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Sustainable Production Assessment of the Bacon-Manito Geothermal Reservoir, the Philippines

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ABSTRACT

Sustainable production capacity of the Bacon-Manito geothermal system (BacMan) is assessed by two models of different complexity. Base case of 150 MW electrical generation is considered and constant production up to end of Geothermal Service Contract for BacMan (year 2031). Models considered are based on the lumped-parameter and a full scale, 3D well-by-well methods. Conceptual reservoir model is proposed based on previous geoscientific research and downhole data. The geothermal reservoir has an estimated area of 23 km^2, its thickness exceeds 1500 m and temperatures range 240°C to 320°C. Lumped model predicts an annual pressure drawdown of 0.67 bars, resulting in a manageable total drawdown of 25 bars in year 2031. For the well-by-well method, a distributed parameter numerical model was developed using the simulator iTOUGH2. The simulator reduces poor matching between observed and simulated response by optimizing a set of 15 model parameters. These include mass and enthalpy of hot and deep recharge and 12 permeability values. Optimization resulted in far-field permeability of 0.5 to 5 milli-Darcies while the productive wellfield ranges from 25 to 100 milli-Darcies. Stable enthalpies of production wells are predicted for the 23 years studied, indicating that reservoir temperature drawdown will be moderate. Instead of predicting reservoir performance for tens or hundreds of year, it was decided to stop production in year 2031 and monitor recovery of heat and mass reserves using lumped and distributed parameter models.

1. INTRODUCTION

Interest in renewable energy sources has been increasing due to rising oil prices. In the Philippines, the government is aiming to lessen the utilization of high-price oil-based plants. Pursuing the Renewable Energy Policy Framework of 2003, the Philippine government aims to increase the share of renewable energy-based capacity from 4449 MWe in 2002 to 9147 MWe by 2013. 25% or 1200 MWe of this capacity will come from geothermal (DOE website).

Geothermal energy is a result of limitless heat emanating from the interior of the Earth and therefore considered as a renewable energy source. The Philippines have a considerable number of high-temperature, liquid-dominated geothermal resources and is considered as second largest geothermal producer in the world next to the United States. The Philippines has an installed capacity of 1959 MWe which generated 10.2 TWh accounting for 18.4% of the power generation mix. The rest of power generation comes from natural gas (29%), coal (27%), hydro (18%), and oil-based (8%) plants (Ocampo, 2007).

Geothermal energy, although renewable and abundant as in the Philippines, can be utilized sustainably or excessively depending on rate of exploitation. According to the former World Commission on Environment and Development:

> *"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."*
>
> -Brundtland Commission (1987)

Sustainability can be assessed by analyzing reservoir response to production load by numerical modeling. Lumped parameter models may be used at constant temperature, single-phase conditions while detailed numerical models is more appropriate when boundary recharge and two-phase conditions has to be considered.

In this study, the sustainability of Bacon-Manito geothermal resource operating at its full-load capacity of 150 MWe until year 2031 is assessed using a lumped parameter and a well-by-well numerical model. Availability of fourteen years of production data is sufficient to warrant a well-by-well numerical modeling approach. Results from well-by-well and lumped parameter models will be compared to estimate obtained from volumetric model.

BacMan is located along the boundaries of Bacon in Sorsogon and Manito in Albay, 300 km southeast of Manila in the Philippines. BacMan lies within Pocdol Mountains, a swarm of volcanic zones of late Tertiary to Quaternary age, which form part of the Bicol arc (Fig. 1). This volcanic complex is part of a NW-SE trending volcanic chain that runs through south-eastern Luzon, which includes active volcanoes such as Mt. Mayon located 35 km northwest of BacMan, and Mt. Bulusan situated 50 km southeast of BacMan (PNOC, 1985). Presently, 51 wells having vertical depths from 372 m to 2973 m have been drilled in BacMan of which 38 wells are deviated; of these wells, 22 production and 11 injection wells support Bacon-Manito.

To accomplish the study objective, the present conceptual reservoir model is first revised through careful analysis of all available downhole pressure and temperature data. Secondly, generating capacity is robustly estimated using a volumetric model. Then a lumped model is used to predict pressure response to production using pressure data from a monitoring borehole and net generation rate. Finally, a numerical model is formulated and calibrated against 14 years of production data. A program for parameter estimation, sensitivity analysis, and uncertainty propagation analysis, iTOUGH2 (Finsterle, 2007), is used to estimate model parameters.

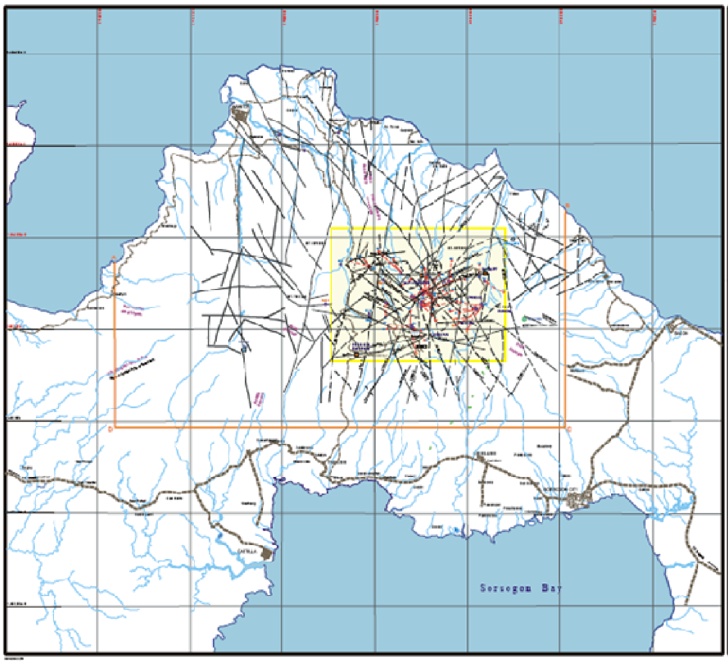

Figure 1: Location of Bacon-Manito Geothermal Field

2. SUSTAINABILITY ASSESSMENT

Axelsson et al. (2001) proposed this definition for the term "sustainable production of geothermal energy from an individual geothermal system." This definition does neither consider economic aspects, environmental issues, nor do technological advances, all of which may be expected to fluctuate with times:

> *For each geothermal system, and for each mode of production, there exists a certain level of maximum energy production, $\boldsymbol{E_o}$, below which it will be possible to maintain constant energy production from the system for a very long time (100-300 years). If the production rate is greater than $\boldsymbol{E_o}$, it cannot be maintained for this length of time. Geothermal energy production below, or equal to $\boldsymbol{E_o}$, is termed sustainable production while production greater than $\boldsymbol{E_o}$ is termed excessive production.*

In Figure 2, the difference between sustainable and extensive production is shown.

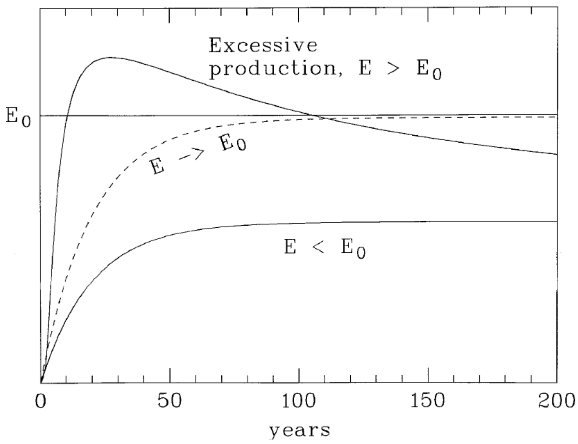

Figure 2: Difference between sustainable and excessive production (Axelsson et al., 2004)

3. CONCEPTUAL MODEL

Synthesizing physical properties from geology, geochemistry, and geophysics and including analyses of more than 300 temperature and pressure logs from 40 wells stored in geothermal database WellTaPPs (Esberto, et al., 2005), a conceptual model is proposed and used in this study.

From the conceptual model, a plume is clearly observed from the temperature planes and vertical temperature sections (Fig. 3). The source of upwelling fluid is identified by presence of fumaroles in Mt. Pangas and steam-heated waters at high elevation. Deep drilling has confirmed that reservoir fluid flows up centrally between wells OP-4D and PAL-10D. This upflowing fluid has a maximum logged temperature of 326°C.

Caprock seals upper part of Palayan-Bayan and creates a cap trapping non-condensible gases and steam from beneath (Castillo, 1990). A conductive temperature gradient is observed from temperature profiles within the upper part of BacMan wells inferring this low permeability caprock.

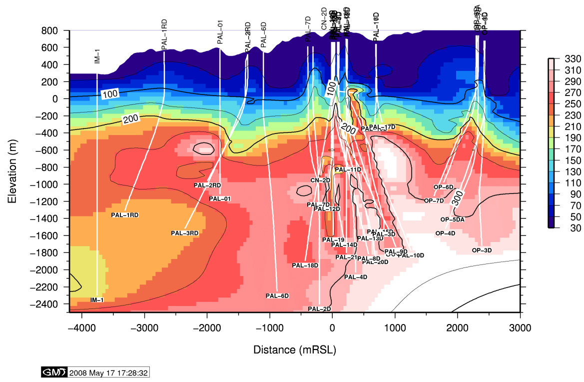

Figure 3: Temperature contour along SW-NE cross section

According to Castillo (1990), the presence of youthful volcanic rocks from Tanawon and Cawayan and mineral geothermometers done on well OP-3D also indicate a minor upflow in Cawayan.

Ramos (2002) claims that the west-northwest (W-NW) and northwest-southeast (NW-SE) trending faults have great influence on flow pattern. The preferential major outflow direction is towards the north-northwest where alkali-chloride fluids emerge as hot chloride springs at Naghaso, Pawa, and in Manito lowlands as observed by Solis et al. (1994). Inang Maharang and reinjection area of Palayan-Bayan lies along outflow path. The outflow towards Inang Maharang is observed from Figure 3 as an elongated plume towards the northwest and is supported by the downflow observed in other wells drilled in this area. According to Ramos, the southeasterly fluid flow direction towards Rangas is facilitated by structural permeabilities related to Makabug, Botong, and Dome faults. These fluid flow directions are consistent with magnetotelluric and geochemical data which define major outflows to the northwest and southeast towards Manito lowlands and Sorsogon, respectively.

4. LUMPED PARAMETER MODEL

The software LUMPFIT developed by Axelsson and Arason (1992) is used for lumped parameter modeling of BacMan. LUMPFIT simulates pressure change with lumped parameter models as an inverse problem and simulates pressure histories very accurately provided data quality is sufficient. LUMPFIT enables automatic fitting of analytical response functions of lumped models to the observed data using a non-linear iterative least-squares technique, from which reservoir parameters are estimated.

A simple lumped parameter model for BacMan field is formulated using pressure data from a centrally-located well and the total generation minus reinjection. Central well is non-productive and has therefore been used as a monitoring well since 1993. Readings are regularly checked by downhole pressure surveys. In Figure 4, it is seen that pressure changes in central well correspond very well to changes in field production.

Data set for calibrating lumped model includes pressure observations from 1993 to 2005 as can be seen in Figure 4. Reservoir response at full load capacity with BacMan 1 operating at 110 MWe, Cawayan at 20 MWe and Botong at 20 MWe is predicted using this data series. The best lumped model is a two-tank open model, which gave an R^2 value of 97%. This best model corresponds well to changes in generation rate and was able to match an observed "hump" in pressure from 2006 to 2007 due to a decrease in generation in period designated by T_{y14}. Superimposed data set from 2006 to 2007, which was not available initially for the study, was found to be in good agreement with predicted pressure trend.

Pressure drawdown is predicted to be 0.81 bar/year (closed 2 tank model) and 0.67 bar/year (open 2 tank model) using data series from 1993 to 2005. An R^2 value of 97% obtained is obtained for both 2-tank closed and open models using data series from 1993 to 2005.

In Figure 5, an imaginary no-load production scenario is simulated to evaluate reversibility after producing the field at full-load until 2031. Recovery of pressure is estimated only up to 80% since the remaining 20% of pressure takes a long time to recover. 80% recovery is attained after 39 years indicating that full-load operation is sustainable.

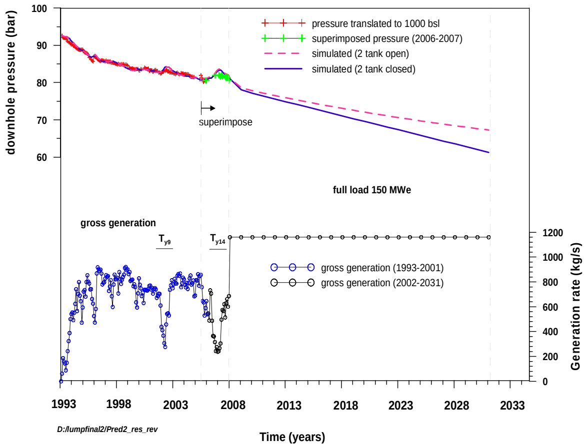

Figure 4: Observed and simulated pressure changes from 1993 to 2005

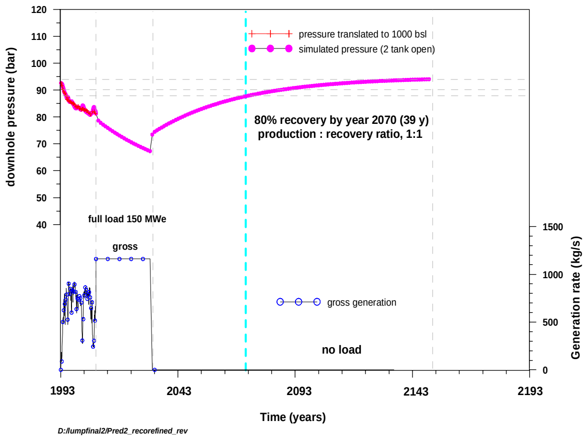

Figure 5: Simulated drawdown and recovery from lumped model

Although lumped parameter models have been developed for isothermal, single phase conditions, lumped parameter models are able to match measured responses very accurately. Care, however, should be put in using lumped models for boiling reservoirs as the governing equations is based on mass conservation only excluding conservation of heat.

5. DISTRIBUTED PARAMETER MODEL

An irregular 3-D cartesian mesh was developed using Voronoi tessalation method (Haukwa, 1998) to model heat and mass transfer within BacMan geothermal system. BacMan's new computational mesh consists of 11 layers, each layer having 277 elements, and a total of 3047 elements. The top and bottom layer and perimeter blocks are set inactive. Model mesh covers an area of 49,730 km^2 (223 km x 223 km) and is 2400 m in thickness. Vertical structure is arranged in alphabetical order starting from top (A) to bottom (K). Small grid blocks are used in mesh centre where most of wells are drilled to resolve detail with strong spatial variability while coarser block are used in perimeter where gradients are expected to be small. The model dimensions correspond to known volume of BacMan reservoir and include all of its main features (Figs. 6a, 6b).

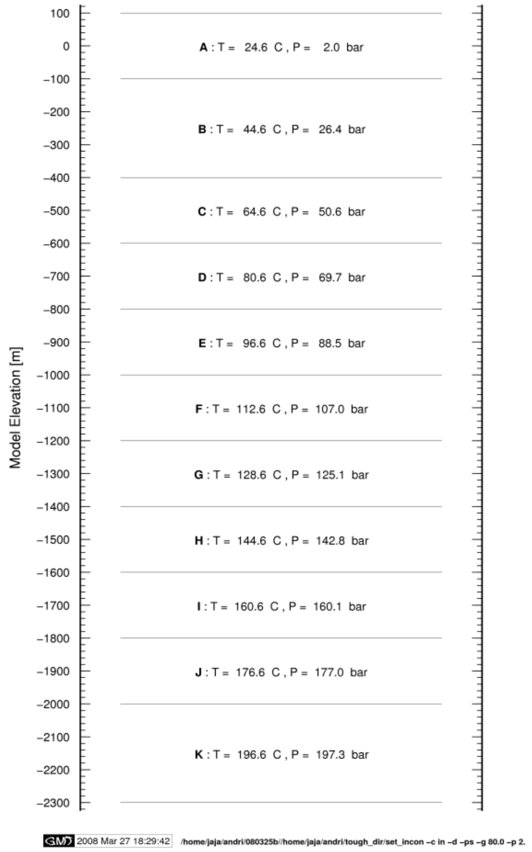

Figure 6a: Vertical layout of Bacman model

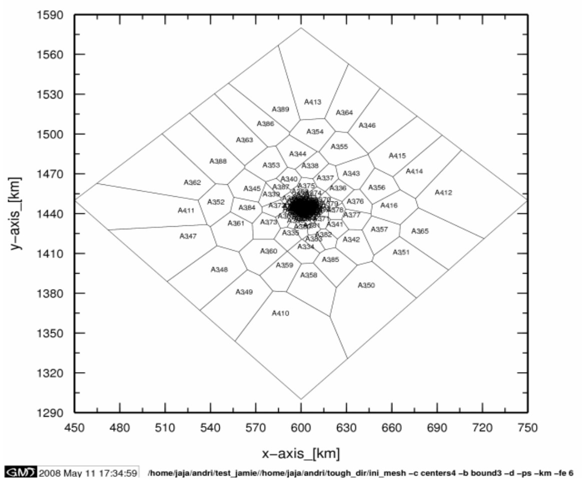

Figure 6b: Vertical layout of Bacman model

Field map is taken with well locations, resistivity boundaries, elevation contours, and major geological structures. Mesh is created in such a way that wells are separated into individual elements and mesh axes are oriented along the structural grain of the field. Mesh is extended by adding peripheral elements 90 km from production area in order to avoid artificial boundary effects. Two new preprocessors are used in this study: a preprocessor using MATLAB developed by Ketilsson (2007) and a beta version of a preprocessor written in UNIX developed jointly by Björnsson and Arnaldsson through a cooperation project between Reykjavik Energy and Vatnaskil Consulting Engineers. A UNIX script is used to create an initial input file for AMESH while the MATLAB pre-processor by Ketilsson is used for mesh refinement.

Composite plots of stable formation temperature and pressure, distribution plots of permeable zones, and wellbore models are used to decide a 2300 m deep model with 11 layers.

Similarly, composite plots of stable formation temperature and pressure, distribution plots of permeable zones, and wellbore models are used to decide locations of sinks and source. Well test results indicate presence of multiple feedzones encountered mostly between -600 and -1600 mRSL. These feed zones are associated predominantly with known faults majority of which are N-S and NW-SE trending structures.

In Figure 7, the permeability variation of elements in model mesh are inferred from temperature distribution by superimposing the computational mesh together with fault structures, well tracks, well bottom, permeable zones, and wellhead locations on temperature contours. The initial permeability distribution assigns high permeability rocks to upflow zone and lower permeability rocks further out. An isotropic model but heterogeneous permeability structures has been considered for BacMan.

Distribution of rock types within model mesh was set using a UNIX script which generates a map of all rocks in BacMan and assigns these rocks to each element. There are 12 material or rock types used. Distribution of materials in layer E using UNIX script is shown in Figure 8.

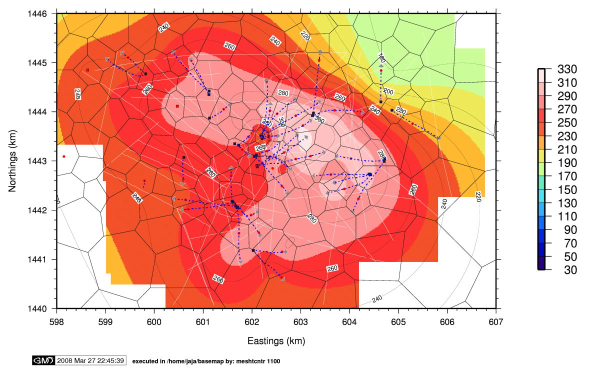

Figure 7: Mesh superimposed on temperature contour at -1100 mRSL

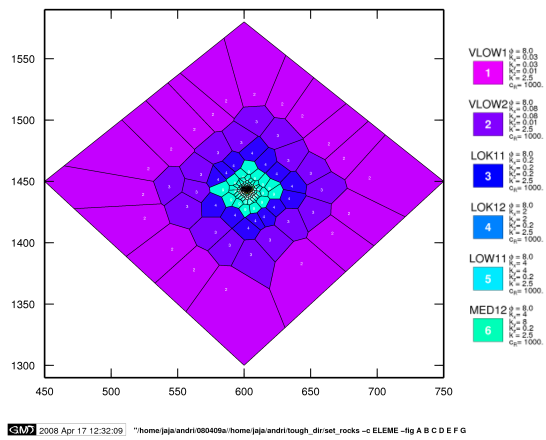

Figure 8: Permeability distribution of E-layer

A temperature gradient of 83 °C/km and initial pressure of 2 bars at sea level are set as initial conditions. The following prior information are provided to the model: hot recharge from below by hot fluid inflow and by heat conduction within a 4700 km^2 area (0.04% of total mesh area). Fumaroles are simulated by six (6) sinks on deliverability. Top layer A and perimeter elements from B layer to K layer are set to a constant temperature and pressure allowing only heat transfer and no mass transport using another UNIX script. Inactive elements can also be set manually in TOUGH2 input deck (refer to Figure 9).

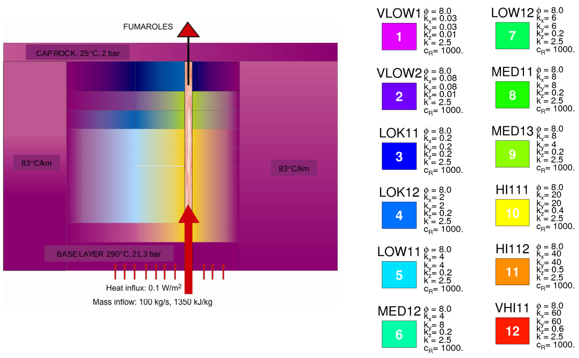

Figure 9: Permeability distribution, boundary and initial conditions

The following key observations were included in the inverse model:

- Rock temperature and pressure profiles. These were assigned to the column containing the well and linearly interpolated to give values at layer centers;
- Pressure and temperature transients. These were assigned to the block containing the well feed zone; and
- Well flowing enthalpy transients. These were assigned to the block containing the well feed zone.

Parameter estimation $\Delta \bar{p}$ was performed on 15 parameters: mass source inflow, enthalpy of source inflow, heat flux, and 12 permeability values. A logarithmic distribution is used for k_x, k_y, and k_z. Mass inflow decreased from 110 kg/s, enthalpy of source inflow increased and permeability values decreased from initial guesses. Sensitivity analysis showed that pressure drawdown is the most sensitive to the objectivity function (46%), followed by enthalpy (38%), temperature (14.3%), and pressure (1.4%).

Results of isotropic and heterogeneous model show reasonable matches between simulated and observed values of steady-state temperatures and pressures. Fine-tuning of vertical permeability is needed to get better match in temperature. Inverting multiple data sets in a joint inversion resulted to lower objective function S_{obj}.

The contour planes provide a view of how the model captures plume propagation from bottom layer to top. Figures 10 and 11 are some of the many figures showing that the numerical model is able to reasonably follow the flow features of the conceptual model.

Transient observations proved more difficult to match, hence, in order to improve model reliability, production history matching should be a continuing process. Model with parameters that are highly correlated will yield biased results and cannot readily be used for forecasting. In iTOUGH2, a correlation chart is available for checking parameter correlation. Error analysis showed that enthalpy of inflow fluid is highly correlated to mass inflow. The 12 permeability parameters have direct correlation of no more than 0.6 hence the model may be tested for prediction purposes.

Using an imaginary no-load production scenario after year 2031, the model is tested for reversibility. 80% recovery takes place after ~86 years after 21 years of production as shown in Figure 12.

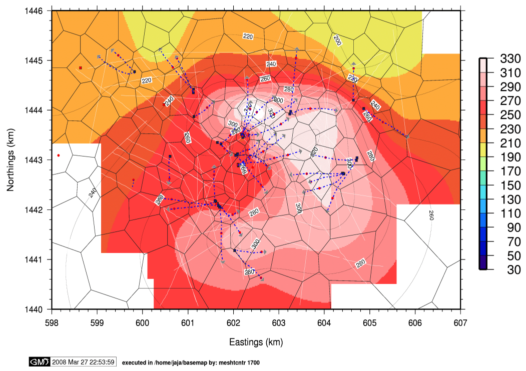

Figure 10: Temperature contours in I layer (-1700 mRSL), observed

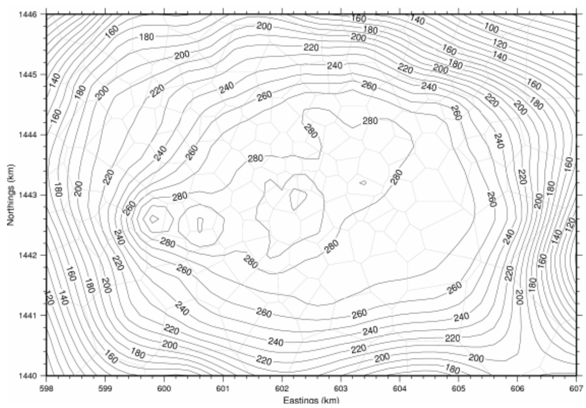

Figure 11: Temperature contours in I layer (-1700 mRSL), simulated

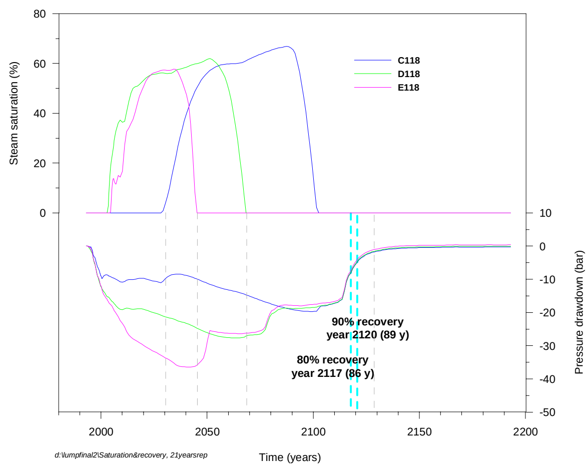

Figure 12: Steam saturation and pressure trend, 21 years of forecasted production

6. SUMMARY

Initial assessment of sustainability of Bacman was conducted by lumped parameter modelling. Fourteen years of production history was carefully analyzed to come-up with the net generation of the reservoir. Net mass withdrawal and pressure data from central monitoring well were used to set-up a lumped model. Although lumped parameter models have been developed for isothermal, single phase conditions, lumped models are able to match measured responses under two-phase conditions in BacMan reservoir very accurately. The best lumped model predicted that BacMan reservoir can support full-load operation for at least 23 more years with minimal pressure drawdown of 0.67 bar per year. The lumped model provides an optimistic scenario where pressure recovery at 80% takes 39 years, for a recovery ratio of 1:1.

Availability of 14 years of production data justified a well-by-well numerical modeling approach. For the well-by-well method, a distributed parameter numerical model was developed using the simulator iTOUGH2. The detailed numerical model included boundary recharge, a reservoir property which allows successful utilization of a resource for generations, which makes it preferable when it comes to addressing environmental issues like sustainable development and renewable power generation. Detailed numerical model accounted for most of the field data requiring major effort. The model mesh covers an area ~49730 km^2, has 11 layers and 3047 elements.

The simulator reduces poor matching between observed and simulated response by optimizing a set of 15 model parameters. These include mass and enthalpy of hot and deep recharge and 12 permeability values. Optimization resulted in far-field permeability of 0.5 to 5 milli-Darcies while the productive wellfield ranges from 25 to 100 milli-Darcies. Sensitivity analyses show that the model is most sensitive to pressure drawdown data followed by enthalpy of flowing wells. Correlation chart shows model parameters are not strongly correlated hence the detailed numerical model may be used for prediction. Since this a study on sustainability, the wells were put on forced mass production except in predictions where make-up wells were put on deliverability. Numerical model predicts total pressure drawdown to be 40 bars by 2031. The numerical model provides pessimistic scenario where pressure recovery at 80% takes 86 years, for a production: recovery ratio of about 1:2. Detailed numerical modeling showed that both mass and heat mining are reversible.

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