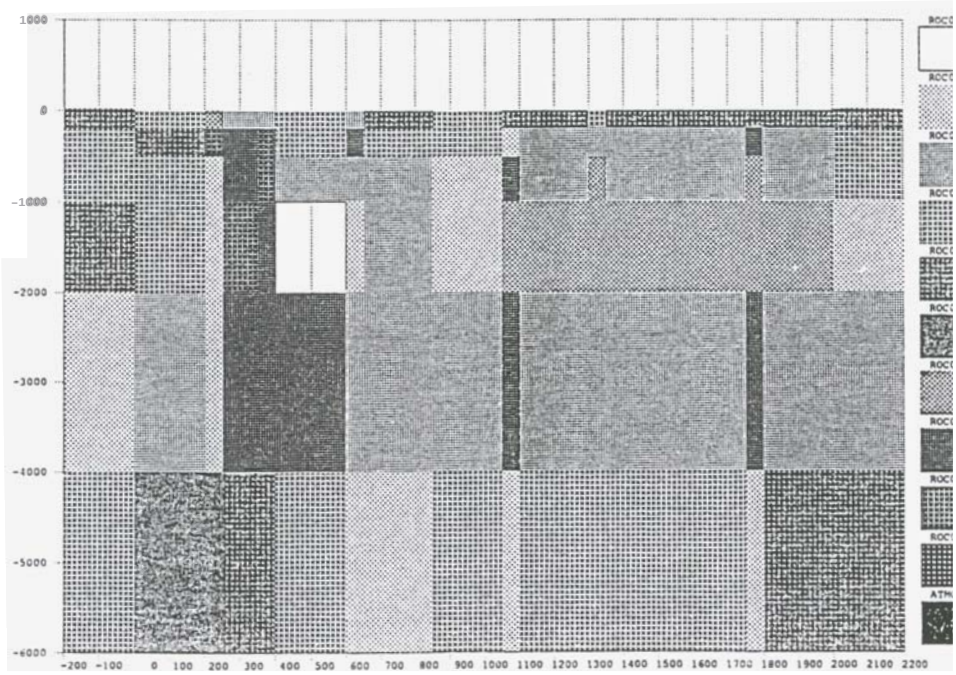

Figure 6. Rock types through a vertical section, from (2000, 3100) to (4000, 3100) of Figure 5, for the 3-D numerical model of the Reshuiwei Geothermal System. Rock parameters are given in Table 2.

Table 1 · The parameters of numerical model

Atmospheric temperature (average)	16.5 °C
Atmospheric pressure	1.05 bara abs
Input heat flow enthalpy	600 kJ/kg
Input mass flow	15-20 kg/s
Porosity range	5-15 %
Variation of permeability	0.1-300 mD
Horizontal to vertical permeability ratio	1-10 times
Mean density of all rocks	2600 kg/m^3
Thermal conductivity of rocks	2.2-3.2 W/mK
Specific heat of the reservoir rocks	1000 kJ/kgK
Number of different rock types	10

Table 2 · Parameters used in the 3-D model of the Rucheng Basin Geothermal System

Rocks	ρ (kg/m^3)	φ	k_x (mD)	k_y (mD)	k_z (mD)	K (W/mK)	c_r (kJ/kgK)
ROC00	2600	0.01	0.02	0.02	0.02	2.2	1000
ROC01	2600	0.01	0.1	0.1	0.1	3.2	1000
ROC02	2600	0.05	10.0	2.0	2.0	3.2	1000
ROC03	2600	0.05	20.0	5.0	5.0	3.2	1000
ROC04	2600	0.05	30.0	5.0	10.0	3.2	1000
ROC05	2600	0.05	50.0	10.0	20.0	3.2	1000
ROC06	2600	0.08	100.0	10.0	20.0	3.2	1000
ROC07	2600	0.15	150.0	150.0	100.0	3.2	1000
ROC08	2600	0.15	300.0	150.0	300.0	3.2	1000
ROC09	2600	0.01	0.1	0.1	0.1	2.2	1000

4.2 Model Modification Process

The final 3-D simulation model of the Rucheng Basin Geothermal System was much bigger than the 2-D model, there being 930 connections (interfaces), with a mesh of 283 elements and 50 sinks/sources. This made the simulation complex and difficult to control and modify. Correcting flow pattern, heat flow, pressure and temperature of the simulation model when run using the MULKOM *Program* was achieved by changing the input meters and initial conditions of the model as follows:

1. According to normal practice, the measured heat flow is used to determine the size or area of the simulation model. To provide enough heating for convection involves considering the parameters which affect the heat flux (normally 65-95 mW/m^2). The simulation area must also fit the actual basin of the geological setting.

2. The results of the simulation modelling depend on the input of various rock parameters of the model. These are the permeability, thermal conductivity of rock, heat flux, porosity, density, specific heat and model geometry and connections. Modifications are made by changing the permeability of each block and surface elevation when these first two items have been completed (see items 3, 4,5 below).

3. Firstly, the correct flow pattern is sought; then the permeability of the peripheral blocks (recharge blocks) was changed from high to small numerical values. The aim was to obtain the practical value of the total flow rate of the springs. This step meant that the pattern of flow in the simulation model on the macroscipic scale must be correct. It should also have a basically correct permeability structure in the small- or middle-size simulation model.

4. Changing the surface elevations of each block can also influence the flow pattern within a certain range. In any event, it must approach the actual geological setting. This is a major modification parameter.

5. When the correct flow pattern was approximately obtained, the permeabilities over a small range for each block were established. No simple words can describe the changing tendency, eg., when permeability is increased, the mass flow goes up but the temperature decreases. The reason is that there is so much water, When permeability decreases, the mass flow reduces and there is often higher temperature in the blocks. The large-size simulation model involves so many blocks and connections that changing one block's permeability influences flow in hundreds of other blocks. The key to successful large-size 3-D simulation model rests on "staying on the chair at the computer's side" in order to run the simulation many times.

5. SUMMARY AND CONCLUSIONS

A conceptual model synthesizing all basic data, has been created.

The reservoir temperature is about 140-170 °C according to the Na-K-Ca geothermometer. There are large variations in permeability though the geothermal system, which is controlled by six fault zones. Fault F3 is the major storage water band and bounds the Reshuiwei Geothermal System.

In the production zone, permeabilities are of the order of hundreds of millidarcies and range fiom 50-300 mD. The horizontal to vertical permeability ratio is between about 1-10 times.

The numerical simulation of natural steady state for the 3-D model has been achieved and a good simulation for the future predicts two choices of well outputs.

The heat source of Reshuiwei reservoir is not provided by a magma intrusion, but rather it is tectonic movement which causes the terrestrial heat flux redistribution to provide heat flow at depth in the basin (4-7 km).

By removing the previous input condition of a fixed hot inflow at depth and setting up a large size (area 136km^2, depth 6km) simulation model fitting the practical geological setting, the results are more satisfactory in that they fit a mare realistic conceptual model.

The numerical simulation of the steady-state for the 3-D model (283 blocks, 930 connections) for the Rucheng Basin Geothermal System has been achieved. The convective fracture zone of the Rucheng Basin System is a very old system. Because of the large setting up time required to obtain steady state (>0.95x10^8 yrs), this verifies that the conceptual model of the Reshuiwei (Rucheng) Project, as outlined by Chen (1990), is correct.

The method used may be useful for simulation of other reservoirs in a similar geothermal Setting. These could be termed "Basin Permeability Structure Zone Intermediate-or Low-Temperature Geothermal Systems" when the natural heat loss is less than 15 MW (thermal).

According to the results of the production simulation model, one of two ways might be chosen. One is middle-development strategy which still uses these shallow drill holes; the usage time is more than 15 years if the total well outputs are less than 35 kg/s. Another possibility is a bigger development in which well outputs sustain 60 kg/s at more than 90 °C for 20 years in this area; this suggests that deep wells (>500 m) must be drilled, but this would hinge on the economic situation of the local government. The Reshuiwei (Rucheng) geothermal area is located in steep mountainous terrain. From the simulation results the maximum amount of energy that can be exploited is approximately 30 MW (thermal). Owing to the logistics involved, it is more advantageous to use this existing energy in terms of direct use. Reservoir simulation research is an important tool for development of this area, and should be used in future planning.

Even though the results obtained from this simulation work are minimal, we believe that the methods and procedures involved are of major importance. The study forms the basis for the evaluation of any geothermal system; thus all development aspects should be considered after a study of this type has been carried out.

6. NOMENCLATURE

mD	milliDarcy (1 Darcy=10^{-12} m^2)
K	conductivity of rock (W/m K)
q	heat flux (W/m^2)
ϕ	porosity
ρ	density (kg/m^3)
c_r	specific heat of the reservoir rocks (kJ/kg K)
k	permeability (mD or Darcy)
V	volume (m^3)

7. ACKNOWLEDGEMENTS

Chen Song would like to thank Prof. Y.H. Cai for his support, and also Prof. D.H. Freeston for discussions. The authors are indebted to Department of Geology of Hunan for providing the basic data and material.

8. REFERENCES

Chen Song (1990) Numerical simulation of Reshuiwei (Rucheng) Geothermal System, Hunan Province, Southern China. Project Report GEOTHERM 90.05, Geothermal Institute, University of Auckland.

DGH (1981a) Geological map of Rucheng, Hunan, southern China. Department of Geology of Hunan, Hunan, P.R.China (in Chinese).

DGH (1981b) Report of geophysical survey of Reshuiwei (Rucheng) Geothermal System. Department of Geology of Hunan, Hunan, P.R.China (in Chinese).

DGH (1981c) Report of geological investigation of Reshuiwei (Rucheng) Geothermal Field. Department of Geology of Hunan, Hunan, P.R.China (in Chinese).

DGH (1981d) Table of forecast of Rucheng Area over the years. Meteorological Department of Rucheng, Hunan, P.R.China (in Chinese).

DGH (1981e) Table of Reshuiwei (Rucheng) geothermal fluid. Department of Geology of Hunan, Hunan, P.R.China (in Chinese).

DGH (1981f) Table and map of drilling information of Reshuiwei (Rucheng) Geothermal Field. Department of Geology of Hunan, Hunan, P.R.China (in Chinese).

Giggenbach, W. F.(1986) Graphical techniques for the evaluation of water/rock equilibration conditions by use of Na, K, Mg and Ca-contents of discharge waters. Proc. 8th NZ Geothermal Workshop 1986, University of Auckland, 37-43.

Hochstein, M. P. and Caldwell, G. (1985) Heat source characteristics of some warm and hot spring systems in China and Thailand. 1985 International Symposium on Geothermal Energy, Geothermal Resources Council, International Volume, 549-555.

Hochstein, M. P. (1988) Assessment and modelling of geothermal reservoirs (small utilization schemes). Geothermics, 17,1549.

Hochstein, M. P., Yong, Z.K. and Ehara, S (1989). "The Fuzhou geothermal system (People's Republic of China): Modelling study of a low temperature fracture-zone system." Geothermics, Vol.19, No. 1. pp. 43-60.

Hochstein, M. P., OSullivan, M. J. and Bhaddee, S. (1987) Modelling of San Kamphaeng Geothermal Reservoir. Proc. 9th New Zealand Geothermal Workshop 1987, Geothermal Institute, University of Auckland. 159-162.

O'Sullivan, M. J. and McKibbin, R. (1989) Geothermal Reservoir Engineering - A Manual for Geothermal Reservoir Engineering Courses at the Geothermal Institute, University of Auckland. Geothermal Institute, University of Auckland.