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RESERVOIR MANAGEMENT AND POWER PRODUCTION IN THE MIRAVALLES GEOTHERMAL FIELD, COSTA RICA

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ABSTRACT

The Miravalles Geothermal Field has been continuously exploited since 1994. The total installed electrical generation capacity of the field has reached 163 MW_e, accounting for about 8% of Costa Rica's installed capacity. The generation in Miravalles is an important part of the electrical supply in the country, accounting for 15% of the total generation. The reservoir has evolved since the beginning of massive production, and different actions and strategies have been implemented to sustain the steam supply to the power plants and for reservoir management. These include reservoir monitoring, control of mass production rates, numerical modeling, pipeline network design, chemical treatment design and implementation, maintenance as well as correction and revision of well programs. The continuous operation and production of the field is also assured by the exploration and development of new exploitation zones.

1. INTRODUCTION

The Miravalles Geothermal Field is the only geothermal field under exploitation in Costa Rica (Figure 1). Deep drilling started in 1978, when a high-temperature reservoir was discovered. Subsequent drilling stages completed the acquisition of steam necessary to feed three flash plants commissioned in 1994, 1998 and 2000, and a binary plant commissioned in 2004, with a total installed capacity of 163 MW_e. Three 5 MW_e wellhead units have also produced during different periods, and one of them is still in use.

1.1. The Reservoir

The geothermal reservoir is 800-1000 m thick of the high-temperature liquid-dominated type, located at about 700 m depth with reservoir temperatures naturally declining to the south and west. The main reservoir fluids have a sodium-chloride composition with TDS of 5300 ppm, a pH of 5.7 and a silica content of 430 ppm. At present there is a tendency for carbonate scaling in the wells. The main aquifer is characterized by a 230-255 ºC lateral flow. A shallow steam dominated aquifer is located in the northeastern part of the field, formed by the evaporation of fluid from the main aquifer that moves along fractures (Vallejos, 1996). Another important sector includes an acid aquifer, yet four out of five wells that have been drilled there to date are systematically neutralized and exploited.

The Miravalles field is associated with a 15 km wide caldera, which has been affected by intense neo-tectonic and volcanic phenomena (Figure 2). The interior of the caldera is in general characterized by a smooth morphology. The proven reservoir area is about 13 km^2, and a similar area is classified as a sector for probable expansion. Another 15 km^2 area is identified as also having some possibilities for future development (ICE/ELC, 1995). These areas may increase as the reservoir is investigated further.

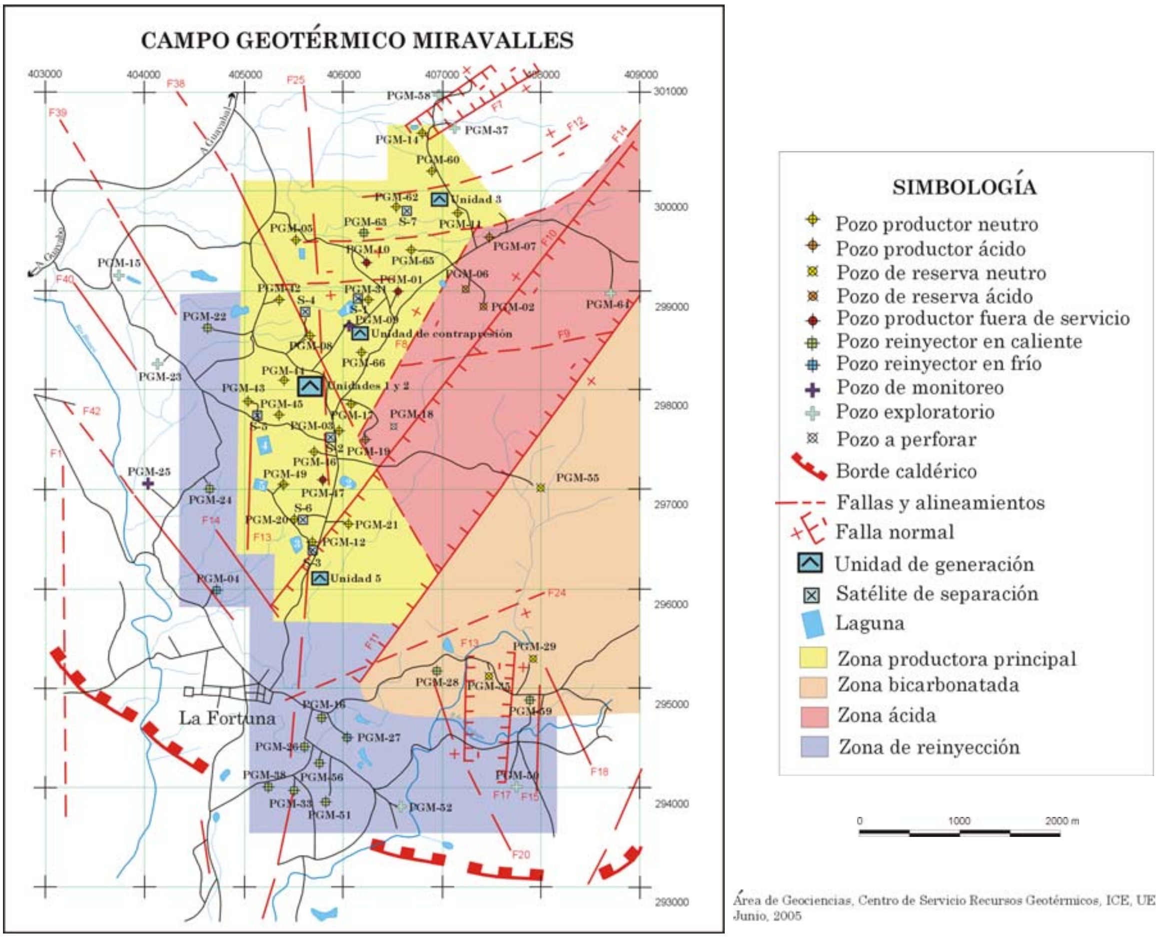

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FIGURE 1: The main features of the Miravalles geothermal field. Also shown are locations of wells, separation stations and power plants

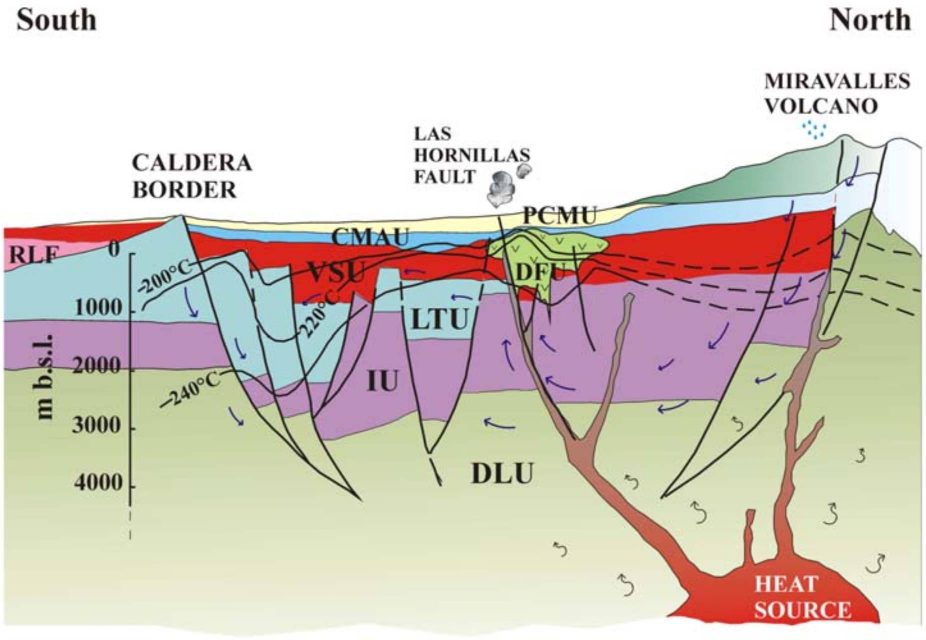

FIGURE 2: Conceptual model of the Miravalles geothermal field (Vega *et al*., 2005)

1.2. Facilities and Equipment

The Miravalles Complex comprises five power units in three different power houses, seven separations stations, the pipeline network, 53 wells (production, injection and observation) and a series of artificial ponds intended for cold injection, maintenance operations and emergencies. A simple scheme of the pipeline network, wells, power plants and other facilities is shown in Figure 3.

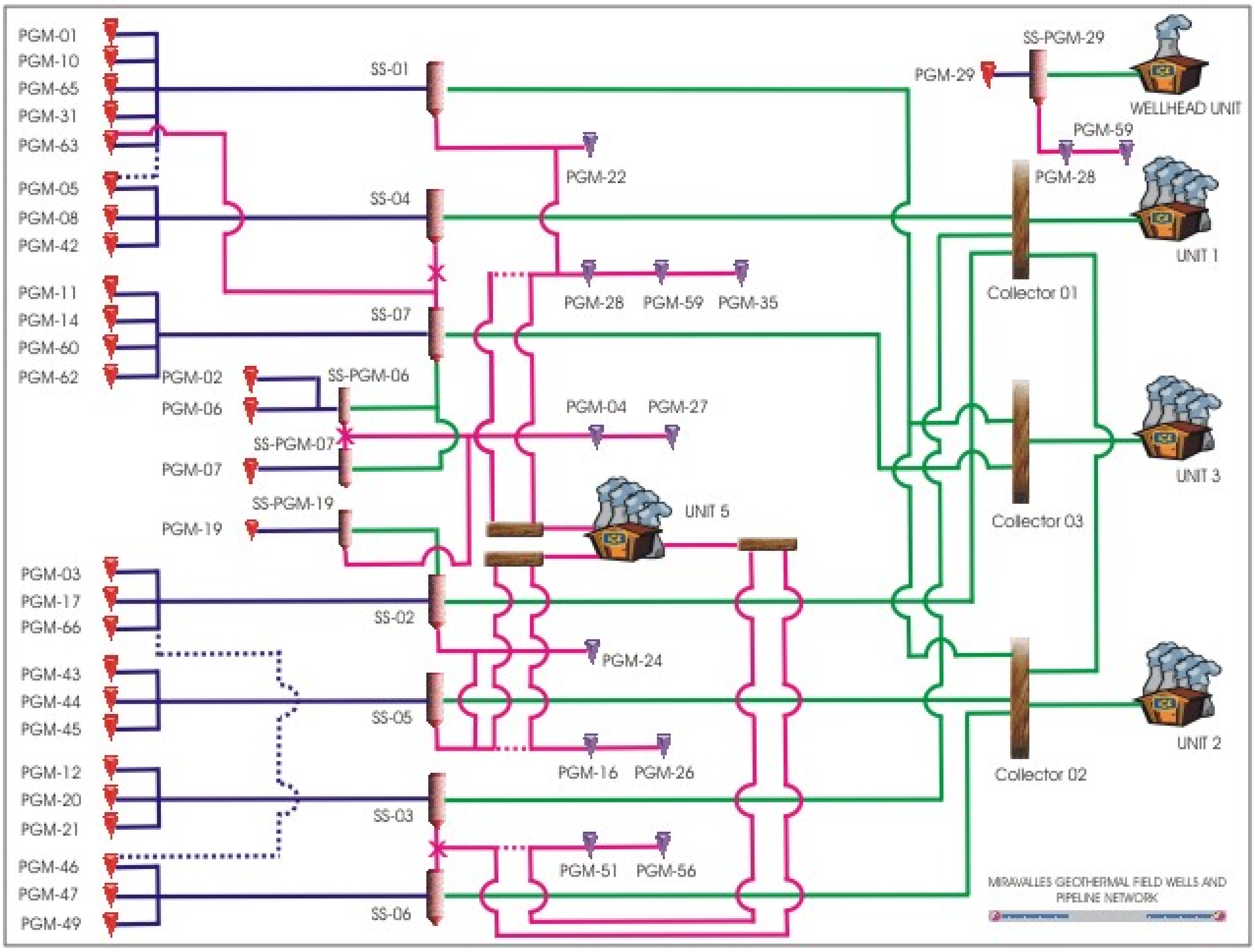

FIGURE 3: A schematic figure showing power plants, wells, separation stations and the pipeline network at Miravalles

The main facilities of the *Centro de Servicios Recursos Geotérmicos* (CSRG), which is the ICE´s department charge of the exploration, evaluation and exploitation of the geothermal resources in the country, is also located in Miravalles.

1.2.1. Power Stations

The installed generation capacity distributed between five power units reaches 163 MW_e (Table 1). Four of them are of single flash type fed by the steam produced in the field (Figure 1 & 4), and the fifth one is a binary type unit that utilizes most of the waste water before it is piped to the reinjection wells.

1.2.2. Separation Stations

Seven stations separate and distribute the steam and brine to the different power stations and injection wells (Figure 1 & 4), each of them handling up to 60 kg/s of steam. The neutralized fluids coming from the acid wells are handled individually, with one separator for each well.

TABLE 1: Electrical generation in the Miravalles geothermal field

Unit	Operator	Power Output (MW)	Operation Time	
			Beginning	**End**
Unit 1	ICE	55	03/1994	---
Wellhead 1	ICE	5	11/1994	---
Wellhead 2	CFE	5	09/1996	08/1998
Wellhead 3	CFE	5	04/1997	01/1999
Unit 2	ICE	55	08/1998	---
Unit 3	Geo	29	03/2000	---
Unit 5	ICE	19	12/2003	

1.2.3. Pipeline Network

The wells are located in an 8x4 km^2 large area (Figure 1 & 4). This extent requires kilometers of pipelines carrying the fluids (steam, brine and biphasic fluid) from production wells to separation stations, power plants and injection wells. The pipeline system has enough flexibility to carry fluids from different wells to different power plants; the same applies to the injection network that allows for the possibility of controlling the amount of brine injected into different injection wells.

FIGURE 4: Examples of different surface equipment at Miravalles

1.2.4. Wells

Drilling at Miravalles has been highly successful, since only 4 out of 53 wells drilled so far have been abandoned. Of the successful wells, 29 wells are producers, 9 wells are injectors and 4 of them are used for continuous (2) and occasional (2) monitoring of the reservoir pressure changes. The rest of the wells remain either as standby production- or injection wells.

Actually, the total combined drilling depth is more than 84 km and a similar combined casing length has been assembled into the wells (both casings and slotted liners). The preferred well design used is a 13 3/8” production casing with a 10 ¾” slotted liner, but a 9 5/8” and 7 5/8” arrangement is also used. The different wells range from 800 to 3000 m in depth, but the normal depth is about 1100-1500 m.

2. PRODUCTION HISTORY

Table 1 shows the commissioning sequence of the different power plants installed in Miravalles. All the presently operative units are owned by ICE.

2.1. Mass Production

The total mass extraction and injection rates in Miravalles are shown in Figure 5. Under full generation conditions (163 MWe), around 1620 kg/s of total mass are extracted from the reservoir, and 280 kg/s are steam used for generation (Moya and Nietzen, 2005). All the waste water is injected back into the reservoir.

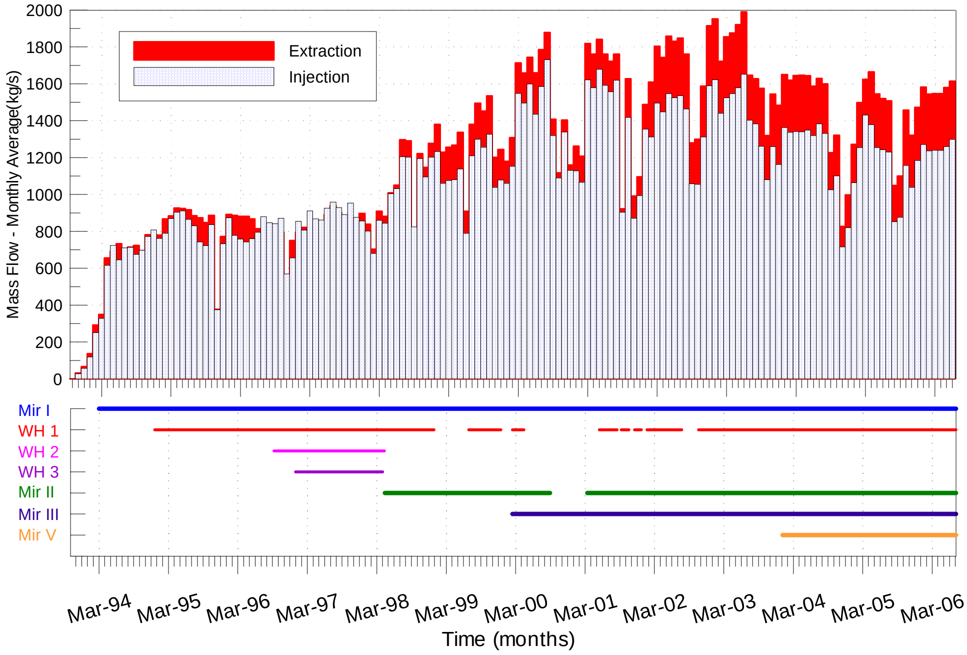

FIGURE 5: Mass production and injection in the Miravalles field

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.

2.2. Waste water injection

Injection has been an essential part of the Miravalles operation from the beginning. Injection normally accounts for about 83% of the total mass extracted from the field. Injection into the different sectors at the Miravalles Field is shown in Table 2 as a percentage of the total injected mass into the field (Vallejos *et al.*, 2005).

The injection of waste brine has mostly been performed under “hot” conditions, that is at a temperature around 165 °C, whike a small proportion has been injected under “cold” conditions (temperature less than 60 °C). These conditions changed when the Unit 5 came online as it recovers some of the heat from the waste brine, lowering its temperature to 136 °C. A great part of the total waste brine will pass through Unit 5 and then be injected into the southern injection zone (see Figure 1). The western injection zone will continue receiving brine at around 165 °C.

TABLE 2: Injection into the Miravalles injection zones

Beginning	End	South[1)]	PGM-22	PGM-24	PGM-04
1994	1998	30%	30%	30%	10%
1998	2000	65%	13%	13%	9%
2000	2002	73%	9%	9%	9%
2002	2003	63%	11%	17%	9%
2003	2006	65%	14%	15%	6%

1) South means injection into wells PGM-16, 26, 27, 28, 51, 56 and 59.

2.3. Electrical Production

The electrical generation, and the plant load factor, for the different power plants in Miravalles are shown in Table 3 (ICE, 2006). The main power plants have been working at high plant load factors (90% under normal operation conditions), due to their excellent performance, maintenance and the good behavior the reservoir during the more than 12 years of exploitation.

TABLE 3: Electrical Generation of the Miravalles Power Plants (March 1994 – July 2006)

Units	Generation (GWh)												
	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Unit 1	341.7	436.5	464.6	460.2	451.0	446.0	438.7	413.9	450.3	450.1	393.3	453.5	275.1
Unit 2	------	------	------	------	70.6	345.8	344.4	332.4	417.6	436.2	428.1	361.0	269.8
Unit 3	------	------	------	------	------	------	186.0	222.1	224.4	224.1	219.2	215.0	123.0
Unit 5	------	------	------	------	------	------	------	------	------	6.3	144.4	18.1	72.4
WHU 1	4.0	31.5	34.7	26.1	31.6	11.3	7.3	18.3	28.6	27.3	20.4	100.6	16.5
WHU 2-3	------	------	10.3	58.0	38.6	0.7	------	------	------	------	------	------	------
Total	345.7	468.0	509.6	544.3	591.8	803.8	977.9	986.7	1120.7	1143.9	1205.3	1149.0	756.8

2.4. Importance of the Geothermal Energy in Costa Rica

The installed electrical generation capacity at Miravalles accounts for about 8% of the country's total installed capacity; however, it has provided around 15% of the country's total generation (ICE, 2005). Since the geothermal power plants produce constantly throughout the year, they are used as a base-load for the country's electrical generation, because of the variation in the production of the hydro-electrical plants due to the seasonal variations of the weather in Costa Rica (Figure 6).

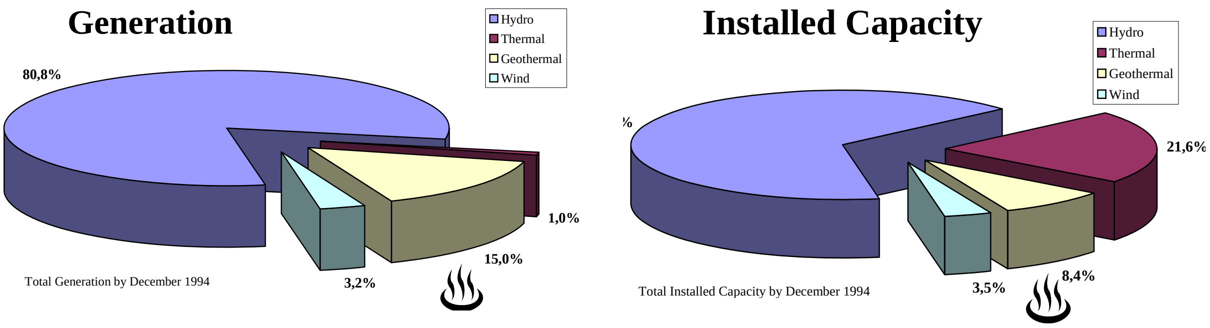

FIGURE 6: Installed electrical production capacity and generation in Costa Rica in the year 2005

The significance of geothermal energy in Costa Rica is increasing. In 2001, geothermal represented 8.6% of Costa Rica’s total electrical production and accounted for 14.2% of the country’s total generation. By July 2005, the installed capacity was essentially the same (8.4%) but the generation was 15.3% of the total supplied by the National Electrical Grid or SEN (in Spanish). SEN includes all the electrical generation companies of Costa Rica (public and private). The total installed capacity of the country had reached 1961 MW_e (Table 4) and the generation equaled 8061 GWh in 2004 (ICE, 2005).

TABLE 4: Installed electrical production capacity and generation in Costa Rica 2001-2005

Type	**Installed Capacity (MW & %) Generation (%)**				
	2001	**2002**	**2003**	**2004**	**by 07/2005**
Hydro	1195.5 (71.3) (81.5)	1271.0 (71.2) (79.8)	1295.6 (66.8) (79.6)	1303.6 (66.5) (80.8)	1303.6 (66.5) (78.1)
Thermal	275.25 (16.4) (2.7)	306.6 (17.2) (3.5)	413.1 (21.3) (3.1)	423.3 (21.6) (1.0)	423.3 (21.6) (3.7)
Geothermal	144.7 (8.6) (14.2)	144.7 (8.1) (15.0)	162.7 (8.4) (15.1)	165.7 (8.4) (15.0)	165.7 (8.4) (15.3)
Wind	62.3 (3.7) (1.6)	62.3 (3.5) (1.8)	68.6 (3.5) (2.2)	68.6 (3.5) (3.2)	68.6 (3.5) (2.9)
Total	1677.7 (100.0) (100.0)	1784.6 (100.0) (100.0)	1940.0 (100.0) (100.0)	1961.2 (100.0) (100.0)	1961.2 (100.0) (100.0)

3. RESERVOIR MANAGEMENT

Since the exploitation of the Miravalles field began, the reservoir’s chemical, hydraulic and thermal parameters have been carefully monitored to assess the changes produced by commercial exploitation. The reservoir response over the thirteen-year exploitation period has evolved notably due to massive production and injection in respective sectors of the field. The reservoir management in Miravalles includes different actions and strategies that have been implemented for sustaining the steam supply to the power plants and for maintaining the productive conditions of the reservoir.

3.1. Monitoring

A monitoring program was set up as soon as during the initial production tests, conducted before commissioning of the first power plant. This provided reference data that was used to assess the reservoir changes that would later be caused by reservoir exploitation. The program is still in operation and includes well output testing, chemical sampling and downhole surveys (flowing temperature and pressure profiles) in all the production wells every six to twelve months. Control sampling to monitor calcium, chloride and bicarbonate content is also performed in production wells, as part of the calcium carbonate inhibition program. Sometimes static temperature and pressure profiles, go-devil and caliper surveys are taken. A three unit down-hole pressure data gathering system was used to monitor the reservoir since June 1994 (Vallejos *et al*., 1995). The system was later upgrated by mid 1998 with five new units. The reservoir pressure is also monitored by measuring hydraulic levels in all idle wells (Castro, 1999). Several tracer tests have been conducted in the field, for tracing the waste brine flow paths and to enable prevention of possible problems due to injection induced reservoir cooling. Some of these tracer tests were conducted in 1995 (Yock *et al.*, 1995) and 2000 (González, 2001).

3.2. Numerical Modeling

Different numerical models of the Miravalles reservoir have been developed over the years, to forecast the future behavior of the field based on the data collected.

In 1991 Lawrence Berkeley Laboratory and ICE developed preliminary natural-state and exploitation numerical models for Miravalles, based on the conceptual model at the time (Haukwa *et al*., 1992). The TOUGH2 numerical modeling code (Pruess, 1990) was used for the 62-block model.

ELC Electroconsult and ICE developed another numerical model in 1995, based on one used for the first feasibility studies carried out in 1985 and 1988 (using the GEMMA code). Natural state and exploitation models were developed based on the information gathered by ICE during exploration and the first eight months of massive reservoir exploitation. TOUGH2 was also used for this 146-block model (ICE/ELC, 1995).

In 1998 GeothermEx, Inc. developed a 1953-block TOUGH2 numerical model, this time based on data from the first three years of continuous field exploitation. The model incorporates an area 12 km long in the N-S direction, and 9 km long in the E-W direction, extending from +100 down to –1500 m m.s.l. (1600 m total thickness) and divided into six layers of non-uniform thickness. The numerical model history matching, as well as forecasts for several different production and injection schemes, were accomplished in this study (Pham *et al.*, 2000). This model was updated by GeothermEx, Inc. in early 2001. The numerical mesh was refined, the number of blocks increased to 5110, and the double porosity and two-waters options used. This model was used to match the chloride returns observed in production well fluids. The model also took into account new information gathered from July 1997 to March 2001 (GeothermEx, Inc., 2002). This current model has been used to evaluate different possible exploitation scenarios proposed, i.e. increasing the generation capacity of Unit 5, injecting waste brine into the north zone of the field, moving the wellhead unit to PGM-29, etc.

3.3. Chemical Treatment

Twenty-six out of twenty-seven production wells in the Miravalles geothermal field require the application of chemical treatment for the produced fluids. Only one of the successful wells does not neet any chemical treatment. $CaCO_3$ scaling is observed in 23 producing wells and four other production wells produce acid fluids that require an acid neutralization treatment. The appropriate chemical treatment for these wells has assured an uninterrupted production for 12-13 years and a continuous operation of the different geothermal plants installed so far.

3.3.1. Calcium Carbonate Scaling

The Miravalles reservoir fluids have a tendency for carbonate scaling in wells, which ranges from strong to severe depending on the area of the field, and the kind of aquifer involved, which causes wells to become obstructed during periods that range from several days to several months, without an inhibition system. This treatment has helped in maintaining a permanent fluid production, thus saving money in lost production and costs needed to clean wells by using drill rigs. The system used for the scaling inhibition is shown in Figure 7(a), this system has been used since the beginning of exploitation in Miravalles and has turned out to be totally reliable (Moya and Sánchez, 2002).

3.3.2. Acidic Fluids Neutralization

The Miravalles reservoir fluids typically have a neutral composition, but five of the wells drilled produce acid fluids. These wells were drilled in the northeastern sector of the field, where a sodium-chloride acidic fluids with pH values between 2.3 and 3.2 are present. The corrosive character of these fluids would cause irreparable damage to well casings and surface equipment, which would force them to be otherwise discarded after a few weeks of production (Sanchez *et al.*, 2005).

Studies started in 1994, aimed at neutralizing the acid fluids and commercially exploiting such wells. The experience gained due to continuous experimentation allowed the commissioning of several acid wells (Sánchez, 2000). Today, four acid wells are an important part of the production system, because the production of some wells exploiting the main reservoir has declined, and the acid wells have been used to meet the steam requirements for maintaining planned production levels. The system designed for acid neutralization by sodium hydroxide injection is shown in Figure 7(b).

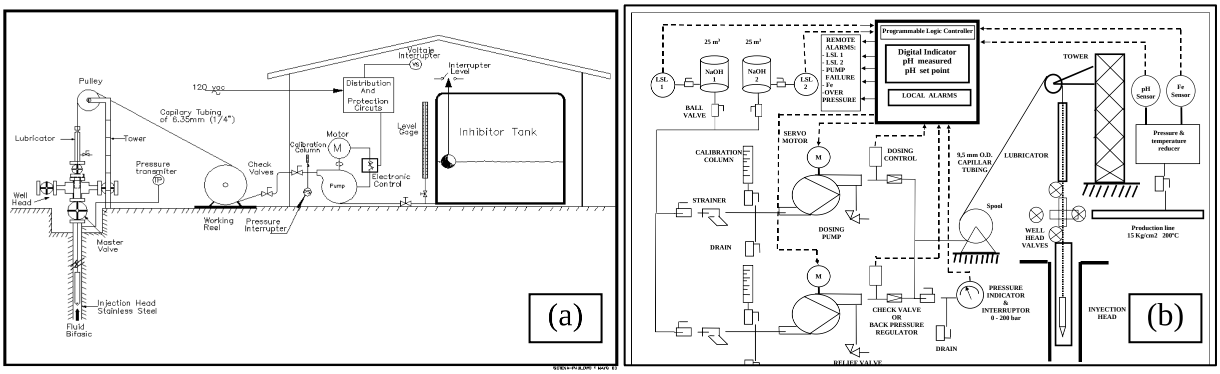

FIGURE 7: (a) The calcium carbonate scale inhibition system and (b) the acid neutralization system

There is, however, a side effect of the neutralization process, which is the unavoidable formation of anhydrite (Sánchez *et al.*, 2000). Currently ICE has carried out some studies focused on controlling the pH to retard or fully avoid the anhydrite formation in the wells. Also, a couple of chemical companies are developing a thermally stable chemical inhibition product, which can be injected through the NaOH dilution system to achieve a constant chemical dosage that will inhibit the formation of CaSO4 and the amorphous silica complex at depth as well as at the surface.

3.4. The Pipeline Network

Pipeline network design has a particular importance in the field management in Miravalles. The network has to be capable of transporting all of the fluids to their planned destinations (wells, separation stations and power plants) and also needs to have enough flexibility to respond to different production and injection schemes. The pipeline network has been modified throughout the evolution of the field, first responding to the increase in production (with the commissioning of Units 2 and 3), then due to variations in the CO_2 content of non-condensable gases, and finally as a result of the changes made due to the commissioning of Unit 5 (binary plant).

The capacity of the turbines for handling CO_2 content is quite variable (e.g. Unit 1 can handle a maximum of 0.66% while Unit 2 can handle 8.88%). This condition represents a serious problem, since the CO_2 content of the non-condensable gases is variable for the different zones of the Miravalles reservoir thus causing differences in the quantity arriving at the different power plants. Also, the CO_2 content in the mass extracted is also influenced by the degassed injection returns, which influences the different injection and production zones of the reservoir locally. This has lead to the requirement for careful monitoring and control of the non-condensable gas content arriving at the turbines, to ensure it doesn't surpass the handling limit of each turbine. Actually, the system is capable of sending fluids from a certain well to different power plants (e.g. fluid from well PGM-05 can be sent either to Unit 1 or Unit 2) in order to control the mass flow-rate and the non-condensable gas content.

3.5. Acidic Treatment and Work-over of Wells

Recovering production losses for some wells in Miravalles has been undertaken by either deepening of wells or through acidizing. Well PGM-46 started as an 11.7 MW_e producer, but its production rate began to slowly decrease and several years later it was down to 4.3 MW_e. Deepening the well was the option chosen for recovering the lost mass flow, after geoscientific information from nearby wells was studied to infer what would likely be encountered below the wells' intial depth (1,200 m). Between July and September 2001 the well was re-completed to intercept a deeper, permeable fracture (Figure 8(a)). Well PGM-46 now actually produces about 10 MW_e (Moya and González, 2003).

Another example, well PGM-03, became completely obstructed by $CaCO_3$ scaling after a production test of 168 days in 1981. Mechanical cleaning of the well was performed in 1984, but this action damaged the production liner. Due to this, the well completion had to be modified as shown in Figure 8(b), changing the accessible depth of the well from the original 1029 m to only 692 m depth. The only feed zone of this well is located between 700-800 m depth, so the completion of the well does not allow the feed zone to be reached. After three years of commercial production the production of the well declined from 7.9 to 4.8 MW_e, because the inhibition dispersion head could not reach a depth below the flashing point, making the inhibition process ineffective. After different actions were taken, it was decided to chemically clean the well. In April and May 1997 an HCl solution was injected into the well and it, consequently, recovered its production by about 93%, reaching an equivalent of 7.2 MW_e capacity. However, the well has to be produced at maximum discharge pressure (MPD) thus reducing the production due to the problem with the flashing point depth (González *et al.*, 1997). Due to the previously exposed, this well has to be periodically treated to recover some of the mass production lost. This action does not eliminate the problem but only reduces the velocity of the position of the wells.

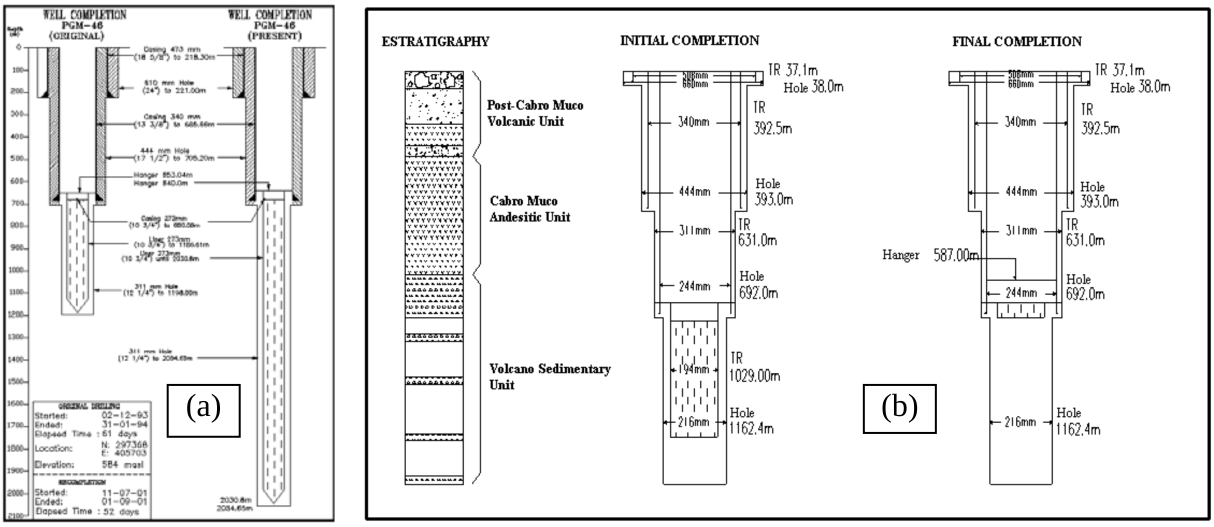

FIGURE 8: Completion programs of wells (a) PGM-46 and (b) PGM-03

3.6. Exploitation Strategies

Different exploitation strategies have been implemented in response specific situations developing in the field. These situations range from operational problems to different reservoir changes (pressure drop, gas content increase, mass production changes).

3.6.1. Production

For location and characterization purposes, the field can be divided in four main productive zones: the north zone, the central zone (main production zone), the acid aquifer zone and the east-southeast zone (Figure 1). Since the north zone has been greatly affected by intensive production, the acid aquifer has acquired breater importance. The production decline in the north zone has been substituted by the commissioning of acid wells.

Shifting of the wellhead unit to well PGM-29 in the southeastern part of the field, which was supported by numerical modeling results, is intended to alleviate the mass extraction load from the central part of the field. This unit used to run on steam taken from separation station 1. The transfer of the unit is expected to be finished in late 2006.

Drilling of new wells targeting deeper productive zones (as discussed in section 3.5.) is intended to avoid scaling problems in wells casing and in fractures next to the wells. This can occur due to local pressure drop and the migration of flashing into fractures intersected by the wells. An example of a deep productive zone is well PGM-46.

In some of the wells in Miravalles the mass production is limited by manipulation of wellhead valves. The operation of some wells at MDP (maximum discharge pressure) is intended to lower the mass extraction and the local pressured drop observed in these wells as well as to lift the flashing point into the wells, thus avoiding the silica deposition in near-well fractures. An example of a well producing at MPD is well PGM-03.

Another exploitation strategy recently implemented in Miravalles is to decrease the electrical generation during the rainy season, when the hydroelectric power plants of the national grid are working under ideal conditions (maximum runoff). This helps in reducing the reservoir pressure drop by reducing the overall mass extraction.

3.6.2. Injection

For characterization purposes, the field can be divided in two main injection zones: the east zone and the south zone. The injection into the reservoir has been modified during the exploitation life of the field. At the beginning its' most important purpose was to avoid the environmental impact that the waste water could cause, but soon the importance of injection in sustaining reservoir pressures became increasingly evident when the reservoir turned out to be affected by injection returns.

The first change in the injection operation was made when Unit 2 was commissioned in 1998. At that time most of the waste water was diverted toward the southern injector wells. This procedure proved to be negative because of reduced pressure support in the central part of the field and some increase in thermal decline seen in the southern production wells. This situation was partly reverted with the shifting of some portion of the southern injection back to the east zone (wells PGM-24 and 22).

The commissioning of Unit 5 has become a new challenge in the injection scheme because of the need of the waste water for feeding this new unit and the need of pressure support in the central part of the field. The geographical location of Unit 5 forces the location of the main injection of the waste water to the southern zone; this situation is actually limiting the possibility of sending more water to the eastern zone. One of the new strategies to be implemented in the near future is to build a new injection line from Unit 5, in order to send more fluid to the eastern injection wells.

By the beginning of 2003, the north production zone showed signs of being highly affected by the productive regime in-place. Three wells (PGM-01, 10 and 63) were neither able to produce nor to stay online due to their low wellhead pressure. At that time the idle acid wells were not ready to be commissioned yet, so it was decided to conduct studies on the possibility of injecting a part of the waste water from separation station 7 and try to get some pressure and mass support in this part of the field. Consequently some studies were carried out involving geology, geochemistry and reservoir engineering characteristics of this zone. Some numerical modeling simulation runs were also conducted in order to find the best candidate wells for injection, if any. For this purpose a theoretical injection scenario was considered involving injection of 25 to 80 kg/s of 165 ºC water into three different wells: PGM-01, 10 and 63. The results showed that well PGM-10, because of its central location, would be the best choice for pressure support, while PGM-63 would be a better choice if thermal impact concerns were the main decisive factors (Vallejos, 2005). Other factors considered were the location of surface facilities (separation station, pipelines already build and the ones to be constructed, etc.).

Well PGM-63 was ultimately chosen due to its favorable geographical location and an injection test started in July 2005 with an injection of 40 l/s, and with monitoring of the nearby production wells (water chemistry and occasional temperature and pressure surveys). Further increases in the injection regime (up to 80 kg/s) showed neither impact on temperature nor hydraulic and chemical parameters, such as pressure (Figure 9(a)) and chloride content (Figure 9(b)), in the nearby wells (Gonzálea and Sánchez, 2006).

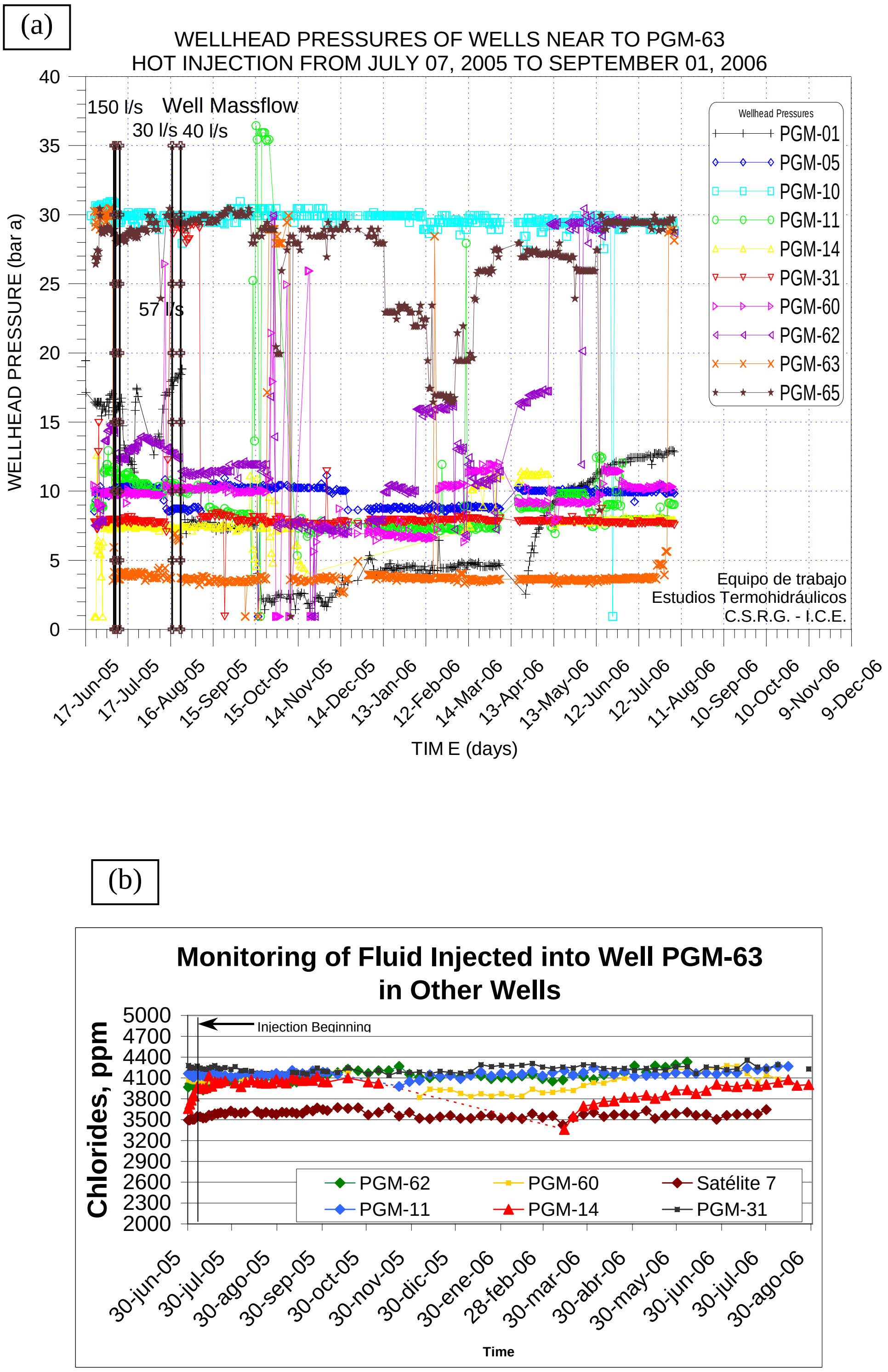

FIGURE 9: Well-head pressure and chloride content monitoring in wells near PGM-63 (González and Sánchez, 2006)

Actually a change will soon be implemented in the injection scheme through the future use of PGM-01 and PGM-10 (one or both wells) in order to get a noticeable and positive change in the pressure and mass production of the northern production zone. This change is expected to be completed in the coming months.

3.7. Exploration and Development of Actual and New Zones

The evolution of the Miravalles field, and the continuous effort of ICE in assuring an adequate mass production for electrical generation, have forced the drilling of some make-up wells as well as a search for new production zones, since additional drilling into the central zones of the field will not increase the actual production in Miravalles.

One of these zones is the east-southeast zone that contains wells PGM-28, 29, 59, 55 and 35. From the geochemical point of view this sector shows some differences relative to the main- and acid reservoirs. The main differences are a high bicarbonates content and the Na/K relationship, which shows a significant difference between geothermometer results and measured temperatures. Similar differences can be seen in calcium and magnesium content. The fluids in this sector have a high tendency to form calcium carbonate deposition as well as a high non condensable gases content in the steam. The first problem needs to be treated successfully by applying the correct inhibitor dosage, but the latter presents a big restriction in the face of the current non condensable gas extraction capacities of Units 1 and 2.

Actual and future studies are now oriented towards defining the dimensions of this aquifer, the stable productive characteristics of wells drilled into it and the correct way to handle the high non-condensable gas content (Sánchez *et al*., 2006 and Cumming *et al*., 2006). Future drilling in this zone is not intended to increase, but rather to support the current rate of production in Miravalles (163 MW), which is believed to have reached its maximum.

4. MIRAVALLES RESERVOIR EVOLUTION

The evolution of the Miravalles geothermal reservoir during the 13 years of production can be divided into four different stages:

a) First period - the initial reservoir conditions: Approximately uniform chloride concentration over the entire field and calcium-enriched fluids in the western sector. Higher temperatures were present in the northeast part, diminishing naturally towards the southwest.

b) Second period - from the beginning of commercial exploitation of the field until April of 1999: The influx of injection fluids coming from the west (wells PGM-22 and 24) toward the center of the field is noticed. The injection returns mix with more calcium-rich waters belonging to this sector. A general temperature increase along a northeast-southwest trend is observed, indicating that the exploitation regime established at the time may be supported by natural recharge from the north part of the field; the flow ascends in a point near the well PGM-11. The existing injection returns did not cause any negative thermal consequences.

c) Third period - from May 1999 to October 2002: An increasing influence of the injection returns in the southern zone of the field is noticed, as clear chemical changes are evident. Declining temperatures and enthalpies along a southwest-northeast trend is observed, indicating not only the arrival of the chemical front but also mixing with colder fluids. A production decline in some of the wells is also observed.

d) Fourth stage - starting in November 2002: A steady production decline is observed in some of the wells located in the northern sector of the field, in association with a reservoir pressure decline and a strong drop in wellhead pressures (PGM-01, 10 and 63, all of which are connected to separation station 1). PGM-01 can no longer produce and PGM-10 is seriously affected. A noticeable steam cap has formed in the northern part of the field due to the massive exploitation. This steam cap seems to be expanding to the rest of the field. The effect of the relocation of reinjection toward the western part of the field in late 2002 (to mitigate the pressure drop) has been noticed chemically, but it is still too soon to quantify its effect on reservoir. The effect of this action is smaller than expected, because of a lack of reinjection water coming from Separation Station 1 (at present only one of five wells connected to this separation station is producing).

Figures 10, 11 and 12 show the variation of some monitoring parameters in selected wells in Miravalles, especially changes observed in some centrally located wells.

Numerical modeling with future reservoir behavior forecasts has shown that, under the current exploitation scheme, injection returns should mostly affect the temperature of the southern production area and the nearby wells. Pressure conditions in the Miravalles field seemed to be seriously affected when injection was shifted to the south in 1998, and it appeared to be necessary to relocate some of the injection back to the west, in order to reduce the reservoir pressure decline (GeothermEx, Inc., 2002). This action was partly completed, but changes in production rates of wells connected to separation station 1 have made it impossible to reach the original rate of fluid injection into well PGM-22 (Moya and Yock, 2004). This poses a special problem, since the plan was to reduce the pressure drop in the northern and central parts of the field through increased injection.

Along with the previsouly exposed, results of modeling runs clearly indicated the need to transfer the back-pressure unit from its current location to well PGM-29, in order to reduce the pressure drop observed in the center of the field.

The operation of Unit V (binary plant) appeared feasible at the point of the numerical modeling update (May 2002), based on forecasting results that showed that the colder injection returns should not seriously affect temperature conditions in the field, and to date no thermal breakthrough has been observed (GeothermEx, Inc., 2002). Monitoring of the field must be strengthened, however, to avoid future problems that might occur if lowering the temperature of reinjection water (from 165 to 136 ºC) will impact the reservoir more than predicted by numerical modeling. Another possible impact of the commissioning of the binary plant is silica deposition in pipes, production casings, and fractures in the reservoir, due to an increase in silica over-saturation. This effect has neither been detected nor quantified yet. Some modeling runs have been made in order to simulate future increasing in the amount of colder injection waters in the west injection zones due to the concerns in this matter, but future investigation must be addressed to forecast a better conclusion (Vallejos, 2003).

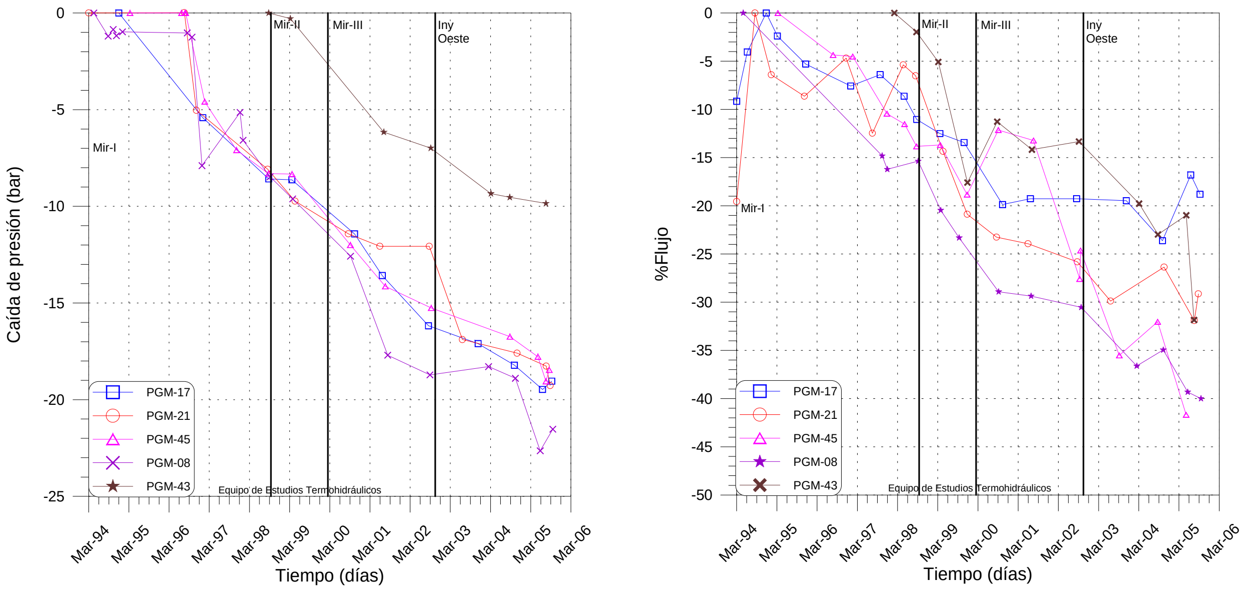

FIGURE 10: Observed pressure drop and relative mass discharge variation (%) in some representative wells in the Central Zone of Miravalles

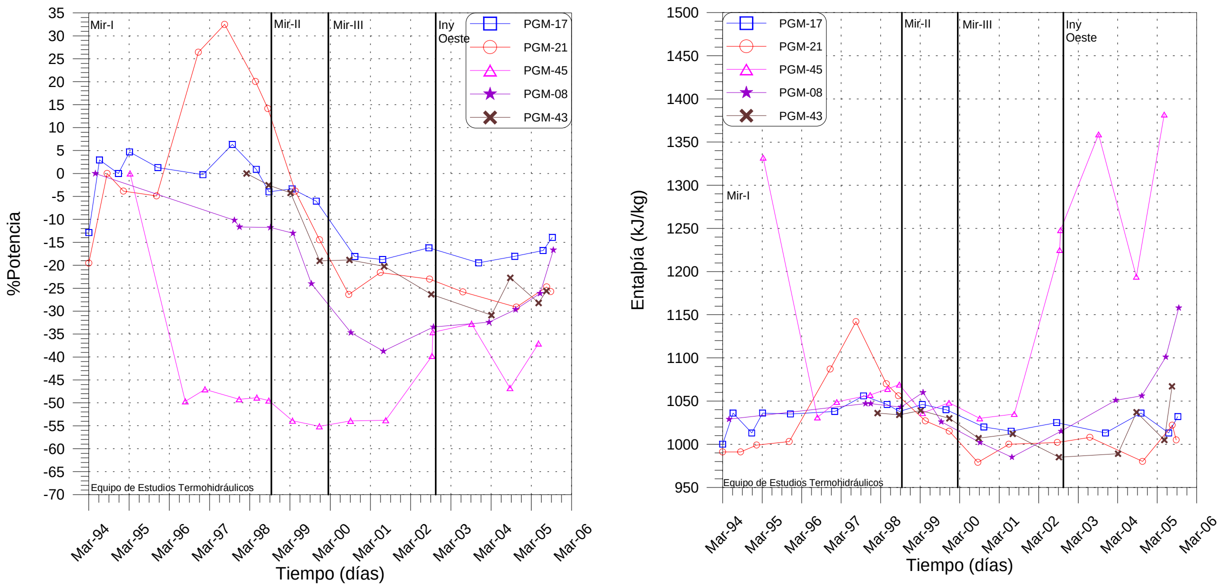

FIGURE 11: Relative electrical potential variation (%) and enthalpy changes in some representative wells in the Central Zone of Miravalles

The most recent numerical model, developed in May 2002, forecasts that the exploitation of the Miravalles reservoir can be maintained for 25 years, under the conditions described below:

UNIT I:	generating up to 60 MW.
UNIT II:	generating up to 55 MW.
UNIT III:	generating up to 27.5 MW.
UNIT V:	generating up to 15 MW (injection temperature 136 °C)
Wellhead unit:	installed at well PGM-29 (generating up to 5 MW).

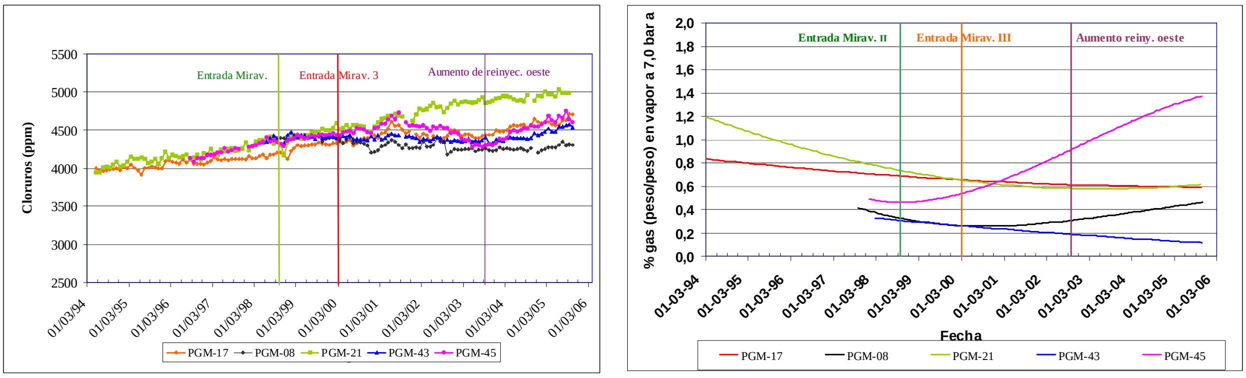

FIGURE 12: Chloride- and non condensable gas content in some representative wells in the Central Zone of Miravalles

Currently, the northern zone of the field is most strongly affected by the continuous exploitation of the reservoir. Specific actions must be implemented in this part of the field to restore some of the seriously affected wells and to avoid future problems in wells that have not been affected yet. Among the actions considered are the injection of controlled quantities of water (at 165 ºC) into the northern part of the field, the transfer of the backpressure unit to well PGM-29, and other possible production schemes (such as reducing the extraction during certain periods of the year).

5. FINAL REMARKS

The Miravalles Geothermal Field has been successfully exploited for than thirteen years, and through continuous exploration and development its installed generating capacity has been increased from 55 to 163 MW_e.

The installed capacity at Miravalles accounts for more than 8% of the Costa Rica's installed electrical generation capacity, and the field yields more than 15% of the country's total generation. This situation gives the sustainability of geothermal energy production from the Miravalles reservoir great weight in the energetic planning strategy of ICE.

ICE has implemented different actions focused on maintaining the steam supply to the power plants in operation in Miravalles and also on reservoir management. So far, these actions have been very successful in maintaining production from the field at the required level. The Miravalles reservoir faces an evolution that must be carefully monitored in order to avoid a future decline in production and electrical generation.

The knowledge on the geothermal reservoir and the evolution trend that has been observed through the years, have lead to the conclusion that the Miravalles field has actually reached its maximum extraction rates. There are still more zones under exploration (east zone and the acid aquifer) that can help (and actually do) alleviate the production decline observed in the main aquifer, as well as to be the foundation for an expansion of the field in the future, if its is proven that these other zones are independent and do not follow the same decline rates as the main aquifer.

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