Update of a Lumped Parameter Model of the Miravalles Geothermal Field, Costa Rica

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ABSTRACT

Lumped parameter modeling is a valuable alternative to the complex process of numerical modeling of a geothermal field. In spite of limited capacity, this modeling process can give an idea of the possible evolution of a geothermal field under different, easily envisioned production scenarios.

In this paper, the results obtained in a new estimation of the behavior of the Miravalles reservoir are compared with the conditions observed in a previous lumped parameter model.

1. INTRODUCTION

The Miravalles Geothermal Field is a high-temperature liquid-dominated reservoir and has been under commercial exploitation since 1994, when its first power plant unit came online. Further development has added four more units, the last one commissioned in late 2003, which increased the installed capacity of the field to 163 MWe (Vallejos et al., 2005).

The main productive area is around 10 km^2, where most of the actual productive wells are located (Figure 1). However, there is good evidence that the reservoir area is much bigger. The actual proven productive area can be extended to about 15 km^2, since some of this area is used for reinjection purposes (Figure 2). Wells PGM-22, 24, 28 and 29 are used as injectors; however, they are capable of producing (the latter two can produce 10 and 12 MWe respectively).

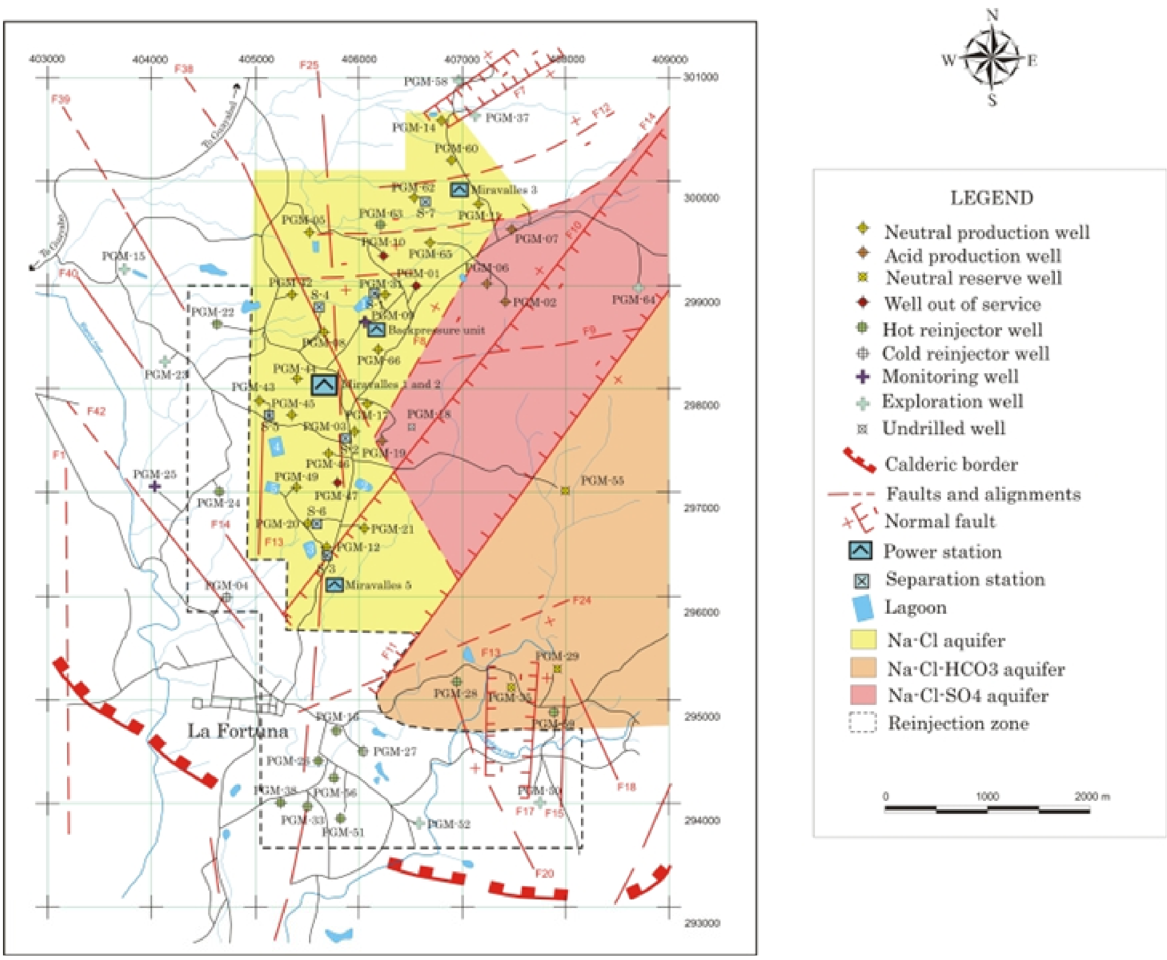

Figure 1: The Miravalles Geothermal Field.

2. PRODUCTION HISTORY

The Instituto Costarricense de Electricidad (ICE) commissioned the first 55 MWe power plant in March of 1994. However, this plant works on a regular basis at nearly 60 MWe. Between 1995 and 1998 three 5 MWe wellhead units were added and produced an additional 15 MWe (but consuming a steam-rate equivalent to 30 MWe, compared with the first unit). Two of them, owned by Comisión Federal de Electricidad de Mexico were retired in August 1998 and January 1999, and the third one was producing sporadically, taking its steam from the wells located at the central part of the field. A second 55 MWe unit was commissioned in August 1998. Another 27.5 MWe power plant was commissioned in March 2000 and operated under a BOT contract for Geoenergía de Guanacaste, a subsidiary of Oxbow-Marubeni. All of these plants are single-flash type units. The last unit added, commissioned in November 2003 by ICE, is an 18 MWe binary unit. In late 2005, the remaining wellhead unit was moved from its original location at well PGM-29 in the south part of the field. Under this scheme, ICE is the sole owner and operator of the field.

There have been some changes in the production and injection strategies in the field. From 1994 to 1998, two thirds of the total waste brine was injected to the western part of the field (equally distributed in wells PGM-22 and PGM-24) and the rest in the southern part of the field (wells PGM-16 and 26). From 1998 to 2000, the production was doubled, and so too were the extraction and injection rates. The injection to the west was decreased to half the previous rate, and the balance was shifted to the wells in the southern part (PGM-16, 26, 51, 52, and 56). From 2000 to 2002, the production was again increased by 25%, and injection was directed to the south. From November 2002 to date, injection to the south was decreased to a rate similar to the injection levels in 1998 and redirected to the west (PGM-22 and PGM-24). This injection strategy was done to minimize the pressure drawdown observed in the field based on the reservoir monitoring conducted and the results of the numerical modeling studies (GeothermEx Inc., 2002).

Figure 3 shows the mass production observed in Miravalles. The rates are obtained by correlating the wellhead pressures of the different wells with their respective output curves. Day 0 corresponds to March 25, 1994 (Vallejos, 1996). Around 1610 kg/s of total mass are extracted from the reservoir under full capacity conditions, and 280 kg/s are steam used for generation (Moya and Nietzen, 2005). All the waste water is injected back into the reservoir. Annual maintenance of the different power plants is historically scheduled during the second half of every year; this explains the observed decrease in mass production during the corresponding periods.

3. RESERVOIR PRESSURE MONITORING

Monitoring of the reservoir pressure drawdown started three months after the commissioning of the first unit in March 1994. This is mainly done by a downhole pressure data gathering system (Vallejos et al., 1995 and Vallejos, 2005). The reservoir pressure is also monitored by taking hydraulic water levels in all the idle wells (Castro, 2008). Among these wells there are PGM-58, 64, 15, 23, 25, 27, 59 and 35.

Well PGM-09 was the first well utilized for pressure drawdown monitoring. Other wells located in different places around the field (Figure 2) have been used as continuous monitoring wells (PGM-08, PGM-28, PGM-52, PGM-47, PGM-25, PGM-59) for different amounts of time. However, well PGM-09 has the most extended and complete pressure drawdown history observed. The different pressure drawdowns observed around the field are shown in Figure 3.

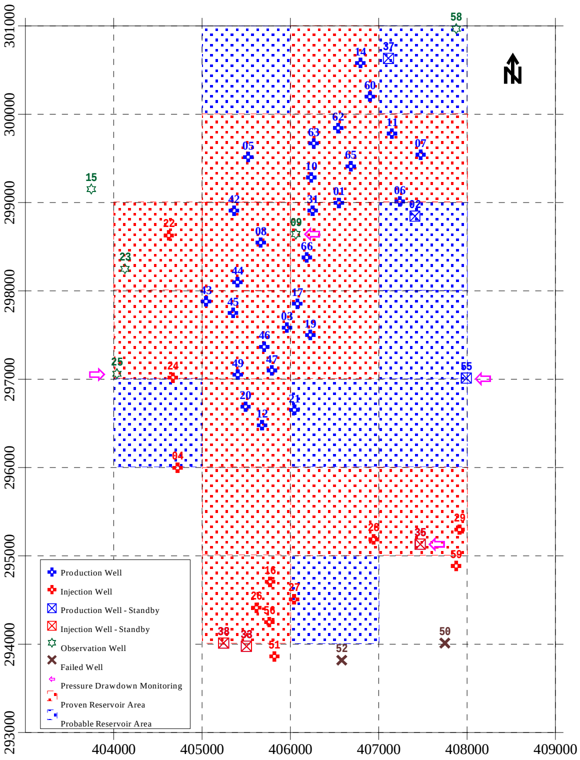

Figure 2: Schematic View of the Miravalles Field.

Since the pressure drawdown monitoring system was not available prior the commissioning of the power plant, an initial reference pressure for PGM-09 and other monitoring wells was missing. In order to find this reference pressure and thus convert the collected pressure difference data in well PGM-09 to absolute pressure, some calculations were made to find this value (Vallejos, 1996). This same procedure was followed with the other monitoring wells, also taking into account the pressure drawdown observed in the reservoir history.

3.1 Well PGM-09

Well PGM-09 is located at the center part of the field, and it has been used as a monitoring well from June 1994 to the present. Because of its location, the well is believed to best represent the overall pressure drawdown of the field due to its closeness to the main mass extraction area.

In 13 years, the overall pressure drawdown in well PGM-09 was almost 27.5 bar, giving a drawdown rate of about 2.03 bars per year. This decline has shown five distinct responses (Figure 3) over the production history: an initial response starting at the first plant commissioning time in early 1994; a second behavior related to the second plant commissioning in late 1998; a third one when the third unit started operations by middle of 2000. A fourth period started around April 2004 and lasted until March 2006 when the pressure decline was somewhat stabilized; this coincided with some reduction in the mass extraction to the reservoir. The last period (November 2006) again showed an increased pressure decline.

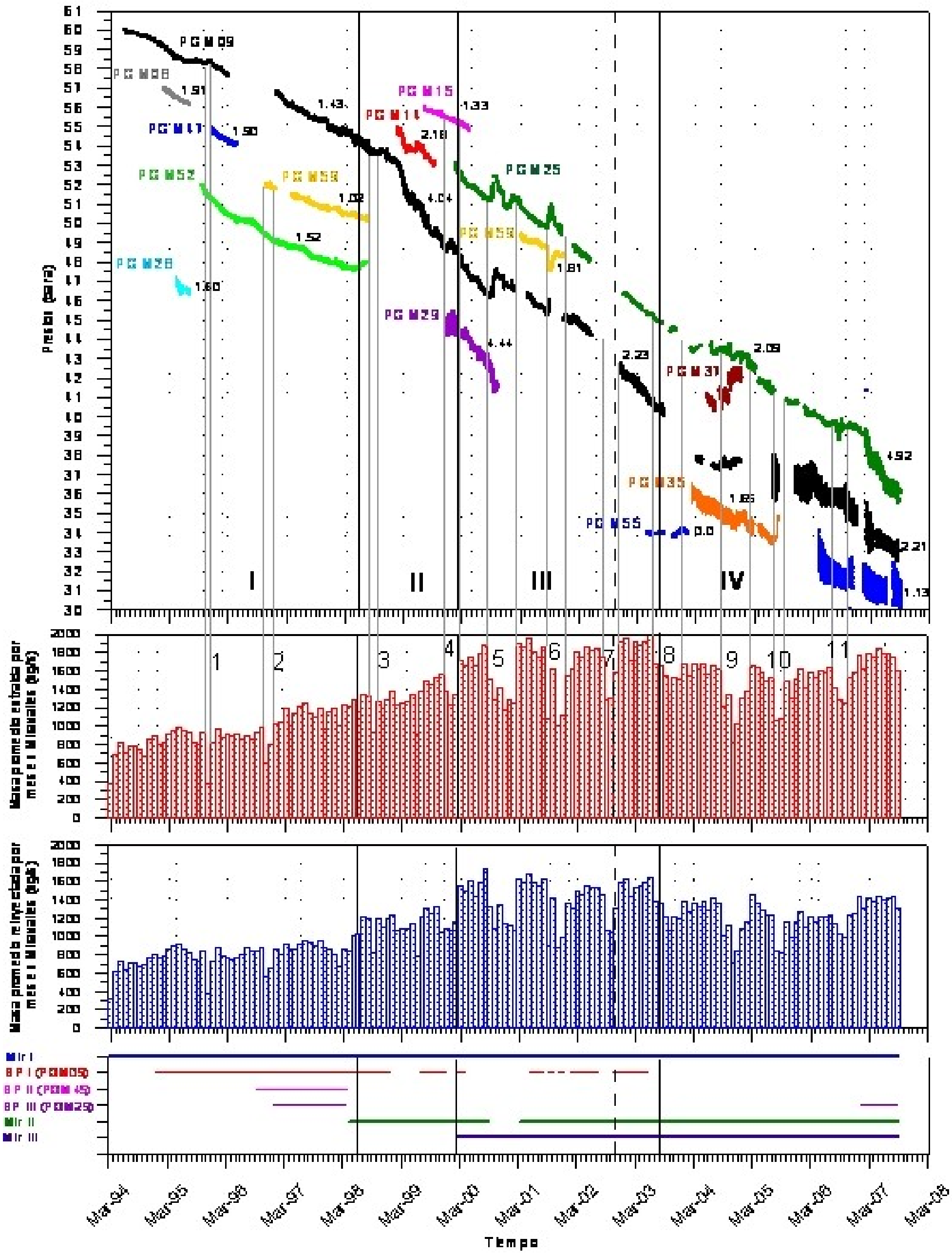

Figure 3: Pressure Decline Trends in Different Monitoring Wells and Production at the Miravalles Geothermal Field from October 1993 to September 2007 (from Castro, 2007).

3.2 Well PGM-25

Well PGM-25 is located at the western part of the field. The monitoring unit was placed and has monitored the pressure drawdown since early 2000. This well is close to the well PGM-24, one of the big reinjector wells of the eastern zone. It is believed then that its closeness to the reinjection zone should be reflected in the pressure behavior.

In 13 years, the overall pressure drawdown in well PGM-25 was almost 23.8 bar, giving a drawdown rate of about 1.76 bars per year. This decline has shown few distinct responses (Figure 3) over the production history: an almost constant pressure decline until April 2007, when the pressure decline rate increased. As in well PGM-09, this well also showed stabilization in the pressure starting in April 2004, but it lasted for shorter time.

3.3 Well PGM-35

Well PGM-35 is located at the southeastern part of the field, and it was used as monitoring well for about seventeen months between the years 2004-2005. This part of the reservoir is slightly different from the rest of the Miravalles reservoir, and is characterized by a sodium-chloride bicarbonate aquifer that presents severe $CaCO_3$ scaling at depth. This condition is observed in all the wells of Miravalles, but is higher in this well than the others.

Before this well PGM-29 was used as a monitoring well in that area (Vallejos, 2005), but it had to be replaced since the wellhead unit was moved there because some concerns of the pressure decline observed in the central part of the field and after numerical modeling studies were conducted (GeothermEx, Inc., 2002). In those months, the overall pressure drawdown in well PGM-29 was 2.56 bar, giving a drawdown rate of about 1.84 bars per year (Figure 3), but considering since the beginning of exploitation in 11 years the pressure drawdown was 22.5 bars or 1.98 bars per year.

3.4 Well PGM-55

Well PGM-55 is located in the eastern part of the field in the section known as the "window" (a small area not covered by a recent lava flow). This well can be characterized as a well belonging to the same sodium-chloride bicarbonate aquifer related to wells PGM-35 and PGM-29.

During the time the well has been monitored, the pressure drawdown observed has been 2.95 bars or 0.70 bars per year (Figure 3). In 13 years, the overall pressure drawdown in well PGM-25 was almost 19.8 bar, giving a drawdown rate of about 1.47 bars per year. The well has shown an initial stable behavior related with the stabilization showed in the other monitoring wells (2004-2006). However, it must be noted that the well had a period of about 2 years (March 2004 to April 2006) after its initial monitoring period (June 2003 to March 2004) when no data was taken (the pressure monitoring unit was moved to well PGM-35).

4. RESERVOIR RESPONSE TO EXPLOITATION

Figure 3 shows the declining trends measured in some wells around the field by the different downhole pressure gathering units installed. The reservoir pressure has declined continuously with time, and north and central zones are the most affected by exploitation.

A good correlation between the reservoir pressure decline and the commissioning of each power plant is observed, where an increase in pressure drop is observed for an increase in mass extraction. Moreover, an immediate recovery in reservoir pressure is observed when the mass extraction was decreased during maintenance of the different power plants (Figure 3). This clearly indicates the hydraulic connection between the wells located in the central-western part of the field. These short periods of maintenance have also produced in some cases an increase in the reservoir pressure. However, this recovery has not been high enough to compensate the total pressure decline observed during the entire Miravalles production history as can be observed from Figure 3.

There is also some connection between the injection and production sectors of the field. The main effect has been positive, as the injection fluids provided pressure support in the reservoir. This effect is mainly related with the injection zone located at the western part of the field (PGM-22 and PGM-24) and its relationship with the north and central parts (where the majority of production wells are located). Injection in the southern part of the field has reflected some minor thermal breakthrough in the closer production wells (especially well PGM-12). Results of the numerical modeling using TOUGH2 have recommended maintaining the injection load in the western part of the field (GeothermEx, 2002) to provide pressure support to the central part of the field.

5. RESERVOIR MODELING APPROACH

Lumped parameter modeling is a simple method where the reservoir is modeled in different parts, each of them having some distinct hydrological properties. Those properties are lumped together, simplifying the reservoir characteristics into a few dependent variables (Axelsson and Arason, 1992). The method visualizes the reservoir as a network of separate tanks and resistors, each of them representing different parts of the reservoir (tanks) and permeabilities (resistors). This network can be open or closed to a constant pressure boundary (Axelsson, 1989). An automated, least squares inversion program, LUMPFIT, is available for solving the parameters that define the lumped models that would fit the observed pressure and production history of the reservoir (Arason and Björnsson, 1994).

Simulations were carried out in wells PGM-09, PGM-25, PGM-35 and PGM-55. Since PGM-09 has the most complete pressure drawdown history (about 14 years from October 1993 to September 2007), its corresponding model provides more confidence than the rest of the models.

These simulations were carried out using either a single closed model or a single open tank model, for each of the different cases. Just in one case a two-tank closed model was used. The available set of historical data for the monitoring wells was used in the simulation runs. Steam flows were used in the modeling process since all the separated brine in Miravalles is injected back to the reservoir, but total mass flow simulations were also done.

5.1 Well PGM-09

An excellent match between the observed and calculated pressures behavior was obtained using an open tank model, giving a determination coefficient of 99.3%. The modeling results are presented in Figure 4 including the future reservoir response estimated by the model.

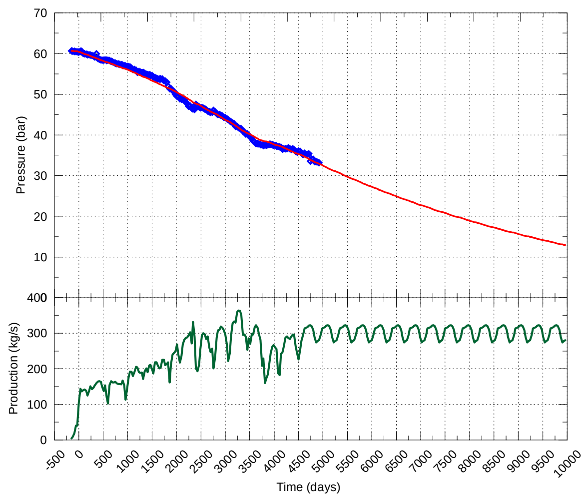

Figure 4: Matching and Prediction of the Future Reservoir Pressure (PGM-09) – Steamflow Rate.

There is also a continuous pressure drawdown observed under the actual exploitation regime over the 10000-day (27.4 years) simulation period. The overall pressure drawdown is 47.7 bar or 1.72 bar per year.

The model produced a continuous pressure drawdown under the actual exploitation regime (about 2000 kg/s of total mass and about 300 kg/s of steam flow) over the simulation forecasted period. The overall pressure drawdown is 20 bar or 1.45 bar per year. The forecasted pressure drawdown tends to reduce and it can be seen that the reservoir pressure would tend to stabilize sometime in the future.

5.2 Well PGM-25

An excellent match between the observed and calculated pressures behavior was obtained using a closed tank model, giving a determination coefficient of 98.8%. The modeling results are presented in Figure 5 including the future reservoir response estimated by the model.

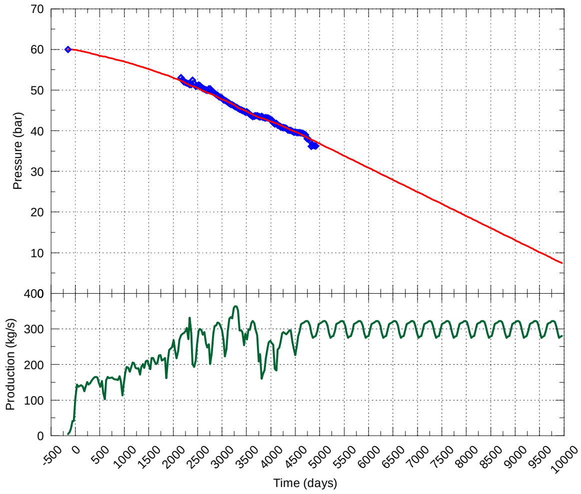

Figure 5: Matching and Prediction of the Future Reservoir Pressure (PGM-25) – Steamflow Rate.

The forecasted pressure drawdown does not show stabilization and it descends continuously, having an overall pressure drawdown of 52.9 bars or 1.91 bars per year.

The overall pressure drawdown over the forecasted period is 30.2 bar or 2.19 bar per year. This is a somewhat unexpected result since its closeness to the reinjector well PGM-24 should have given it some pressure support. This pressure support was not seen in the period monitored. However, there is a hypothesis in the sense that well PGM-24 has not given a good pressure support to the central part of the field. This hypothesis is partially supported by the continuous annual monitoring of the nearby wells, but it actually needs more data to be completely proven.

5.3 Well PGM-35

A good match between the observed and calculated pressures behavior was obtained using an open tank model, giving a determination coefficient of 91.3%. The modeling results are presented in Figure 6 including the future reservoir response estimated by the model. The short pressure drawdown history of this well is a negative in regard to the accuracy of this result and must be taken into account when analyzing the behavior of the zone where the well is located.

The model forecasts a steady pressure drawdown of 55.6 bar or 2 bar per year over the 10000-day simulation period. The forecasted period shows a higher pressure drawdown, showing a 33.3 bar pressure drop or 2.41 bars per year. This pressure drawdown cannot be related with the recommissioning of the wellhead unit in the wellhead PGM-29, since it happened after the pressure monitoring equipment was placed and also retired from well PGM-59.

5.4 Well PGM-55

A fair match between the observed and calculated pressures behavior was obtained using a two-tank closed model, giving a determination coefficient of 86.3%. The modeling results are presented in Figure 7 including the future reservoir response estimated by the model.

The overall pressure drawdown over the 10000-day simulated period was 34.8 bar or 1.26 bar per year. The pressure drawdown over the forecasted period was 15 bar or 1.09 bar per year.

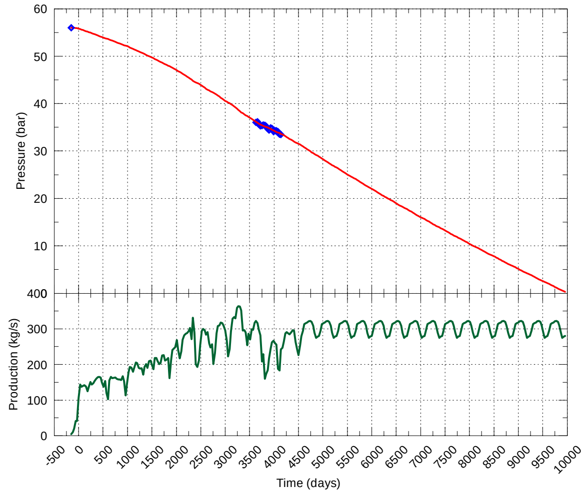

Figure 6: Matching and Prediction of the Future Reservoir Pressure (PGM-35) – Steamflow Rate.

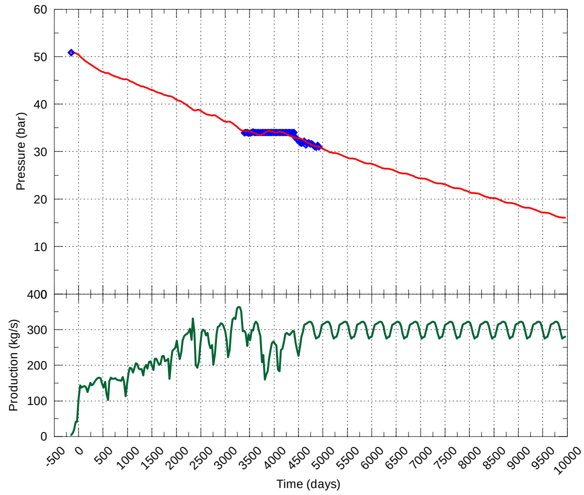

Figure 7: Matching and Prediction of the Future Reservoir Pressure (PGM-55) – Steamflow Rate.

The pressure drawdown in this well was the smallest observed in the monitored wells. The zone where well PGM-55 is located has not been intensely exploited due to the high CO_2 content present; only well PGM-29 has been produced but it is more than 1.6 km from PGM-55. This poses an interesting question regarding the relationship between the eastern-southeastern sodium-chloride bicarbonate aquifer and the sodium chloride main aquifer in the central part of the field. This eastern-southeastern zone is envisioned as either an expansion zone for the Miravalles Field or a zone that can give support for maintaining the installed capacity production at the actual levels (Sánchez et al., 2010).

6. DISCUSSION AND COMPARISON WITH PREVIOUS MODEL

A previous development of a lumped parameter model of the Miravalles Geothermal Field was made in 2004 (as discussed in Vallejos, 2005). This approach was made considering the wells PGM-09, PGM-14, PGM-29 and PGM-52. These wells had pressure monitoring units in different times of the field exploitation, being that only well PGM-09 had a pressure drawdown recorded during almost all the Miravalles Field exploitation history. The modeling parameters obtained for the whole models of the new estimation are shown in Table 1.

Table 1: Best-Fit Reservoir Parameters.

	WELLS			
	PGM-09	**PGM-25**	**PGM-35**	**PGM-55**
Parameters	**1 Open Tank**	**1 Closed Tank**	**1 Open Tank**	**2 Closed Tank**
A	$0.3309x10^{-4}$		$0.2670x10^{-4}$	$0.7619x10^{-4}$
L	$0.1518x10^{-3}$		$0.5514x10^{-4}$	$0.2384x10^{-2}$
B	0	$0.1986x10^{-4}$	0	$0.9566x10^{-5}$
κ_1	$0.7834x10^{+11}$	$0.1305x10^{+12}$	$0.9707x10^{+11}$	$0.3023x10^{+11}$
κ_2				$0.2407x10^{+12}$
σ_1	4.58629		2.06488	24.69620
Det. Coef.	99.340	98.813	89.446	86.308

For this paper it was not possible to continue the evaluation of the same wells, because in most of them the pressure monitoring units were removed for various reasons. The only well that remained was PGM-09, and the wells PGM-25, PGM-25 and PGM-55 were added. For comparison purposes, the forecasted pressure behavior of the previous model for well PGM-09 was compared against the corresponding new model. Also, it was tried to compare the possible evolution of the models by using the forecasted pressure behavior of well PGM29 (made in 2004) against the forecasted pressure behavior of well PGM-35. This was considered because these wells belong to the same area and are less than 500 m from each other.

In the case of PGM-09, the previous model was rerun with the updated mass extraction data and a new estimation for future steam production in order to compare the models under similar conditions; the results are shown in Figure 8.

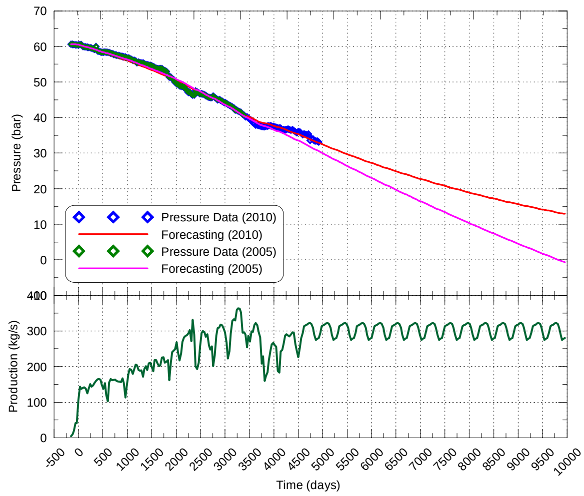

Figure 8: Matching and Prediction of the Future Reservoir Pressure (PGM-09) – Steamflow Rate: Comparison Between Previous and Updated Lumped Parameters Model.

As can be seen from Figure 8, the forecasted pressure behavior with the newer model shows that the mass extraction is impacting the reservoir pressure less than in the previous model. This can be explained for a possible combination of reasons: 1) the reservoir has evolved and actually is developing a bigger steam cap in the northern zone of the field which appears to be extending to other zones of the reservoir; this means that more steam available allows the extraction of less mass thus reducing the pressure drop; 2) after the year 2004 the reduction in the mass extraction of the field has been reinforced, taking advantage of the annual maintenance of the different power plants at Miravalles; it has been tried to extend the time the power plants generate electricity at an amount below their installed capacity; 3) the reinjection scheme was improved, trying to divert as much water to the western zone as possible. This appears to have reduced the pressure drawdown in the wells located at the central part of the field (including PGM-09).

Wells PGM-29 and PGm-35 share some similarities, starting with the fact that both wells belong to the same zone (south zone). Both wells have only short pressure monitoring history; for this reason in both cases the lumped parameter models developed had a poorer determination coefficient (less than 90%). The forecasted pressure behavior of both wells is shown in Figure 9.

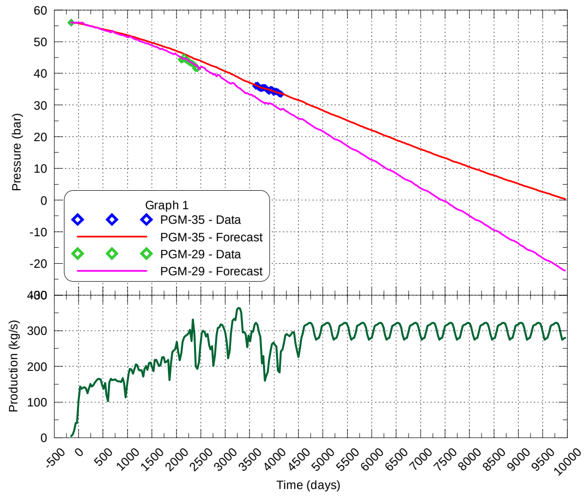

Figure 9: Matching and Prediction of the Future Reservoir Pressure (PGM-35 and PGM-29) – Steamflow Rate: Comparison Between Previous and Updated Lumped Parameters Model.

As can be seen, well PGM-29 (with the model developed in 2004) presents a higher pressure drop compared with the one belonging to the well PGM-35 (with the newer model). However, the pressure drawdown in both cases is higher than the one observed in PGM-09. It seems that the diverting of water from the reinjection wells located closer the wells PGM-29 and PGM-35 in favor of a higher reinjection in the western zone can be impacting the reservoir pressure in the south zone of the field. As well as PGM-09, it can be seen that the pressure drop is reducing with the new model data (taking the license of considering wells PGM-35 and PGM-29 both as the same well); the overall effect of the evolution of the field to a higher steam fraction against the reduction in pressure support of the zone due to the shifting of reinjection is that the pressure will fall in a higher rate than the drop in the central part of the field. The mixing of pressure drawdown data of both wells as a single one would show a less decrease rate, but this exercise must be carefully reviewed prior to considering it as a valid situation.

7. CONCLUSION

The results of the lumped parameter models discussed in this paper are in good agreement with the pressure drawdown observed in the Miravalles Geothermal Field up to date.

The models presented in the last section suggest a continuous pressure drawdown in the production zones of the field, as shown in the results of PGM-09 and PGM-35 lumped parameter models. The pressure drawdown predicted is about 1.72-2.41 bar per year. The central zone seems to be less affected than the south productive zone.

The results in well PGM-35 must be considered carefully, since the pressure drawdown history has very few data compared to the extended history of well PGM-09 or well PGM-25. If we consider the history of wells PGM-35 and PGM-29 as a single well, the pressure drawdown would have a closer behavior to the one of well PGM-09, but the data has not been carefully analyzed

The lumped parameter model of well PGM-25 suggests a fast pressure drawdown in the western injection zone of the field, showing that injection has not had a positive impact over the pressure drawdown in the zone near this well. This does not consider negative impacts like a possible thermal breakthrough due to major or fast injected water return. The possibility of reinjector well PGM-24 not giving enough pressure support has been considered, but monitoring of the area is an ongoing process and this hypothesis will be confirmed or discarded when sufficient data become available.

The accuracy and results of the lumped parameter modeling can be limited for some situations that will affect the reservoir behavior, like temperature changes or expansion of boiling zones into the reservoir due to massive exploitation. Some of these conditions have been actually observed (expansion of the boiling in the reservoir at the north zone of the field reaching the central part).

When comparing the results obtained with these new simulations against the simulations done five years ago (Vallejos, 2005), it can be noticed that the pressure drawdown of the field is less now than in the past. It appears that some actions taken in order to reduce the impact of the exploitation over the reservoir and the reservoir evolution itself have influenced this improvement in the reservoir pressure behavior. However, the forecasted behavior obtained for the different lumped parameters models is very pessimistic due to the continuous pressure drawdown simulated. This is a warning signal to implement more actions to minimize this problem even more.

Actions must be taken to slow the pressure decline observed in the field. Some of these actions include the finding of new injection schemes in order to improve the pressure support of the field without affecting the temperature of the reservoir fluids. Other action includes the possible exploitation of the unexploited southeast zone in order to lessen the mass extraction of the central part of the field (as discussed in Sánchez et al., 2010). The injection of small quantities of separated waters (165 ºC) into the north zone of the field is also considered, but intensive temperature and pressure monitoring is highly advisable if a possible acceleration of the temperature decline in this zone of the field is observed. A previous exercise made by using the well PGM-63 as a reinjector for around a year did not show conclusive results but the tests are expected to continue in the near future and it has also been considered to extend the test to other idle or damaged wells of that area (Vallejos, 2006).

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