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Groeber, P. 1954. Geología e hidrogeología de Mar del Plata en relación con el problema de suministro de agua potable a la población urbana. *Rev. Mus. Cienc. Nat. y Trad.*, vol. 1 (2); 5-25.

Hernández, M.A. & Ferrante, V. 1987. Saline intrusion in the Mar del Plata aquifer (Argentina): presents days situation. Studies and measures undertaken. Groundwater Problems in coastal areas. *Studies and reports in Hydrology*, 45, UNESCO, París; 494-498.

Hernández, M.A., Fasano, J. & Bocanegra, E. 1989. Prevención de riesgos en la recuperación de niveles piezométricos en áreas urbanas de Argentina. In: *Segunda Conferencia Latinoamericana de Hidrología Urbana*. ALFHSUD - IDRC - UBA, Buenos Aires.

Ruiz-Huidobro, O. 1971. La intrusión de agua de mar en el acuífero de Mar del Plata. *In: I Congr. Iberoamer. de Geol. Econ.*, Madrid, vol. 2, Sec.3; 845-858.

Sala, J. M., Hernández, M. A., González, N., Kruse, E. & Rojo, A. 1980. Investigación geohidrológica aplicada en el área de Mar del Plata. *Con. Obras Sanitarias de la Nación-Univ. Nac. de La Plata*. Inf. inédito. Mar del Plata.

Zárate, M. A. & Fasano, J.L. 1989. The Plio-Pleistocene Record of the Central Eastern Pampas, Buenos Aires Province, Argentina: the Chapadmalal Case Study. *Palaeogeography, Palaeoclimatolog, Palaeoecology*, 72; 27-52.

EVALUATION OF HYDROTHERMAL SOURCES THAT SUSTAIN AN OVEREXPLOITED AQUIFER AT SAN LUIS POTOSI, MEXICO

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ABSTRACT. A numerical model is implemented for the aquifer of the City of San Luis Potosi, which takes into account the contribution of an underlying thermal source. Previously, it was thought to be overexploited. By means of the numerical model, it is shown that this is not the case, because there is a contribution from the underlying thermal source. Since the properties of the thermal source are not known, the procedure used to incorporate them is to adjust the values of the vertical hydraulic conductivity between the thermal source and the aquifer until the actual piezometric levels in the aquifer were reproduced. For this case study, such a procedure has produced useful results.

INTRODUCTION

The Valley of San Luis Potosi, is located in the high plateau of the Republic of Mexico (Fig.1) and it lies in the semi-arid region. The water demand of the City of San Luis Potosi, capital of the state of the same name, for agricultural, urban and industrial uses, has been steadily increasing. Most of the water supplied to the city is from underground sources, because due to the reduced rainfall, the surface water contribution is small (only 8 %).

There is concern with respect to the future evolution of the aquifer, because in the last few years the observed speed of drawdown has reached the rate of 1.3 m year^{-1}. However, if the hydraulic balance of the aquifer is carried out taking into account only what is known about the aquifer, the predicted rate of drawdown is even larger. On the basis of thermal, chemical and hydraulic evidences, in a previous study: Instituto de Geofisica, UNAM (1988), it was established that the differences between the observed and the predicted rate of drawdown is due to water supplied by deeper geological formations with thermal activity.

Taking into account these facts, it was decided to implement a numerical model of the aquifer to improve the understanding of its behavior, specially with respect to the deep thermal sources, and to predict the system behavior under different exploitation policies for the next twenty years.

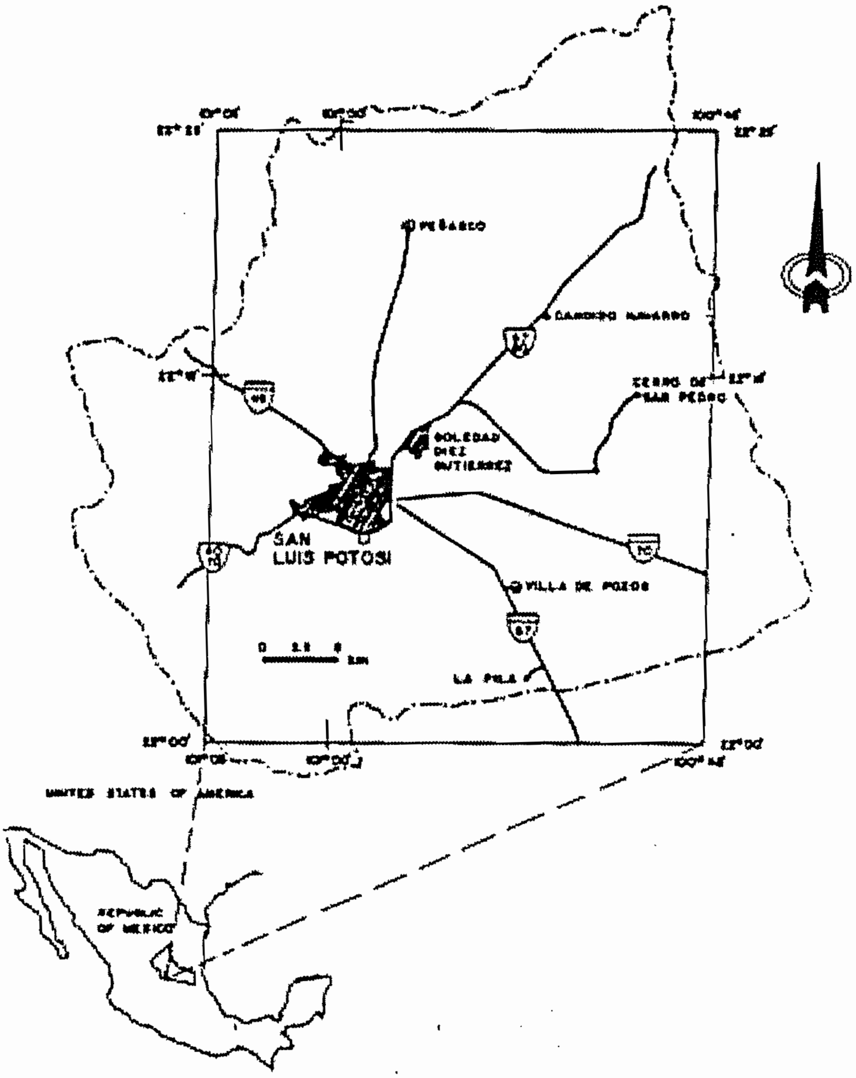

Figure 1: Location map of San Luis Potosí Basin.

HYDROGEOLOGIC MODEL

On the basis of the available geological, geophysical, piezometric and hydrochemical information, the proposed hydrogeological model of the system includes a "shallow aquifer" of reduced yield and poor quality water. This aquifer overlies a "clay formation" which in turn confines a deeper aquifer. Most of the water is produced at this "deep aquifer", which has thermal activity (Fig.2). Below it, lay the "thermal sources".

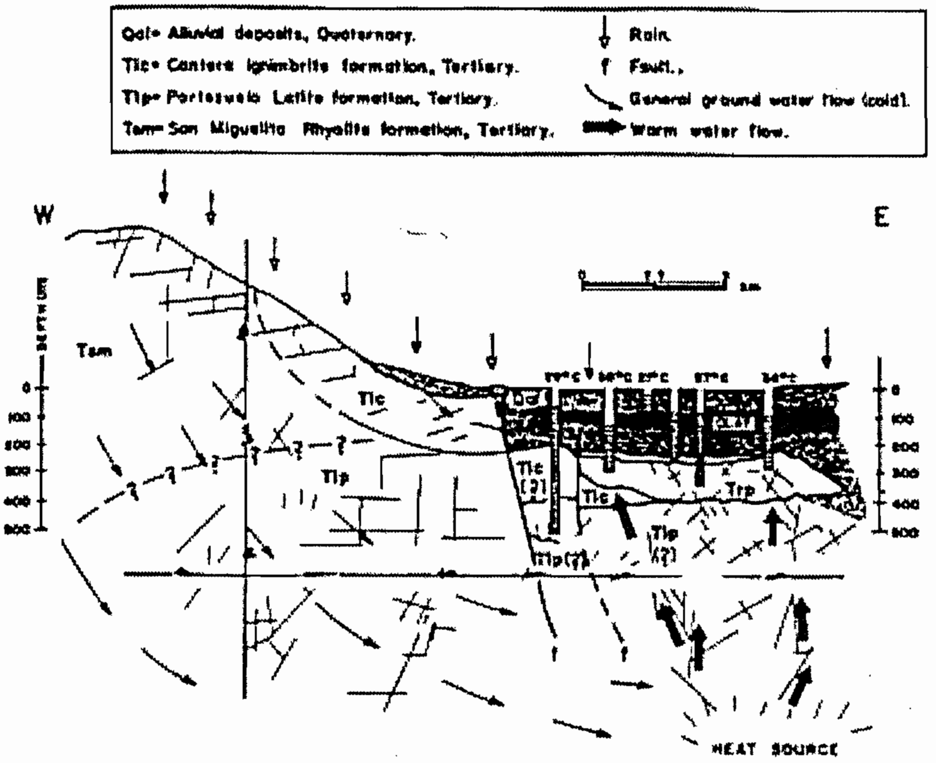

Figure 2: The hydrogeological model.

In this figure, it can be observed that the system of regional flow is important for aquifer performance, producing a vertical component of hot water. For a detailed geological description of the system, the reader is referred to the previous study: Instituto de Geofisica, UNAM (1988).

MODELLING OF THE SYSTEM

For the implementation of the numerical model, a conceptual model of its behavior was defined, suitable differential equations were adopted, a computer program was selected and its calibration was carried out using the available information. The piezometric levels produced by the program were interpolated using the package SURFER: Golden Software, Inc., (1989) to obtain a more convenient graphical representation.

The conceptual model

The limits of the area included in the model, are shown in Fig. 3 and were based on geological considerations.

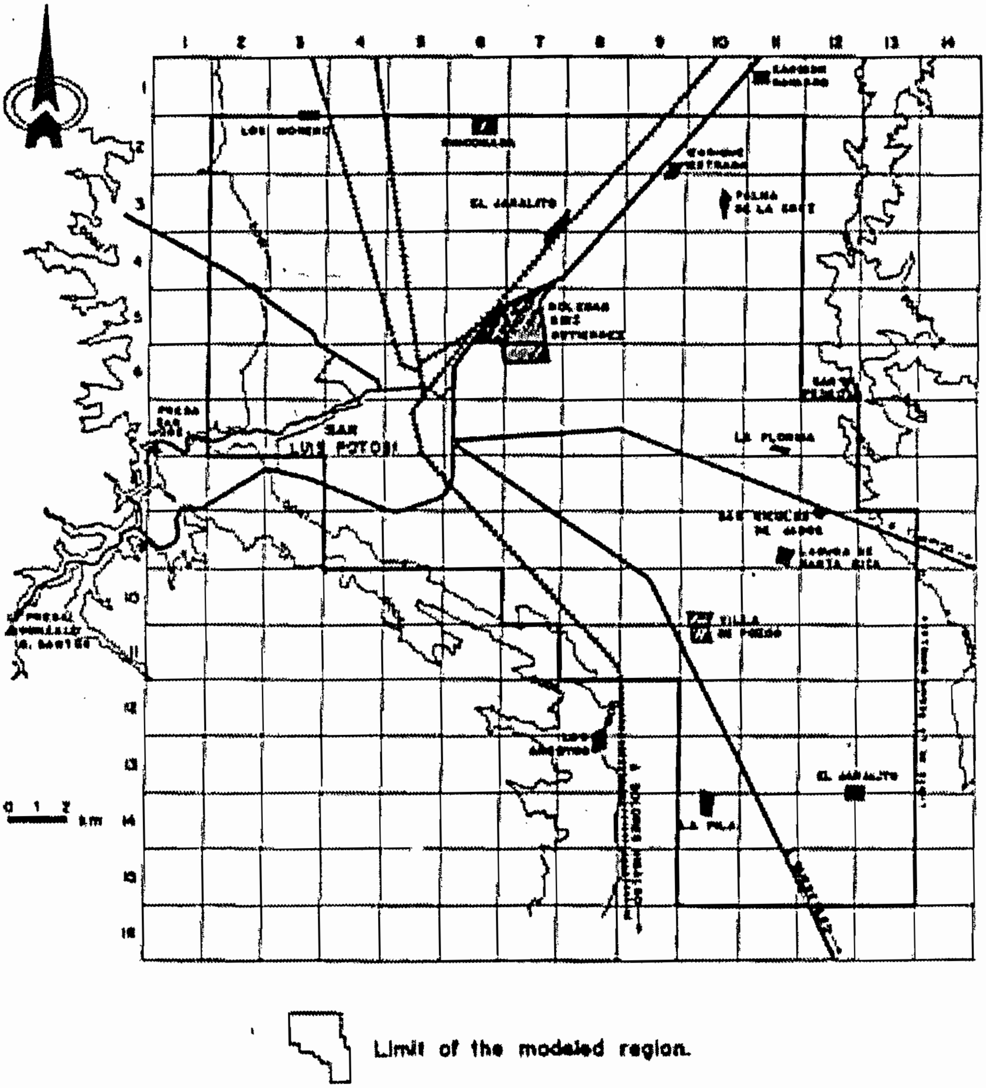

Figure 3: Grid used in the numerical simulation.

The San Miguelito range at the west and the San Pedro range at the east, constitute natural boundaries because they present conditions of no flow, and at some places constant head (Fig. 4).

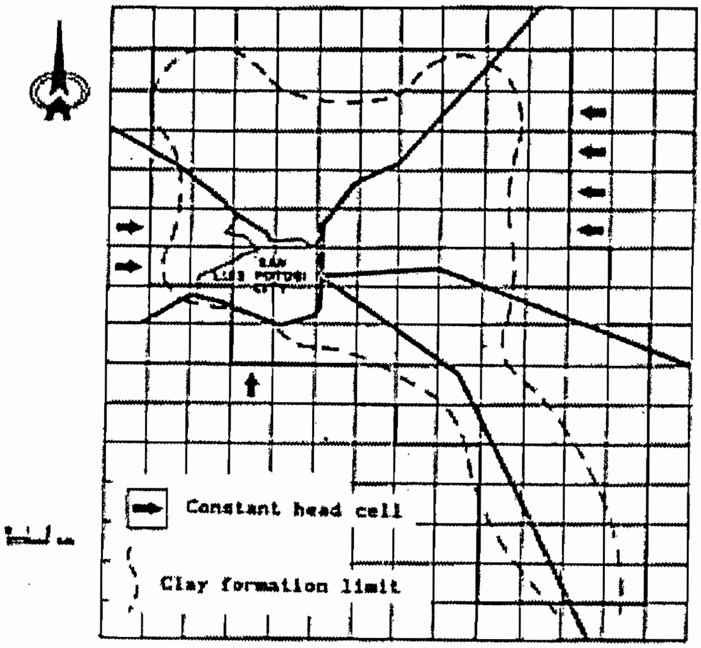

Figure 4: Area covered by the clay formation

The northern and southern limits were selected on the basis of the piezometric information that was available and they were taken as impermeable, because there is evidence that the flow there is negligible. The shallow aquifer, located on the upper part of the system, functions as a unit independent of the deep aquifer, because the clay layer that separates them is sensibly impervious. Taking into account that most of the water is produced at the deep aquifer, the purpose of the model is the prediction of its behavior exclusively, leaving aside the shallow aquifer.

The basic Equation

The governing equation used was:

$$\frac{\partial}{\partial x}\left(Kx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Ky\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kz\frac{\partial h}{\partial z}\right)=S_s\frac{\partial h}{\partial t} \qquad (1)$$

where S_s = specific coefficient of storage $[L^{-1}]$

K = Hydraulic conductivity $[LT^{-1}]$

h = Hydraulic head $[L]$

t = Time $[T]$

However, the analysis of the flow was mainly two-dimensional, because only two horizontal layers were incorporated in the model.

The computer code MODFLOW: McDonald & Harbaugh, (1984), was used in all calculations. This model applies the cells method which yields finite difference approximations.

The deep aquifer can be satisfactorily modelled using a 2x2 Km grid and applying finite difference schemes on them, as illustrated in Fig. 4. Layer I includes the best known part of the system, where the value of the hydraulic properties are known or at least can be estimated. Layer II was introduced to model the deeper, less known geological formations which supply the thermal water. The flow and interaction between layers I and II is due to the differences of hydraulic head between them. In layer II, it was assumed a constant hydraulic head that remained greater than the head of layer I, throughout the runs. This induces a vertical component of flow whose magnitude can be adjusted varying the ratio of the hydraulic conductivity (Kz) to the thickness of the layer where the flow takes place.

An upper boundary condition of no flow was considered in layer I, which corresponds to the clay layer whose hydraulic conductivity is neglected. In the horizontal limits of the aquifer, either constant head or no flow boundary conditions were considered, as indicated in Fig. 4.

CALIBRATION

In the period January 1987- July 1989, heads were measured monthly in observation wells distributed throughout the region that was modelled. At the same time, the pumping rate was measured in some cases and estimated by indirect means in others.

In addition, the piezometric head distribution corresponding to 1960 is available and there are estimates of the historical evolution of the pumping rates.

The hydraulic properties of the known part of the aquifer were obtained by means of pumping tests and also some pumping tests available from previous studies were interpreted. Transmissivity varies between $1x10^{-5}$ and $8x10^{-4} m^2 s^{-1}$. The calibration for layer I started with these values and then were modified on the basis of the results of the calibration. The properties of layer II were adjusted until the behavior of the system was reproduced in a satisfactory manner.

In spite of the additional piezometric information that was available, the calibration was based on the period 1987 - 1989, which covers 30 months only. This was due to the better quality of the data for that period. Once the results of the calibration were obtained, the data of less quality that were available for the period 1960 - 1988 were used to verify it.

In the evaluation of the storage coefficients of the region modelled, 10 values that were determined by pumping tests were incorporated. The extension of the confining clay layer was determined by means of the analysis of the prevailing geological conditions (inferred from well logs) and geophysical surveys. The values of the storage coefficients that were used for the cells that behave as confined are between 2×10^{-4} and 7×10^{-3}. In the case of cells that perform as unconfined, values between 0.02 and 0.15 were used.

The initial runs, using the estimated values of S and T, led to the distribution of the piezometric heads shown in Fig. 5.

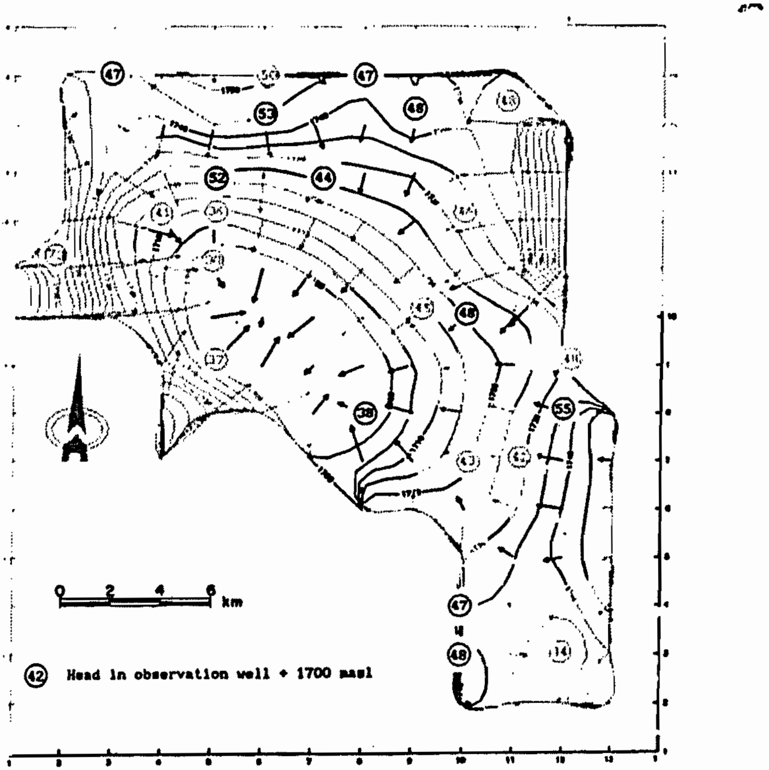

Figure 5: Contour map of predicted piezometric heads, without thermal sources.

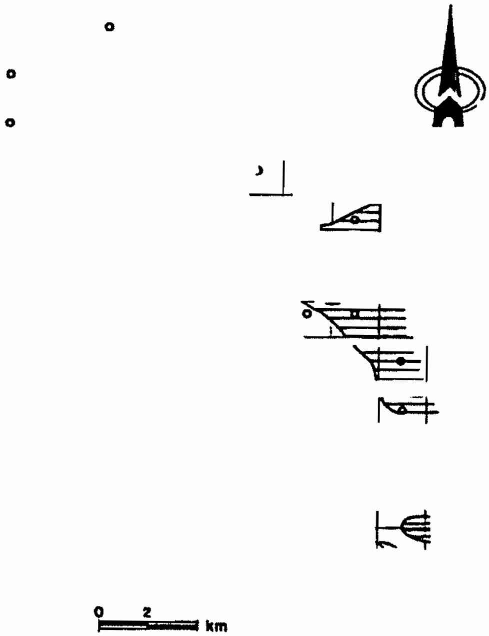

Figure 6: Location of thermal sources.

(a) increasing the storage coefficient of the aquifer, considering it as unconfined in all the region modelled;

(b) incorporating additional sources of water in the cells, where required.

The first option is unrealistic, since it contradicts geologic evidence directly supplied by well logs and must be discarded, in spite of the fact that it was used in a previous study: Niedzielsky, (1990).

On the other hand, the inclusion of additional sources in the model is fully justified by the hydrochemical and thermal evidence : Cardona (1990), Carrillo-Rivera (1992). They represent the vertical component of the regional system of flow that has been observed in the thermal area of the Valley of San Luis Potosi (Fig. 6). Therefore, this was the option that was adopted in the model. It was incorporated by means of an additional layer (layer II) whose properties were adjusted in the calibration of the model, assuming the piezometric head of that layer is constant.

Since the hydraulic properties of the main aquifer (layer I) are the best known, in the calibration emphasis was placed in determining the properties of the thermal sources. A first guess of the values of the hydraulic conductivity in the vertical direction (Kz) between layers I and II, based on the temperatures and well discharges measured in the field, was used in the initial simulations, and then they were adjusted until the actual piezometric distributions in the thermal area were reproduced. The stopping criterion for the calibration process was that the actual heads should be predicted with an error of less than one meter in the thermal zone, as shown in Fig. 7.

Using the calibrated model, a global mass balance of the region was carried out. The results obtained are listed in Table 1.

Concept	$Q(m^3 s^{-1})$	%
Aquifer storage	0.34	13
Lateral recharge (cold water)	0.36	14
Upward supply (hot water)	1.90	73
Total well extraction	2.60	100

The distribution of the supply shows clearly that the most important contribution comes from the vertical flow which originates in the regional system and exhibits thermal anomalies.

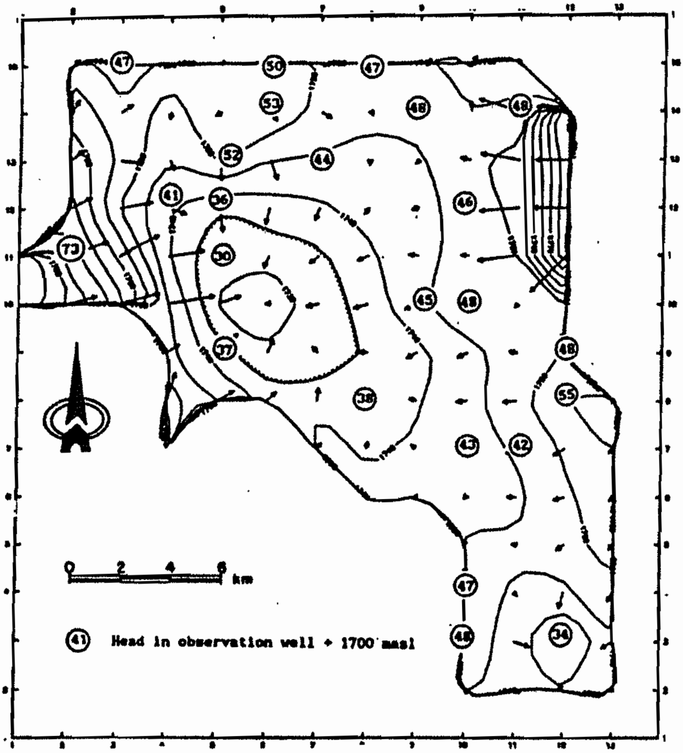

Figure 7: Contour map of predicted piezometric heads, after calibration.

Long period verification

As was already mentioned, the information available for the period 1960 - 1988 was used to test the results of the calibration. Thus, after the calibration was completed, a run covering that period was carried out.

Taking the known initial conditions for 1960 and estimating the evolution of the rate of pumping in the period, the piezometric heads were predicted using the calibrated model. The results of the simulation after 29 years had differences of less than 3 meters between the observed and computed heads in the thermal area. This indicates, specially taking into account the low quality of the information available for the period, that the parameters that were obtained in the calibration are acceptable to make predictions of the behavior of the system within a moderate range of accuracy.

TESTING DIFFERENT PUMPING POLICIES

The analysis of a wide range of exploitation policies of the system is necessary, to quantify the potential of the thermal sources as a water supply for the city of San Luis Potosi.

Predictions of the behavior of the system for a period of 21 years (1989 - 2010) under different exploitation policies were carried out. The options considered were:

- I.0- Keeping the present extraction rate fixed during the whole period.
- I.1- Increasing the rate of extraction 5 % every 5 years.
- I.2- Increasing the rate of extraction 10 % every 5 years.
- I.3- Increasing the rate of extraction 20 % every 5 years.

- II.1- Increasing the rate of extraction in the thermal area exclusively (13 cells) 5% every 5 years.
- II.2- Increasing the rate of extraction in the thermal area exclusively (13 cells) 10% every 5 years.
- II.3- Increasing the rate of extraction in the thermal area exclusively (13 cells) 20% every 5 years.
- II.4- Increasing the rate of extraction in the thermal area exclusively (13 cells) 40% every 5 years.

In Table 2 the results obtained for the different policies that were tested are shown. For each policy the total volume extracted during the period of 21 years is given and then the percentages which originate in the thermal sources, the storage of the aquifer and the neighboring regions is indicated. Finally, in the last column the total volume of drawdown produced during the whole period in the modelled region is given in millions of cubic meters. These results are also illustrated in graphical form in Fig. 8. Clearly, to ensure a drawdown as low as possible, locating the additional demand in the thermal region is the best option.

Table 2: Predictions for the period 1989-2010 under different policies.

Policy	Total Pumped Volume	Of Thermal Origin	From Aquifer Storage	From the Boundary	Drawdown Volume
	(m^3x10^6)	(%)	(%)	(%)	(m^3x10^6)
I.0	1698	81	3	16	3440
	When increments in pumping are uniformly distributed				
I.1	1915	81	5	14	6000
I.2	2153	76	7	17	8800
I.3	2702	77	11	12	16000
	When all increments of pumping are taken from thermal area				
II.1	1866	83	4	13	4800
II.2	2069	81	5	14	6400
II.3	2184	82	6	12	7600
II.4	2946	82	8	10	13600

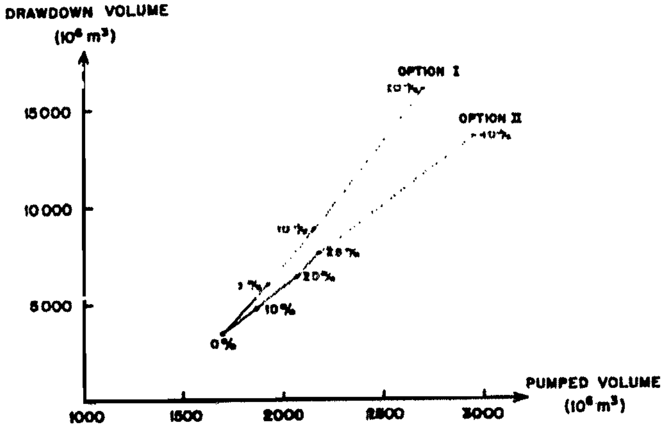

Figure 8: Comparison of simulated policies.

CONCLUSIONS

A numerical model that takes into account the contribution of thermal sources was developed, and using it, different operation policies have been tested for the aquifer of the City of San Luis Potosi.

Initially, it was intended to implement a model without thermal sources. However, it turned out to be impossible to achieve a model capable of predicting the observed behavior when only horizontal flow was modelled. This pointed out the need of incorporating thermal sources in the model, in order to explain the vertical flux coming from deeper geological formations whose hydraulic properties are unknown. This vertical supply was incorporated in the model, introducing a layer of constant hydraulic head in the lower aquifer.

Since the properties of such layer were unknown, it was necessary to derive them during the calibration process. The main parameter that was adjusted was the vertical hydraulic conductivity that exists between layers I and II. At the same time, the hydraulic properties, T and S, of the aquifer and the boundary conditions were also adjusted. The fact that an additional parameter was introduced in the calibration made this process more complicated than is usual for this kind of application . However, this form of proceeding is similar to what is usually done when applying modelling techniques in the horizontal plane, for which it is standard to eliminate neighboring regions with insufficient hydrological information by imposing suitable boundary conditions. In many cases, the supply coming from such regions is quite significant for the behavior of the part of the aquifer which is modelled.

The results of the calibration were satisfactorily verified by reproducing the observed behavior in a longer period (1960-1988) of exploitation of the aquifer, for which incomplete hydrometric information was available. The results of this study indicate that the procedure used here to study a deep geological formation for which no information is available, may be useful more generally. In particular, in the case study here reported, in spite of the insufficient knowledge of the deep formation it was possible to make recommendations for the policies to be followed in the production of the aquifer. These recommendations are better founded than if the lack of information about the thermal sources had inhibited the development of such model.

The distribution of piezometric heads predicted on the assumption that the present rate of pumping is continued through the whole period 1989 - 2010 (Fig. 9 option I.0) indicates that the present extraction can be continued without producing exceedingly large drawdowns.

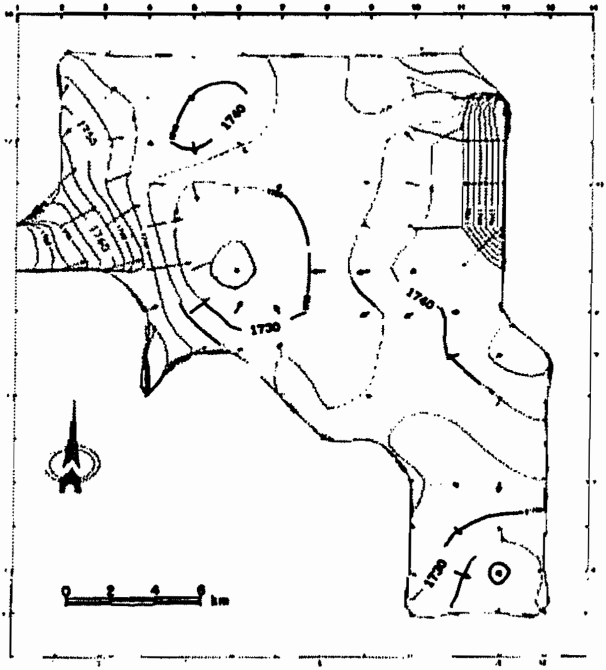

Figure 9: Contour map of predicted piezometric heads (1989 pumping rate).

Figure 8 clearly illustrates the fact that if the pumping rate is to be increased, the most convenient option from the point of view of keeping the drawdowns as small as possible is to concentrate the demand in the thermal area. However, if such policy is adopted, the supply would contain a greater volume of thermal water, which would deteriorate its quality. Thus, in such case, it would be important to monitor the dissolved ions and the water temperature. If this is done, it should be recommended that the information gathered in this manner be used to improve the numerical model and to test the assumptions on which it is based.

REFERENCES

Cardona A., 1990. *Caracterización Físico-Química y origen de los sólidos disueltos en el agua subterránea en el Valle de San Luis Potosí: su relación con el Sistema de Flujo.* M.S. Thesis, Universidad Nacional Autónoma de Nuevo León, México.

Carrillo-Rivera J.J., 1992. *The hydrogeology of the San Luis Potosí area.* Ph. D. thesis, London University, U.K.

Golden Software, Inc., 1989. Surfer reference manual. P.O. Box 281, Golden, Colorado 80402 U.S.A.

Instituto de Geofísica UNAM, 1988. *Estudio geofísico-geohidrológico del Valle de San Luis Potosí*: Contrato cc-86-3140, Informe Interno Secretaría de Agricultura y Recursos Hidráulicos, México, D.F.

McDonald M. & Harbaugh A., 1984. *A Modular three-dimensional finite-difference ground-water flow model.* U.S. Department of the interior U.S. Geological Survey, National Center, Reston, Virginia.

Niedzielski H, 1990. Perspectivas del suministro de agua a la Ciudad de San Potosí. Ciencia, *Revista de la Academia de la Investigación Científica. vol 41*, No. 5 México, D.F. 153-162.

THE RISK OF OVEREXPLOITATION OF A MULTI-LAYER HETEROGENEOUS AQUIFER SYSTEM. HYDROGEOLOGICAL CONSIDERATIONS IN MAJOR GREEK BASINS

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ABSTRACT. Major parts of neogene and pleistocene basins with a multi-layer confined aquifer system, are subject to overexploitation due to their lithological and structural heterogeneity which obstructs the recharge from the adjacent high potential quaternary aquifers.

INTRODUCTION - GENERAL SETTING

In several extensive regions in Greece, neogene and pleistocene deposits are developed, either forming a hilly environment or covered by the recent alluvia of plains. Those deposits of fluviotorrential or lacustrine origin, consist of alternations of coarse and fine materials, e.g. sands, sandstones, gravels, conglomerates, silty mixtures, clays and marls, forming a resemblance to a multi-layer system.

This system offers a sequence of confined aquifers of significant potential for local use. The recharge of the aquifers (II, III, A, B in fig. 1) is achieved through underground lateral inflows from the termination of the torrential fans at the borders of the basins (I in fig. 1). In the fans, very effective phreatic water tables are developed, recharged mainly by infiltrations from the river beds. In some cases, the multi-layer system communicates laterally with the limestones of the borders which discharge their karstic waters in the form of huge springs; a dynamic hydraulic continuity from the karst to the porous media is then established.

Wells of depths between 100 and 200 m are found to deliver yields from 50 to more than 300 $m^3 h^{-1}$ However, after several years of exploitation of the ground-water of these regions, a general decline is observed which cannot be attributed only to the construction of new wells or the aging of the old ones. Many of these regions are already under a regime of overexploitation and new irrigation plans will be mainly based on water from surface reservoirs.