Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Random Simulation with Geologic Control in Assessment of Geothermal Resources of the State of Goiás, Central Brazil

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Keywords: Random Simulation, Resource estimates, Goias (Central Brazil)

ABSTRACT

Recent results obtained in evaluation of geothermal resources of the state of Goiás (central Brazil) are presented. The procedure adopted is based on random simulation of the main geothermal parameters over a regular mosaic of elemental areas defined over the study area. The observed values of temperature gradients and heat flow from 18 localities as well as available data on flow rates of 636 shallow wells were used as bounds in the simulation process. In addition, weighting factors were assigned depending on the geotectonic characteristics of the study area. The simulation of resource estimates was carried out over a network of 6400 regular grid points. The table below provides a summary of the results obtained.

Simulation Scheme	Search Radius (degrees)	Energy Flux (GW)	Resource Base (10^{21}J)
1	0.5	18.39	1.13
2	1.5	27.32	1.75
3	2.0	29.30	1.89
Volumetric	--	36.31	2.54

There are indications that resource estimates based on random simulation process are better representative of in-situ conditions those based on the conventional volumetric methods. However the estimates are to some extent dependant on the search radius, parameter specifications and on the weighting scheme used in random simulations. More meaningful results can be obtained through the use of finer grids but such improvements are dependant on the availability of detailed geologic maps. Another advantage is that the random schemes can easily be adjusted for eventual changes in the constraints and parameters used. It also allows virtual experimentation of resource estimates. The method is potentially useful in cases where the data distribution is poor and non-homogeneous.

1. INTRODUCTION

Random simulation methods have been employed over the last few decades in the study of stochastic phenomena in engineering, economy and medicine. Applications in the area of geosciences include, among others, assessment of natural resources (Agterberg et al., 1993; Crovelli, 1995; Turcotte, 1986). In this work we discuss the methodology of random simulation and present a case study of its application for geothermal resource assessment of the state of Goiás, in central Brazil. In this region the heat flow data density is poor and, in addition, its geographic distribution is highly non-homogeneous. In addition, only scanty complementary information is available for estimating recoverable resources. It is in this context that recourse to random simulation methods were made. It should be considered as part of an attempt to minimize uncertainties in resource estimates, arising from low data density and its non-homogenous distribution.

As a brief note on the history of the development of the motives behind this work, we mention that geothermal resource assessments of the state of Goiás, in central Brazil, were carried out as part of an M. Sc. thesis work by the first author. The purpose is to estimate the thermal energy content of subsurface layers, down to a depth of ten kilometers, using different assessment methods. Initially, conventional volumetric methods were employed, supplemented later with some heuristic schemes. Random simulation schemes were developed as continuation of these earlier works.

2. GEOTHERMAL AND HYDROGEOLOGIC DATA

The data considered in the present work include results of both geothermal and hydrogeologic studies, carried out in the study area over the last few decades (Campos and Costa, 1980; Hamza and Grassi, 2000). As can be seen from the geographic distribution, illustrated in figure (1), most of the available data are from wells located in the southern and southeastern parts of the state of Goiás. The data density is poor in the northern and western parts of the study area.

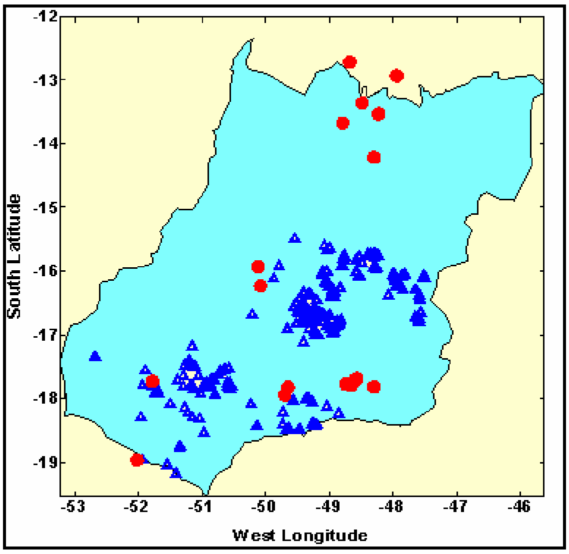

Figure: 1 Geographic distribution of the geothermal (circles) and water well (triangles) data in the state of Goiás, central Brazil.

Geothermal data refer to measurements of temperature gradients, thermal properties and determination of heat flow carried out at 18 localities, mainly in the eastern parts of Goiás. A summary of the main results compiled by Ferreira and Hamza, (2003) are presented in Table (1).

Hydrogeologic data refer to shallow wells drilled in the study area for groundwater, during the last few decades. This information has been organized in the form of a digital database by the Geologic Survey of Brazil (CPRM). It is in fact part of a public domain data base, designated SIAGAS, (acronym for ´Information System for Groundwater´). Each record in this data base has a large number of independent fields, with information on such basic items as locality, coordinates, altitude, depth, flow rate, water levels and aquifer type as well as complementary information on pumping tests. It is available for download from the website of the Geologic Survey of Brazil (CPRM), www.cprm.gov.br, or from its ftp address ftp.cprm.gov.br. Several formats are available: ASCII text, MS-Access and MS-SQL-Server. From a Linux user's point of view, it is interesting to port the database to either MySQL or PostgreSQL format. In the present work we used the MS-Access version of SIAGAS, downloaded in the year 2001. This old version is in fact an un-normalized database (in other words, a large table). CPRM has recently introduced some modifications, and what is available currently at the website appears to be a normalized version, with dozens of tables rationally organized and cross-linked among themselves. However, the advantage of opting out for the un-normalized version is almost exclusively related to making SQL statements easier to write (and, later on, read) and in our opinion fits well to promote a simplification of SQL statements inside the programs.

Table 1: Summary of heat flow (q) and temperature gradient (Γ) data in the study area.

N	Coordinates		q	Γ
	longitude	latitude	(mW/m^2)	(ºC/km)
1	-48.7475	-17.7765	350	100
2	-48.5810	-17.6904	250	88
3	-48.6628	-17.7939	34	11
4	-48.6251	-17.7361	200	76
5	-49.6500	-17.8250	54	18
6	-49.7040	-17.9500	240	81
7	-48.3030	-17.8230	180	58
8	-48.7911	-13.6749	167	56
9	-48.4851	-13.3619	143	48
10	-50.0833	-16.2333	38	38
11	-52.0167	-18.9667	51	17
12	-48.2333	-13.5333	48	18
13	-50.1167	-15.9333	71	24
14	-51.7806	-17.7317	68	29
15	-48.3000	-14.2167	63	63
16	-47.9467	-12.9338	110	37
17	-48.6848	-12.7188	131	44
18	-47.4849	-10.0374	72	24

3. ASSESSMENT OF RESOURCE BASE

An essential early step in geothermal resource assessment is the evaluation of the spatial distribution of heat flow. Thus a preliminary automatic contour map of heat flow of the state of Goiás was prepared. This map, presented in Figure (2), reveals a region of high heat flow (>150 mW/m^2) in its southeastern parts and normal to low heat flow (<100 mW/m^2) in the remaining parts. However, the transition from high to normal heat flow is rather smooth, a consequence of the use of numerical scheme employed in interpolation of data over large areas of low data density. Such transitions are unrelated to the geological characteristics of the study area. Consequently use of maps based on simple numerical schemes is likely to lead to a distorted view of the distribution of geothermal resources at depths.

The heat flow data in Table (1) along with available information on vertical distribution of thermal conductivity and radiogenic heat production in generating typical steady state temperature profiles of the crust in the study area. The temperatures (T) were obtained as solution of the one-dimensional heat conduction equation:

$$\frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) + A = 0 \qquad (1)$$

where Z is the depth, λ the thermal conductivity and A the radiogenic heat production per unit volume. It is assumed that the dependence of thermal conductivity with temperature and decrease of radiogenic heat production with depth are given, respectively, by the relations:

$$\lambda(T) = \frac{\lambda_0}{1 + \alpha T} \qquad (2)$$

$$A(z) = A_0\, e^{-Z/D} \qquad (3)$$

where λ_0 is the thermal conductivity at temperature T_0 and α the coefficient of variation of λ with temperature. The solution of (1) subject to conditions (2) and (3) may be written down as:

$$\left(\frac{\lambda_0}{\alpha}\right) \ln\left(\frac{u}{u_0}\right) = (q_0 - A_0 D) Z + A_0 D^2 \left[1 - e^{-Z/D}\right] \qquad (4)$$

where $u = 1 + \alpha T$. Examples of such temperature profiles calculated using model parameters given in Table (2) are presented in Figure (3).

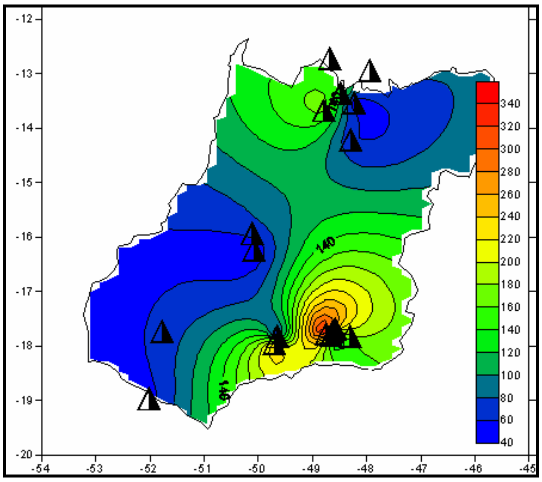

Figure 2: Preliminary flow map of the state of Goiás.The triangles indicate locations of heat flow measurements.

Table 2: Parameters used in calculation of crustal temperatures.

Parameter	Value	Unit
Surface Temperature	24	ºC
Depth	10^4	m
Density	2650	kg/m^3
Thermal Conductivity	3.0	W/m/^{0}C
Specific Heat	836	J/kg/ºC
Radiogenic Heat Production	10^{-6}	W/m^3

Initially conventional volumetric method (Muffler, 1978) was employed in estimating the resource base. In this case the appropriate relation for resource base (Q_{RB}) is:

$$Q_{RB} = \rho C_P \, A d \int_0^d \left[T(z) - T_0 \right] dz \qquad (5)$$

where $T(z)$ is the temperature at depth Z given in equation (4), (ρC_P) is the heat capacity, d the thickness of the upper crust and A the area. Contour maps of heat flow distribution allows temperature excess ($T - T_0$) and resource base (RB) to be estimated for any specific area. In the present case resource estimates were made at the nodal points of the grid system used in mapping heat flow. The total value of RB is then obtained as a simple sum of the nodal values. Table (3) provide a partial list of incremental values of heat flow, respective area segments and basal temperatures as well as corresponding values of RB. According to the conventional volumetric method, the total value of RB for the state of Goiás is of the order of 2.5×10^{24} J.

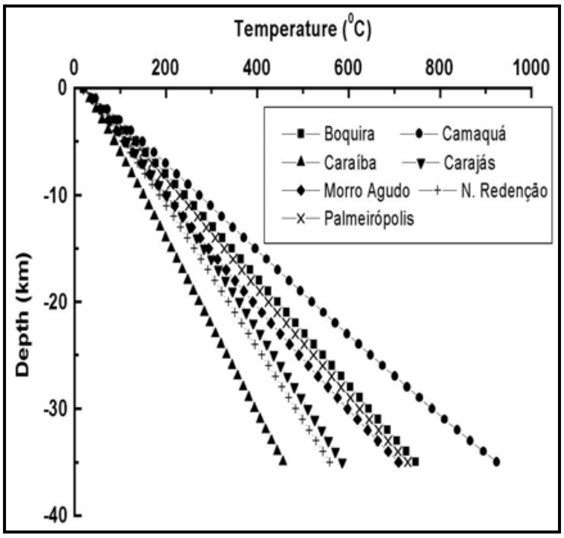

Figure 3: Vertical distribution of crustal temperatures in selected Precambrian areas in Brazil.

Table 3: Sample values illustrating estimates of resource base (RB) by the conventional volumetric method.

Heat Flow (mW/m^2)	Area (m^2)	Basal Temperature (T_d)	Resource Base (J)
43	$9,3 \times 10^8$	151	$2,6 \times 10^{21}$
44	$3,3 \times 10^9$	154	$9,6 \times 10^{21}$
45	$3,5 \times 10^9$	157	$1,0 \times 10^{22}$
: :	: :	: :	: :
319	$6,7 \times 10^7$	1071	$1,5 \times 10^{21}$
340	$6,7 \times 10^7$	1141	$1,7 \times 10^{21}$
Total	$3,4 \times 10^{11}$	-	$2,5 \times 10^{24}$

3. NUMERICAL SIMULATION SCHEMES

As mentioned in the previous item the approach to evaluate spatial distribution heat flow and crustal temperatures, based on simple interpolation schemes, leads to some degree of uncertainty in estimates of geothermal resources. A convenient means of minimizing this uncertainty is to make use of suitable simulation schemes, to generate values that complement observational data. In the present work a "filter-like random number selector", was used in generating random values of heat flow over a regular grid covering the study area. The choice of this random value is subject to guidelines and/or filters and these are in turn related to the specific geologic characteristics of the media. The temperature distribution in the crust at the grid point is derived from this randomly drawn value of heat flow. Thus the simulation scheme allows estimation of the amount of thermal energy at the grid elements.

The aspects of grid granularity and resolution also need to be examined. By granularity we mean the possibility to work with smaller areas and randomly cast values that are more "refined". The granularity proposed here is relatively large, but there are possibilities for improvements as more detailed local geologic maps become available. We also note that better schemes of grid refinement and mesh improvement may be devised, be it by looking into fractal behavior or, as some other research path to experiment, implementing artificial intelligence techniques, such as fuzzy logic approaches to random simulation.

The usefulness of such virtual scenario can be improved by establishing "connecting links" between the simulation scheme and real field data sets which have some direct or indirect bearing on the resource estimates. In the present work we consider information available on wells drilled for groundwater in the study area and make use of geographic distribution and flow rates of these wells as the connecting links. This procedure has the additional advantage that it allows new options for a variety of simulations giving a broader perspective for the final results. In this context the following pseudo-random simulation schemes were considered:

1- In the first scheme simulation is carried out for the sites of SIAGAS wells. Each datum is drawn from within a specific interval, determined by the local geology. The details of this 'geologic control' are discussed in the next section.

2- In this second scheme random simulation is restricted to sites of SIAGAS wells situated away from localities where field measurements of heat flow have been carried out. For this purpose, circular areas are specified around localities where heat flow has been measured, designated as ´forbidden areas´. For those wells falling within such forbidden areas the heat flow value assigned is the arithmetic mean of measured values within that area.

3.. In the third scheme a regular mesh is cast over the study area and simulation carried out at the nodal points. Thus, instead of using real SIAGAS wells, the system conceives virtual wells. The value of flow rate attributed to such virtual wells (nodal points) is based on corresponding value of the nearest SIAGAS well.

4.. The last one is a combination of schemes 2 and 3, in which simulation is restricted to nodal points falling outside ´forbidden circles" around the localities with known heat flow data.

The software used in the random simulation computational package is written in Python Language (Saenz et al, 2002). A listing of the source code is available from authors upon request. The user concerned with running the program under Linux should make appropriate changes compatible with the specific operational system. The programs run without problem in Microsoft platforms and in Linux with a suitable modification of the ODBC class object.

4. IMPLEMENTATION OF 'GEOLOGIC CONTROL'

In simulation procedures it is common practice to impose physically meaningful limits on the operation of the random number generator. In the present work this was accomplished by setting site-specific intervals for the heat flow values. The intervals themselves were selected on the basis of the empirical relation between heat flow and age of tectonic event, proposed by Hamza and Verma (1968), and making use of complementary information on geological characteristics available in local geologic maps. The limiting values of these intervals are represented by an indexing system in the computational scheme. The study area is divided into a regular grid and heat flow at nodal points randomly drawn from this range of possible values. The range can be narrowed or optimized for convergence.

The procedure used for implementation of geologic control makes use of the tectonic map of the study area (Lacerda et al, 2000), a simplified version of which is reproduced in figure (4). As a first step representative heat flow values are assigned to the major tectonic units. These are designated the primary groups. Following this each elemental area in the grid system is assigned a classification index depending on its tectonic characteristic. This index depends on the relative proportions of the main tectonic units in that segment. These are designated mixed groups, to which heat flow values, proportional to the area coverage of the primary tectonic groups, are assigned. An example of this classification scheme is illustrated in Table (4).

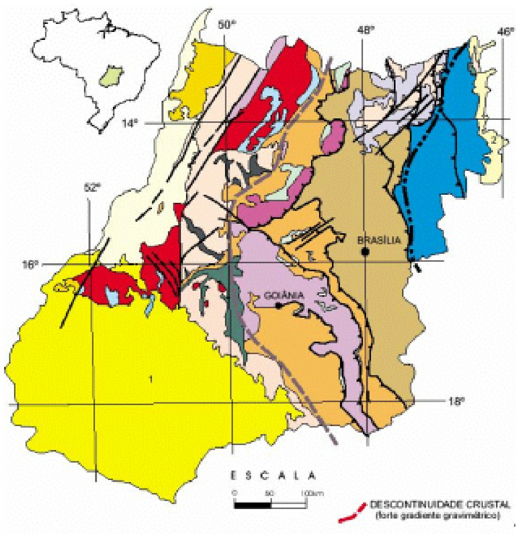

Figure 4: Tectonic Map of the study area (Adapted from Lacerda et al, 2000).

Table 4: Illustration of the scheme employed for implementing 'geologic control'.

Geology		Heat Flow (mW/m²)	
Description	Index	Minimum	Maximum
Primary Groups			
Cratonic Nucleus	A	30	50
Proterozoic fold belts	B	50	80
Phanerozoic Strata	C	60	100
Mixed Groups			
Craton & Proterozoic	AB	40	65
Craton & Phanerozoic	AC	45	75
Proterozoic & Phanerozoic	BC	55	900

5. RESULTS OF NUMERICAL SIMULATIONS

The results of the various simulation schemes are virtual data sets which may be used for estimating resources and in understanding its spatial distribution. As an illustrative example we present in figure (5) the map of the geothermal resource base (RB) of the state of Goiás based on data generated in the second scheme. Here the 'forbidden circle' around sites of heat flow measurements is assumed to have a radius of one degree. The main feature here the presence of a well defined region in the southeastern part of the study area where RB per unit area is in excess of 10^{19} J/m^2. It also reveals a region of intermediate RB (> 60×10^{18}J/m^2) in the western parts and a region of low RB (<60×10^{18}J/m^2) in the northern parts. This pattern of regional variations in RB have some degree of correspondence with the local geologic structure, a consequence of the 'geologic control' on the random generator. Also the pattern of RB has relatively sharp boundaries, that appear to be consistent with the local geologic pattern and compatible with the region of known geothermal manifestations. Another important feature is that the spatial dimensions of high RB area is large relative to that in the previous heat flow map (see Figure-3). This size, however, depends to some extent on the radius of the forbidden circle, as illustrated in the maps of figures (6). Here the maps of the top and bottom panels refer to cases where the radii are 0.5^0 and 1.5^0 respectively.

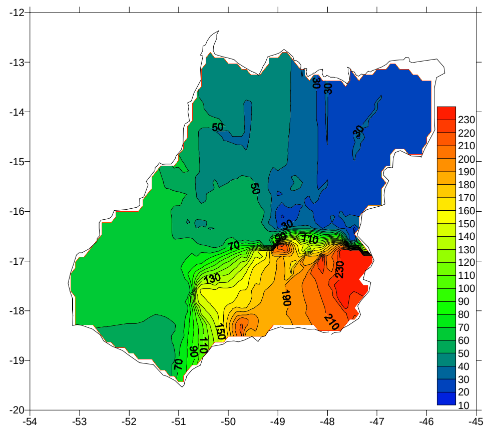

Figure 5: Resource Base per unit area of the state of Goiás, by random simulation methods.

Estimates of heat flow pattern generated by the random simulation schemes were also used in calculating resource base. In this case, it is convenient to integrate the surface heat flow over the study area and use this integrated flux as a measure of the resource base. Results of estimates obtained in five independent random simulation runs is presented in Table (5). Note that the differences in such estimates are less than one percent, indicating that the method based on random simulation is robust and convergent. Also provided in this table is the result of integrated flux by the conventional volumetric method. As can be seen, random simulation has lead to estimates that are about 50% lower than those by the conventional volumetric method.

Table 5: Results of integrated flux given by simulation schemes and its comparison with the volumetric method.

Description	Number of Grid Points	Integrated Flux (GW)
Simulation 01	7100	19,7433
Simulation 02	7100	19,0499
Simulation 03	7100	19,0499
Simulation 04	7100	20,6084
Simulation 05	7100	19,4670
Volumetric	5100	36,3079

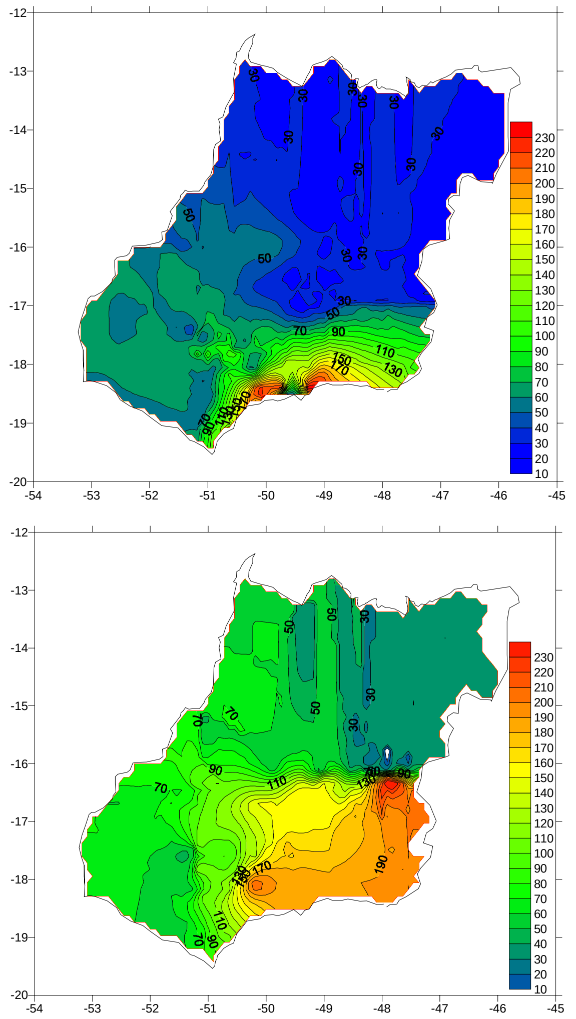

Figure 6: Maps of RB with 0.5^0 (top) and 1.5^0 (bottom) as the radii of forbidden circles in random simulation

6. ESTIMATION OF RECOVERABLE RESOURCE

The methods described in the previous section may easily be extended for estimation of recoverable resources as well. However we discuss first the results of conventional approach based on volumetric methods. To begin with it is necessary to establish a means of estimating the recoverable fraction of the resource base. Ferreira and Hamza (2003) made the assumption that equivalent porosity of deep aquifers are related to the fluid flow rates determined in pumping tests of shallow (<1000m) wells. This assumption allows a convenient means of obtaining a rough estimate of the recoverable resource. For example, a cross plot of grid values of fluid flow rate and heat flux can be used to obtain geographically representative estimates of the recoverable resource. The values of flow rate and porosity constituting the empirical relations are given in Table (6). Sample values of the results obtained are presented in Table (7) and the spatial distribution of recoverable resource illustrated in the map of figure (7).

Table 6: Values of flow rate and equivalent porosity used in estimating recoverable resource.

Flow rate (m^3/h)	Equivalent Porosity (%)	Fraction of Resource Base
< 5	1	0.005
5 - 10	5	0.025
10 - 100	10	0.050
> 100	15	0.075

Table 7: Sample values illustrating estimates of recoverable resource in simulation schemes.

Grid Coordinates		Recoverable Resource(J)
longitude	latitude	
:	:	:
-48,2	-19,0	1,63 x 10^{19}
-48,0	-19,0	3,23 x 10^{19}
-47,8	-19,0	3,21 x 10^{19}
-47,7	-19,0	3,19 x 10^{19}
:	:	:
Total		8,1 x 10^{21}

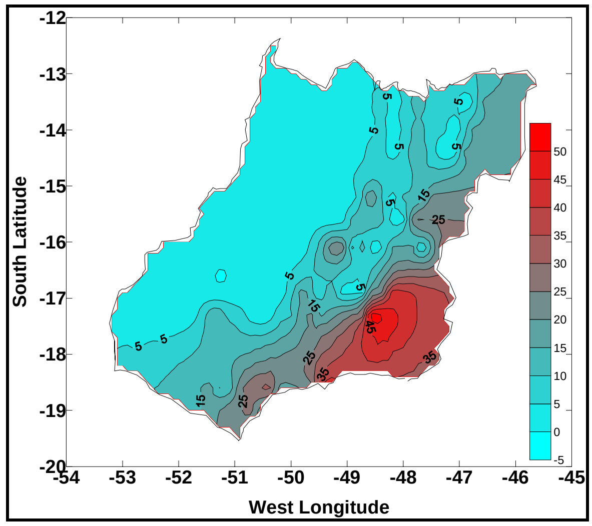

Figure 7: Distribution of recoverable resources in the state of Goiás. The contours are in units of 10^{18} J.

The estimate presented in table (7) is a theoretical upper limit and can be improved by assuming that recoverable portion is limited to the fraction that can be extracted through a network of wells, with flow rates compatible with those observed in shallow groundwater wells drilled in the study area. In implementing this scheme it is assumed that virtual producer wells exist at 6100 nodal points generated for the grid of flow rate data. Temperatures at these virtual sites are computed from the grid values. The virtual wells are set to have a uniform reference depth of 3 km. The computer output for this scheme generates a quadruple record containing values of flow rate, heat flow and coordinates of nodal points (longitude, latitude). However, unlike the previous case the program does not determine directly the recoverable resource but the thermal power output at each nodal point, based on the calculated value of the flow rate. The results indicate an integrated thermal power output of 7,1 x 10^9 W. A rough estimate of the recoverable resource may be obtained by assigning a time period for extraction of thermal fluids. In the present work this time period has been arbitrarily set at 30 years, which imply an equivalent recoverable resource of 6,7 x 10^{18} J. This is nearly three orders of magnitude lower than the estimate by the conventional method, a consequence of the large grid spacing used in the computational procedure. The contour map of the thermal power output is presented in figure (8). The main features in this map are quite similar to the one in figure (7), implying that the thermal power is closely related to the distribution of recoverable resources.

7. DISCUSSION AND CONCLUSIONS

Earlier works in assessment of geothermal resources in Brazil (Hamza and Eston, 1983) have made use of conventional volumetric methods. These methods employ simple numerical schemes in interpolation of temperatures and heat flow in areas of low data density. There are indications that results of such methods lead to overestimates of resource base and also of the recoverable fraction. Some of these difficulties can be minimized by the method proposed in the present work, which make use of random simulation of heat flow, with built in constraints that take into account the geological characteristics of the study area.

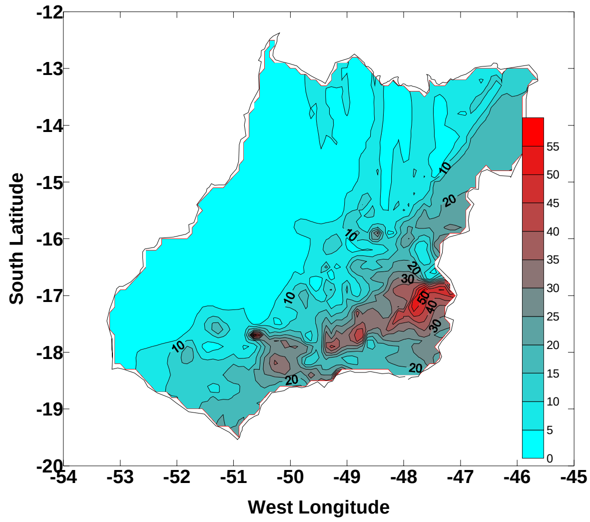

Figure 8: Map of thermal power, based on virtual producer wells. Contour values are in units of 10^5J/s.

The method was applied in evaluation of geothermal resources of the state of Goiás (central Brazil). The observed values of temperature gradients and heat flow at 18 localities as well as available data on flow rates of 636 shallow wells were used as bounds in the simulation process. In addition, weighting factors were assigned depending on the geotectonic characteristics of the study area. The simulation of resource estimates was carried out over a network of 6400 regular grid points.

The geographic distribution of recoverable resources indicates that eastern and southern parts of the state of Goiás may hold potentially interesting targets for exploration of low enthalpy geothermal resources. There are indications that the results of random simulation provide estimates of resources that are compatible with thermal power output observed in areas of known geothermal manifestations in the state of Goiás.

ACKNOWLEDGMENTS

The first author was recipient of a post-graduate scholarship granted by Fundação Amparo á Pesquisa do Estado de Rio de Janeiro - FAPERJ, during the period 2000 - 2002.

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