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MODELLING THE DEWATERING AND DEPRESSURISATION OF THE LIHIR OPEN PIT GOLD MINE

Stephen P. White[1]
Ashley L. Creighton[2]
Paul F. Bixley[2]
Warwick M. Kissling[1]

[1]Industrial Research Ltd.
P.O. Box 31310,Lower Hutt, New Zealand
e-mail: S.White@irl.cri.nz

[2]Lihir Management Company Limited,
PO Box 789, Port Moresby, Papua New Guinea

ABSTRACT

The open pit at the Lihir Gold Mine, Papua New Guinea is planned to ultimately reach more than 200 metres below sea level. Cooling and depressurisation of the geothermal resource associated with the gold mineralisation is an essential part of the mining operation. Eight deep, deviated geothermal wells were completed during 1999 to investigate geothermal conditions beneath the mine pit. Information from the deep well programme, together with information from the shallower mineral exploration wells drilled and tested in the 1980's has been used to develop several new numerical models using the TOUGH2 (Pruess *et al*. 1999) simulator. which incorporate the development of the mine pit, shallow groundwater, interaction with the sea and the deep geothermal resource.

Use was made of iTOUGH2 (Finsterle, 1999) running on a cluster of LINUX workstations to aid the fitting of some model parameters. Use of this program in a parallel computational environment was essential to complete the parameter fitting in an acceptable time.

A detailed model containing 70000 elements has been developed as an aid to pit wall stability calculations and this has been run on a Cray and a LINUX cluster using a multiprocessor version of TOUGH2 recently developed at LBNL (Zhang 2001).

INTRODUCTION

The Lihir Group consists of four islands, of which Lihir (or Niolam) is the largest. Lihir Island is located about 700 km north-east of the national capital, Port Moresby, and forms part of the New Ireland Province of Papua New Guinea (Figure 1).

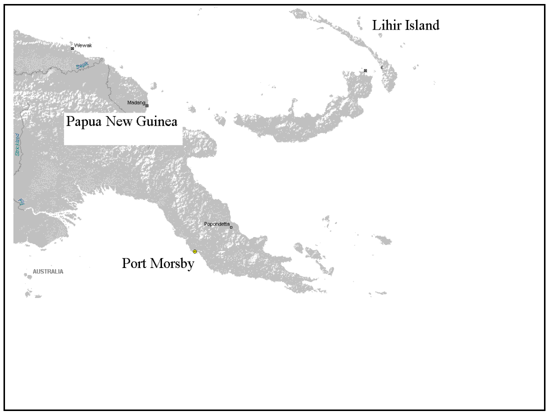

Figure 1. Location map

Lihir experiences a high rainfall, averaging about 3.7 metres per annum, with mean relative humidity of 80%. Air temperature varies between 20 and 35°C. Being situated only 3° south of the equator Lihir is not subjected to the effects of cyclones. Natural vegetation is predominantly tropical rain forest.

Geology

Lihir is made up of five Miocene-Pleistocene volcanic units, of which three are recognizable volcanic craters, including the Luise caldera, which is the youngest major volcanic centre on Lihir (refer Figure 2).

The Lihir Gold Project mineral deposits are located within the Luise Caldera, which is considered the remnants of an extinct volcano. The caldera is well defined, with the rim rising steeply to over 600 mASL in places. It is open to the north-east where it is breached by the sea to form Luise Harbour. Defined gold mineralisation occurs within an area of about 2 by 1.5 km.

Exploration work since 1983 has defined a number of adjacent and partly overlapping mineral deposits within the Luise caldera, the principal ones being

Leinetz, Minifie and Kapit, with definition of the latter being restricted due to near surface geothermal conditions.

At the end of 1999 the total gold ore resource was calculated at 93.1 Mt with an average grade of 3.74 g/t.

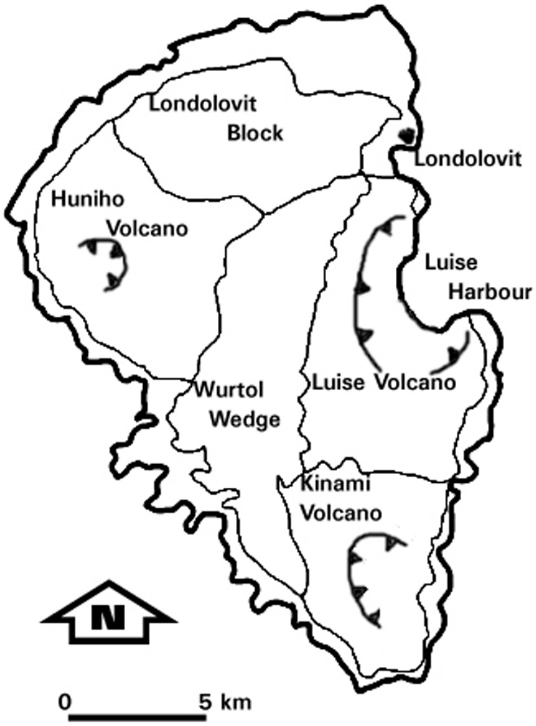

Figure 2. Simplified geology of Lihir Island showing the main volcanic units.

Mine Production

Open pit mine production began in late 1996. By the end of 1999 the base of the pit was about 70 mBSL. Total material movement at this time was about 82 Mt, 18 Mt of which was a combination of direct feed high grade ore and stockpiled low grade ore.

Open pit mining is scheduled to be completed by about 2012, at which point pit dimensions will be about 2 by 1.5 km and extend to a depth of 200 – 250 mBSL.

Geothermal Manifestations

Geothermal manifestations are common within the Luise Caldera and in places overlap the mineralised area. The geothermal surface manifestations include fumeroles, chloride springs and hot springs on the shoreline and offshore. The natural heat flow through the system is in the order of 50 MW(th).

Coordinate System

This paper uses the Luise mine grid system. Sea level is at 1000 m elevation in this system. Elevations are referred to in terms of metres relative level (mRL). Sea level is, therefore 1000 mRL.

MINE DEWATERING

Objectives

Figure 3 shows the final pit immediately adjacent to the sea and extending to depths of 200-250 mBSL. To allow successful progression of the mining schedule the shallow geothermal and groundwater system will need to be dewatered by 200-250 m.
The primary objectives of the mine dewatering system currently in place and planned are as follows:

- Depressurisation and cooling of the “shallow” geothermal reservoir.
- Interception of seawater recharge from Luise Harbour.
- Enhancing the stability of pit slopes by reducing pore pressures in the rock mass.
- Depressurisation of the “steam cap” as rapidly as possible in the vicinity of the mining area.
- Minimize the geothermal hazard for operational personnel and mining equipment.

Methods of Dewatering

To achieve the required levels of dewatering, the following methods are used:

- Horizontal Drainholes drilled from within the open pit.
- Deep Geothermal Wells.
- Steam Relief Wells.
- Pumped Dewatering Wells.

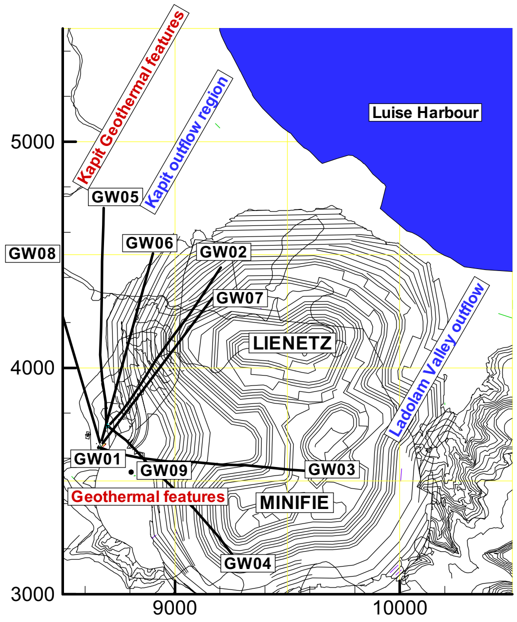

Figure 3. Field map showing location of final pit and location of recent geothermal wells.

CONCEPTUAL MODEL

The conceptual model for the shallow part of the geothermal resource is based on earlier work (Kennecott 1992) and was derived using a combination of:

- downhole temperature and water level measurements,
- pumping/interference and tidal response tests,
- fluid chemistry,
- geology,
- estimated surface infiltration,
- estimated outflow from the system.

The shallow Luise geothermal system is seen as a permeable bathtub, surrounded on three sides by low permeability rock (outside the Luise collapse structure boundary), and on the fourth side by the sea. There is a connection between the hot resource and the sea at shallow levels where most of the natural flow exits the system, while at deeper levels the sea is isolated from the geothermal resource by low permeability rock. For the undisturbed geothermal reservoir this arrangement allows outflow of hot fluids to the sea at shallow levels with minimal cold recharge to the geothermal reservoir from the sea at depth where the hydrostatic pressure is significantly greater outside than inside the geothermal reservoir. Deep recharge is spread along the western and northern sectors of the geothermal system.

There have been several estimates of the fluid flow characterising the natural state system (Allis and Henley, 1988, Feasibility Study 1992, Kingston Morrison Ltd, 1996). For the present model the flows shown on Figure 4 are used.

For the present model, the conceptual model described in the Feasibility Study has been largely retained, with refinement based on the information from the deep geothermal wells drilled in 1999. Temperatures and permeabilities encountered by the deep wells confirmed the widespread low permeability conditions below 400 mRL down to 0 mRL. Higher permeability and higher temperatures were found at depth in a limited area beneath the Lienetz area, about 1 km northeast from the GW-02 wellpad. Based on this information this area is assumed to be the deep upflow/fluid recharge zone.
Even with new information on the deeper part of the resource, some of the previous uncertainties remain. The most important of these is the full extent of the high temperature resource. Electrical geophysical surveys have been carried out, but provided limited information due to rugged local topography, the massive sulphide orebody and relatively high salinity groundwater adjacent to Luise Harbour. The southeastern flank of the resource has been proven in some detail by the mineral exploration wells and by the deep wells. However, at present there is no direct information available to determine reliably the location of the northern and western boundaries of the permeable high temperature geothermal resource. For modelling purposes, the rim of the Luise collapse structure has been used to locate the western and northern boundaries of the high temperature resource. Low permeability, cool formations are assumed to lie outside the structure with enhanced permeability and high temperatures confined within the collapse structure.

Figure 4 summarises the flows in this conceptual model. Numerical values shown in this figure are the values used in the current numerical model.

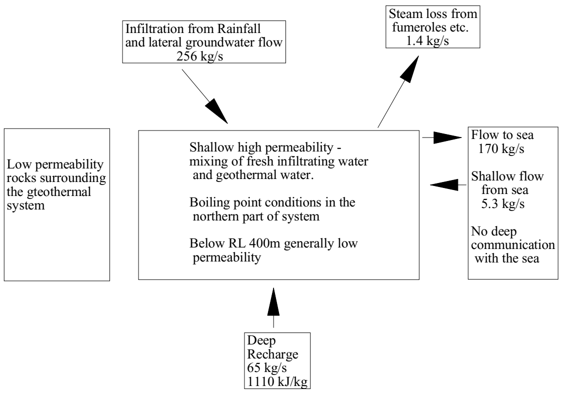

Figure 4. Conceptual model of the Luise geothermal system

NUMERICAL MODEL

There were several objectives for the numerical modeling of the groundwater and geothermal systems associated with the Luise geothermal system. Firstly there was the need to verify the conceptual model and increase our understanding of the behaviour of these systems. Second was the need to develop sound dewatering and depressurisation strategies that would allow the safe mining of the gold resource. Finally there was a need for detailed predictions of fluid pressures in the pit walls for slope stability calculations.

Modelling of the Luise geothermal system is quite challenging because of the need to represent both the shallow groundwater system and the deep geothermal system. Further complications are added by the need to include the changing topography of the ground surface as the pit is developed the rock topography both above and below sea level. Since one of the key outputs of modeling is the location of the water table we must also include the atmosphere in any numerical model. GeoCad software has been used to develop a TOUGH2 (Pruess 1991) model of this system, this simplified the inclusion of surface topography and time staging of the pit excavation. Several models have been developed to meet the different needs. Figure 5 shows the grid structure for model 1 but this topography is used in all models.

Model 1 provided a horizontal resolution of 200 metres over most of the mine pit area with a finer resolution of 60 metres between the pit and the sea. Layer thickness above 700 mRL is 40 metres with layer thicjness increasing with depth below this. The entire modelled region is divided into 24 layers and contains over 5500 elements.

Model 2 increases the vertical resolution from 40 meters to 10 meters above 700 meters RL and increases the minimum horizontal resolution from 250 meters to 60 meters in the area containing the pit.

Model 3 retains the same vertical resolution as Model 2 and decreases the minimum horizontal resolution to 12 meters in the region of the pit wall[1]

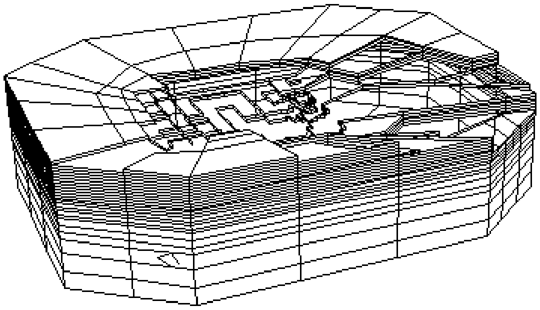

Figure 5. Grid structure for model 1.

ROCK PROPERTIES

The shallow geology (above 700 mRL) in and around the mine pit has been defined in some detail by the mineral exploration drilling. This geological model was used to define rock types in the numerical model. Interference tests carried out during the exploration phase allow initial estimates of permeability to be assigned according to some of these rock types.

Above 700 mRL the main rock types are; Siliceous Breccia (high permeability) Boiling Zone (high permeability) Clay (moderate – low permeability) Anhydrite Seal (moderate permeability), Ladolam valley infiltration area (high permeability) and ‘outside caldera’ (low permeability). Below 700 mRL, outside the caldera structure and beneath the sea there is little information available on the geology or permeability. The rapid increase in groundwater levels and the existence of perched aquifers at the margins of the caldera structure suggest low permeability in this area. The deep wells that have been drilled have found low permeability at depth in the south of the caldera. There appears to be a vertical structure with some permeability around 4200 mN.

In the undisturbed state the pressures within the geothermal resource and in the sea are balanced at about 850 mRL. Below this level, pressures beneath the sea exceed the geothermal fluid pressures. The reservoir fluid chemistry indicates that the connection to the sea at depth is poor. Accordingly the permeability between the sea and the geothermal system has been adjusted to reduce cool recharge flowing from the sea. This is consistent with the retrograde solubility of anhydrite ($CaSO_4$) with increasing temperature. Heated seawater is expected to precipitate anhydrite and the permeability of any connection between the sea and the hot reservoir would therefore diminish over a period of time. At shallow levels where hydrostatic pressure in the geothermal reservoir slightly exceeds seawater pressure, the flow direction is from the reservoir to the sea and the shallow rock types (defined by

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[1] The position of the pit wall and bottom changes in time and this is modeled in a series of 3 or 6 monthly steps. The grid of Model 3 is designed to provide a 12-meter resolution at the pit wall after each of these steps.

exploration) determine the permeability of this connection.

Below 700 mRL but within the caldera the rock is divided into three types:

fault - a high permeability zone in the upflow region,

upflow - a moderate permeability region included in the model to represent the region of geothermal fluid upflow from depth.

downflow - a low permeability region that allows a small amount of cooler vertical recharge to the deeper parts of the reservoir.

In the Ladolam Valley measurements of tidal efficiency showed the wells communicated with the sea through a zone of high permeability. The well temperature profiles indicate this was also an area with high infiltration of cool near-surface waters. In this area, high permeability has been assigned irrespective of the rock type.

BOUNDARY CONDITIONS

The base of the model, at –500 mRL, is mostly defined as a no fluid-flow boundary. A heat flow of 0.15 W/m^2 is applied to all elements of the bottom layer of the model. This represents heat conduction from hotter rock at depth. In addition to the heat flow there is hot fluid recharge into some of the bottom elements in the area.

The vertical sides of the model are assumed to be no-flow boundaries. It is considered that the areal extent of the model is sufficient to include the whole catchment likely to contribute recharge to the geothermal system. These boundaries are sufficiently far away from the geothermal system for this to be a reasonable choice of boundary condition.

The upper surface of the model represents the topography of the area. At the ground surface 'air' (actually CO_2 gas) with a temperature of 30°C and a pressure of one bar is specified. The surface thermal features in the Kapit area are represented by 'deliverability' wells.

Cold recharge to the system is largely from rain falling on the surface of the model, with a small amount of deep recharge from the sea. The rain is modelled by adding sources of 30°C water in all the elements at the surface of the model. These sources represent the portion of the rain that infiltrates into the groundwater system and mixes with the up flowing geothermal fluid. The rain does not infiltrate uniformly over the whole model but at different rates in different areas. At 1100 mRL and above, 0.15% of the rain is assumed to infiltrate into the groundwater system. Most of this is high ground with steep topography and low permeability and is not expected to absorb rain at a greater rate. Over the rest of the model 6% of the rain is assumed to infiltrate into the groundwater. In the Ladolam Valley and Kapit areas up to 50% of the rain is assumed to infiltrate into the groundwater. Contours of model infiltration rates are shown in Figure 3.

MODEL VERIFICATION

The parameters defining the model are:

- Magnitude, enthalpy and location of the sources representing the geothermal recharge into the system
- Permeability, porosity, specific heat and density of each element in the model.
- Magnitude and location of surface infiltration
- Non-condensable gas content in the deep recharge fluid

These parameters are adjusted until the model calculates an acceptable match to a number of measured or interpreted properties of the system.
The information used in calibrating this model was:

- Temperature and pressure measurements from the shallow mineral exploration wells
- Pressure and temperature measurements from the deep geothermal wells drilled in 1999
- Pressure and temperature measurements from the shallow geothermal wells
- Estimated fluid flows through the system. These values were taken from Allis and Henley (1988)
- Pressure drawdown resulting from dewatering
- Interference test results
- Chemical changes in the dewatering wells

Steady State

The first step in the verification of a geothermal model is the simulation of the natural state of the system. This is calculated by applying all boundary conditions, setting initial conditions to arbitrary values and then allowing the system to evolve in time until it ceases to change. Calculated pressures, temperatures and flows are then compared with measured or estimated values for the field in the natural state. Parameters defining the model are then adjusted to improve the match between calculated values and measured data and the model is rerun.

This process is repeated until an acceptable match to measured data is obtained.

Once an acceptable steady state is obtained, the shallow permeabilities are refined by matching the response of the dewatering monitor wells. The steady state is then rerun and parameters further adjusted to improve the match to observation.
Table 2 shows the calculated flows for the reservoir and compares these with the most recent estimated values.

Table 2. Comparison between estimated and modeled fluid flows through the Luise geothermal reservoir.

Source	Deep Recharge (kg/s)	Surface Infiltration (kg/s)	Steam from surface features (kg/s)	Outflow to sea (kg/s)
Allis and Henley	50-150	150-400	4-8	200-550
Model	65	191	1.4	256

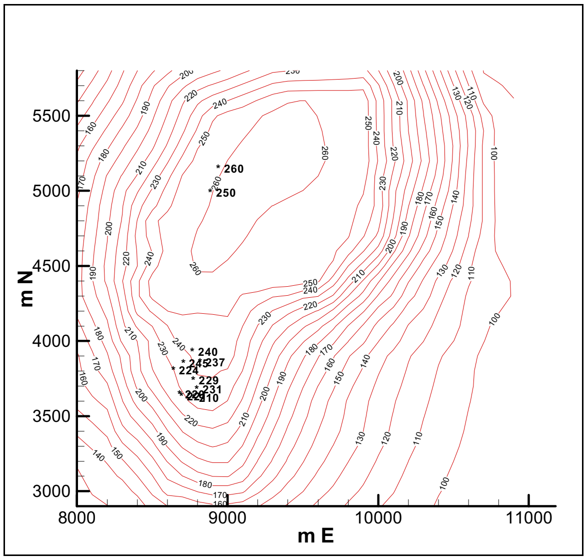

Figure 6. Natural state temperatures at RL500. Measured data is shown as spot values.

In Figures 6 and 7 comparisons between calculated temperatures and measured values are shown. Over the entire reservoir there is an acceptable agreement between the model results and field measurement. There is considerable measured temperature variation on a fine scale, reflecting local geological structures. The model does not represent this fine detail but only a more average condition.

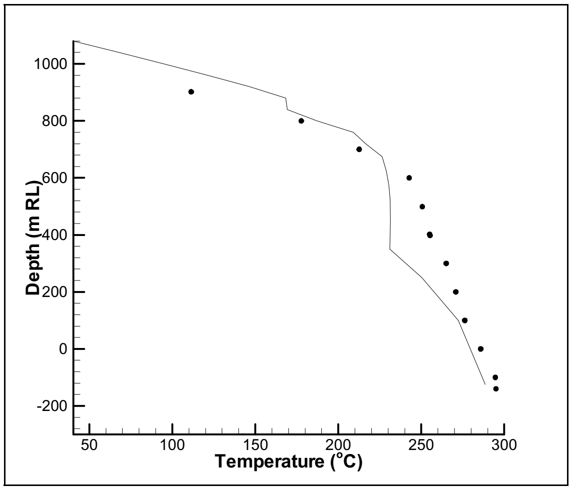

Figure 7. Match to natural state temperatures along the GW05 wellbore, measured data is shown as spot values.

Shallow Model Refinement

An extensive program of dewatering and monitoring of groundwater levels has been underway since September 1997. The data from this program has been used to refine the permeabilities assigned to the shallow areas of the model.

The procedure used was to model the dewatering over the period from September 1997 to January 2002. This produced estimates of the pressure draw down at each of the monitor wells. The permeability of regions affecting the calculated pressure draw down was adjusted to improve the match to measurement and the process repeated. This procedure used the inverse modelling program iTOUGH2, which repeatedly adjusts parameters until an optimum match to measurement is obtained.

As might be expected, the match to pressure drawdown in monitor wells was only sensitive to the permeabilities of rock types containing either dewatering wells or monitor wells. This allowed the adjustment of horizontal and vertical permeabilities of three rock types. The simulations involved are quite time consuming, as it takes about 12 hours (Athalon 1800) to simulate the dewatering period. Fortunately it was possible to take advantage of the parallel computing features of iTOUGH2 to reduce about a month of computing to a few days. Figure 7 illustrates the use of the parallel version of iTOUGH2

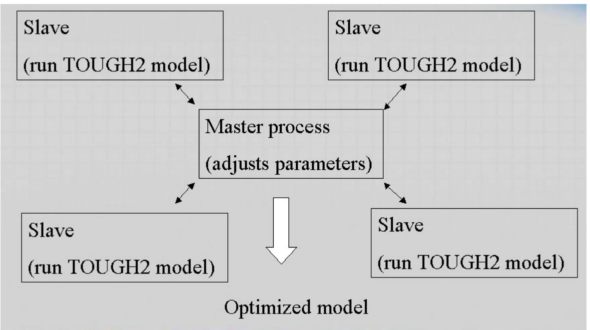

Figure 8. Parameter refinement using iTOUGH2 on a workstation cluster.

Figure 9 shows the match to pressure draw down at monitor bores in the North Ladolam region. Generally pressure draw down at the monitor wells was well matched although there were some outliers. The average mismatch over the simulated period was about 2 bars and the standard deviation of the residuals 2.5 bars.

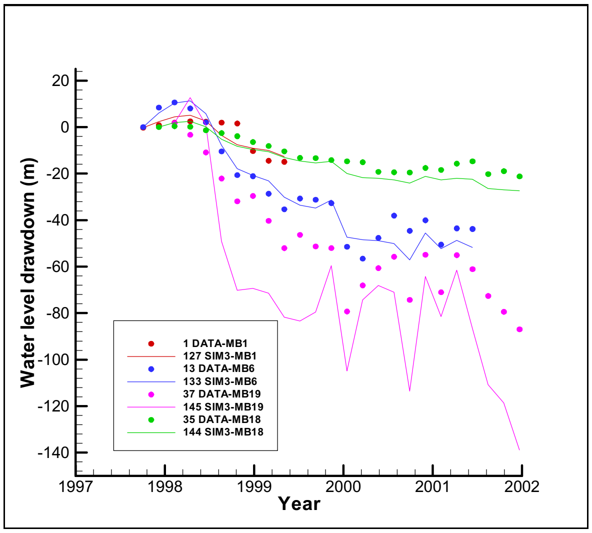

Figure 9. Match to pressure draw down in the North Ladolam region.

To increase confidence in the numerical model further we simulated the incursion of seawater into the dewatering wells. This was done using the EOS14 module of TOUGH2 that simulates reservoirs containing NaCl and CO_2 along with water. Model seawater content is shown in Figure 10, the match between measured and observed data suggests the model values are a good representation of the current state of the groundwater.

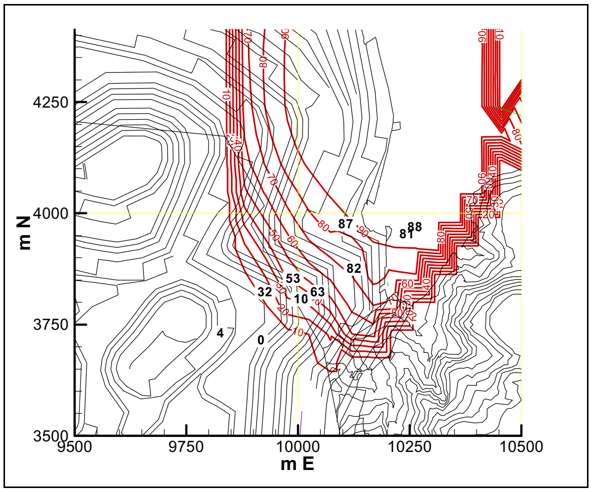

Figure 10. The red contours show calculated percentage seawater in groundwater in 2002. Measured values are shown as black numerals.

CONCLUSIONS

We have developed several models of the Luise geothermal system based on knowledge up to the end of 2001. These models share common boundary conditions and geological structure but have different mesh sizes to deal with different aspects of mining an active geothermal system.

The models provide a good match to historical data, and good match to recent pressure and temperature measurements to the west and east of the pit. Although the models have not been calibrated against the chemical changes observed in the dewatering wells they provides good predictions of changes in the chemistry of these wells.

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