Heuristic Schemes in the Assessment of Geothermal Resources of the state of Goiás

Ferreira, L. E. T.and Hamza, V. M.

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Abstract

Available data on heat flow and hydraulic characteristics of wells were used in obtaining estimates of resource base and recoverable resources. 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. Results of computational schemes indicate that the conventional approach for determining recoverable resources leads to unrealistically high estimates of resources. For example, in the present case, the conventional approach is found to produce a value of 8,1 x 10^{21} J, an unrealistically high estimate, as it imply a thermal power output incompatible with that found in known geothermal areas in the state of Goiás. Heuristic schemes in which power output is tied to measured values of flow rates and depths of groundwater wells are found to lead to estimates much lower than the conventional ones. In the present case these are found to fall into the more reasonable range of 18 to 7000 MW.

Introduction

In this work, we propose the use of heuristic schemes in assessment of geothermal resources and consider their application to the Brazilian state of Goiás. The first heuristic scheme used is based on the traditional approach of estimating recoverable resource as a suitable fraction of the area's total resource base. The second and third schemes are proposed here as alternative means of obtaining representative values of recoverable resources. These schemes make use of information available in the SIAGAS/CPRM database which contains data on flow rate, depth, and geographic location of groundwater wells and also data on heat flow determination at eighteen sites scattered through the states of Goiás and Tocantins.

An integrated analysis of these data sets is found to be capable of providing valuable insights into the thermal field of the earth's crust in the highland region of central Brazil. In the present work we discuss the implications of this data and its relevance to heuristic schemes for the assessment of geothermal resources of the state of Goiás.

Method

As noted by Muffler and Cataldi (1978, 1982) the terminology in the assessment of geothermal resources must be compatible with that proposed by McKelvey (1968) for mineral resources. According to these authors the term resource base refers to the total amount of thermal energy in the earth's crust and recoverable resource is the fraction of that energy that man might be able to recover, using presently available technology.

Several methods are currently employed in the assessment of geothermal resources, depending on the nature of available data on the thermal and hydraulic characteristics of the crustal layers and access to related information on regional geology and geophysics. The present work focuses on the use of heuristic schemes towards an integrated analysis of thermal and hydraulic data leading to the assessment of recoverable resources of geothermal energy in the state of Goiás. We believe that results obtained in such computations may be of help in improving the procedures used in previous assessments of geothermal resources.

Each of the three heuristic schemes proposed in this work is implemented by a computer program (or script) written in the Python language. Due to the size limitation of the text, the programs are not listed here, but for illustrative purposes, important program fragments are reproduced as a convenient aid in clarifying important ideas behind each heuristic scheme.

Sources of Data

New geothermal data have been acquired in recent years in the central parts of Brazil as part of a project for evaluation of subsurface thermal energy resources. In addition, information on hydraulic characteristics of deep aquifers are also available currently as part of public domain data bases.

The primary geothermal data used in heuristic schemes are taken from a recent compilation carried out by the Geothermal Laboratory, Observatório Nacional–ON/MCT (Ferreira, 2003). At present geothermal data are available for 36 sites distributed at 18 localities in the study area.

Data on hydraulic characteristics were extracted from SIAGAS, a public domain database on groundwater wells organized by CPRM (Companhia Pesquisa de Recursos Minerais). At present SIAGAS contains records concerning 712 groundwater wells in the study area. The relevant information can be filtered out from this data base using standard SQL query statements.

Regional Characteristics

An examination of the thermal and hydraulic data gathered in the present work has allowed valuable insights into the general regional characteristics of the study area. For example, geothermal data have been useful in preparing a contour map of heat flow of the state of Goiás, presented in figure (1). The prominent features in this map are the presence of regions in the southern (Caldas Novas, Rio Quente and Cachoeira Dourada areas) and northern parts (Formoso and Minaçu areas) of Goiás where heat flow is higher than 80 mW/m^2. The geologic significance of this large scale thermal anomaly is not well understood as it is located within the highland area in central Brazil, usually considered as tectonically quiescent.

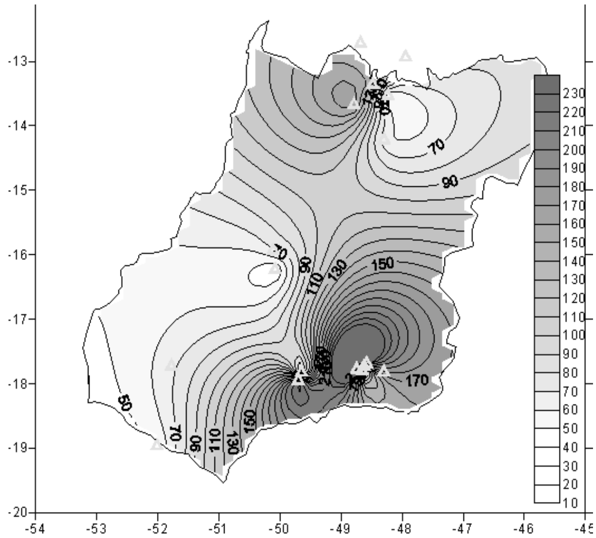

Figure 1. Contour map of heat flow of the state of Goiás. The units are in mW/m^2.

Similarly data on groundwater wells has been useful in obtaining an understanding of the hydraulic characteristics of the study area. As an illustrative example we present in figure (2) the flow rate contour map. The geographical distribution is not uniform as the western and northwestern parts of the state are almost devoid of wells. Nevertheless the map reveals that flow rates are relatively higher (values in excess of 10m^3/h) in the eastern parts of Goiás.

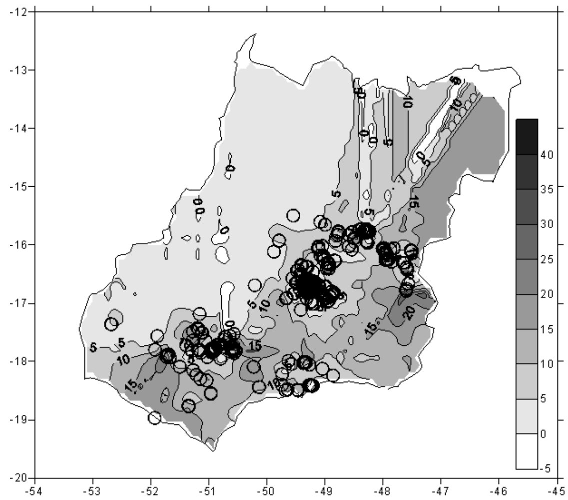

Figure 2. Contour map of flow rates of groundwater wells in the state of Goiás. Circles indicate locations of wells.

Actually specific flow rate is a better indicator of the hydraulic properties of the subsurface strata than flow rate itself. Unfortunately, specific flow rate measurements have been carried out only in very few localities in the area of survey. On the other hand, most of the wells in the state of Goiás have been drilled under similar technical conditions. Thus absolute flow rate may be considered as a first order estimate of the specific flow rate. In the present work absolute flow rates were used in the heuristic schemes for resource assessments.

The volume method to estimate resource base

Volume method is one of the standard methods used in resource assessments (Muffler, 1979). It consists of estimating resource base as the total amount of thermal energy available down to a suitable level, considered as the accessible depth for resource assessment, in the earth's crust. The energy content is estimated from the relation:

$$Q_{RB} = \rho c_p A\, d (T - T_0) \quad (1)$$

where ρ is the mean density of the layer that extends downwards to depth *d*, c_p its specific heat, *A* the land area, T_0 the mean annual surface temperature and *T* the temperature at depth ***d***. Since temperature varies with depth it is necessary to integrate the right hand side of equation (1) taking into account relevant values for the parameters that determine the local temperature regime. Assuming that thermal conductivity (λ) and radiogenic heat production (*A*) remain constant, the value of excess temperature ($\Delta T = T\text{-}T_0$) as a function of depth can be estimated from the relation:

$$\Delta T = \frac{q_0}{k} d - \frac{A_0}{2k} d^2 \quad (2)$$

where q_0 is the local heat flow. Use of equations (1) and (2) along with contour maps of heat flow distribution allows resource base to be estimated for any specific area. In the present case the resource base for the state of Goiás has been estimated at 2,5 x 10^{24} J.

Estimation of Recoverable Resource

Initially an empirical relation between flow rate and porosity was adopted as a convenient means of obtaining a rough estimate of the recoverable resource. The values of flow rate and porosity constituting the empirical relation are given table (1).

Table 1 - Estimation of the Resource Base fraction as the 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

The fractions chosen are heuristics themselves and are based on the assumption that equivalent porosities of deep (3000m) aquifers are in some manner related to the flow rates in shallow (< 500m) wells. In other words, a cross plot of gridded values of flow rate and heat flow can be used to obtain geographically representative values of the recoverable resource.

The First Heuristic Scheme

In this scheme a regular network of flow rate values was generated using 608 SIAGAS data points, a process which produced 6100 gridded points. Similarly a regular network of heat flow values were generated using 18 geothermal data points (Ferreira, 2003), a process which produced 5100 gridded points. Because the number of points in the two grid schemes (heat flow and flow rate) are different an algorithm was devised to map each flow rate nodal value onto a geographically closest heat flow datum point. The result of this procedure has been a quadruple record set of nodal coordinates and the parameter values. This data set was used as input to a computer program in the Python language for implementing the heuristic scheme.

The relevant segment of the computer program (HS-1) that implements this scheme is given in listing (1). It shows, in the sample line before the last, how the two methods (program functions) are called. To the recRecup() function two parameters are passed in, ie, *hf* (heat flow) and *vazao* (flow rate) which in turn is returned from the getFraction() method. The latter method simply implements table 1. Method recRecup() calculates Q_{RB} (equation 1) and makes a cut in it, so to say, to produce the desired result. It's a common use to pre-compute constant values to speed up processing, so variables starting with "preCalc" show this trend. It's been tried to name variables so that its meaning might be self-explanatory by their names.

Listing (1) Segment of computational procedure in Python used to implement HS-1 scheme.

```
:
:
def recRecup(hf, fraction):
    global preCalc_zmax_by_condT,
           preCalc_radiogenic,
           preCalc_density_calorEsp_areaGrade_zmax
    dt=hf*preCalc_zmax_by_condT-preCalc_radiogenic
    recBase_in_J=dt*preCalc_densCalorEsp_areaGrade_zmax
    return recBase_in_J*fraction

def getFraction(vazao):
    if vazao <= 5: return 0.005
    elif vazao > 5  and vazao <=10: return 0.025
    elif vazao > 10 and vazao <=100: return 0.05
    return 0.075   # ie, elif vazao > 100: return 0.075
:
:
    recRecov = recRecup(hf, getFraction(vazao))
    total = total + recRecov

:
:
```

The input data for the program are given in table (2). The variable "total", declared in the program (see Listing 1), integrates the result providing the value of the total recoverable resource. Table 3 shows a small output sample from the HS-1-related program. The final output, given in last line in this table, gives the recoverable resource as 8.1×10^{21}J.

Table (2) Input data used in program HS - 1

Surface area of Goiás	340165.9 km^2
Area per elemental grid	~ 55.76 km^2
Number of grids for Heat Flow	5100
Number of grids for Flow Rate	6100
Surface temperature	24ºC
RR crust mean depth	3000m
Crust's density	2650 kg/m^3
Specific heat	836 J/kg ºC
Thermal conductivity	3.0 W/m K
Heat production rate	0.000001 W/m^3

Table (3) Sample results from HS – 1 Python Program for computing recoverable resource.

Grid		Recoverable Resource
lon	Lat	(J)
:	:	:
:	:	:
-48.2	-19.0	1.63×10^{19}
-48.0	-19.0	3.23×10^{19}
-47.8	-19.0	3.21×10^{19}
-47.7	-19.0	3.19×10^{19}
:	:	:
:	:	:
Total		8.1×10^{21}

A contour map of the calculated values of the recoverable resource (RR) is presented in figure (2). As can be seen from this figure there is a region of high RR values (above 30×10^{18}J) in southeastern Goiás. In general, the southern and eastern parts of the state show higher RR values. Also noticeable is the area covering a large part of western and northwestern Goiás where the RR values are less than 5×10^{18}J. In this region heat flow is relatively low. In addition, well flow rates are also lower than normal. Nonetheless, the total RR value is estimated at 8.1×10^{21} J.

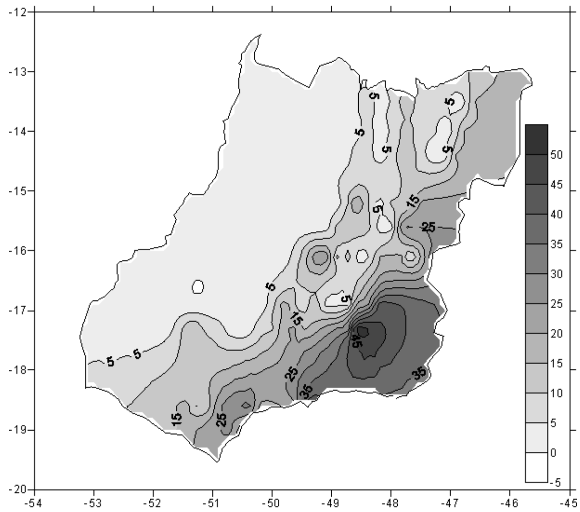

Figure (2) Contour map of recoverable resource values calculated by HS–1. The contours are in units of 10^{18}J.

The Second Heuristic Scheme

The second heuristic scheme (HS-2) assumes that virtual producer wells exist at 6100 nodal points generated during gridding of flow rate data. Excess temperatures at these virtual sites are computed from the gridded heat flow values. The virtual wells are set to have a uniform reference depth of 3 km. The result is a quadruple record containing values of flow rate, heat flow and coordinates of nodal points (longitude, latitude). It serves as the input for the computational program HS-2 (in Python language). The key segment of this program is reproduced in listing (2).

Note that 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.

Listing 2 – Segment of the computational program used to implement HS 2.

```
:
:
def calcQ(hf, vazao):
    global depth_by_k,a_by_2k_sqrDepth
    dt=hf*depth_by_k-a_by_2k_sqrDepth
    q_by_s = vazao * 4184 * dt
    return q_by_s
:
:
    joule_by_s = calcQ(hf, vazao)
    total = total + joule_by_s
:
:
```

According to the results obtained the integrated thermal power output for the state of Goiás is 7,1 x 10^9 W. The contour map of the thermal power output is presented in figure (3). The main features in this map are quite similar to the one in figure (2), implying that the thermal power is closely related to the distribution of recoverable resources.

In fact 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 as 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 first heuristic scheme, a consequence of the large grid spacing used in the computational procedure.

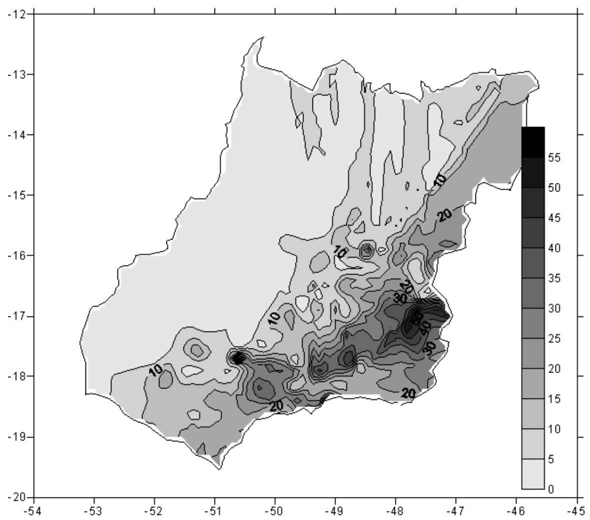

Fig. 3 - Contour map showing "thermal power", according to EH-2 with 6100 flow rate gridded points (from SIAGAS) as 3000-m depth virtual thermal water producer wells. Values are in units of 10^5 J/s

The Third Heuristic Scheme

The third heuristic scheme assumes that virtual thermal energy producer wells exist at the locations of SIAGAS wells. These virtual wells are also assumed to have the same flow rates and depth levels as the SIAGAS wells. As in former schemes, excess temperatures are specified on the basis of gridded heat flow values. The result is a quintuple record containing values of depth, flow rate and heat flow and coordinates of nodal points (longitude, latitude). It serves as the input for the computational procedure HS-3 (in Python language). The key segment of this program is reproduced in listing (3).

Listing 3 – Key segment of the program used to implement HS-3.

```
:
def calcQ(hf, vazao, depth):
    global k, a_by_2k
    dt = hf * depth / k - a_by_2k * (depth**2)
    q_by_s = vazao * 4184 * dt
    return q_by_s
:
:
    joule_by_s = calcQ(hf, vazao, depth)
    total = total + joule_by_s
```

A sample output from the HS-3 program is given in table (4). According to the results obtained the integrated thermal power output for the state of Goiás for this third heuristic scheme is 1,8 x 10^7 W, more than two orders of magnitude less than the estimate obtained under HS-2 scheme.

Table (4) Sample of the output from the HS-3 program giving the input data as well as the thermal power output.

longitude	latitude	heat flow (W/m^2)	flow rate (l/s)	depth (m)	thermal power (W)
-52.68388	-17.35833	0.051	0.833	70.0	4185.98
-52.68166	-17.35777	0.052	3.333	150.0	36359.3
-52.67388	-17.36111	0.053	1.388	68.0	6985.40
-51.93138	-18.96972	0.054	5.0	96.0	36163.9
-51.92416	-17.79916	0.055	2.222	85.0	14545.9
:	:	:	:	:	:
:	:	:	:	:	:
-52.68388	-17.35833	0.051	0.833	70.0	4185.9
-52.68166	-17.35777	0.052	3.333	150.0	36359.3
-52.67388	-17.36111	0.053	1.388	68.0	6985.4
-51.93138	-18.96972	0.054	5.0	96.0	36163.9
-51.92416	-17.79916	0.055	2.222	85.0	14545.9

The contour map of thermal power output under the HS-3 scheme is illustrated in figure (4). This map also reveal features similar to those present in maps resulting from the previous schemes. Thus the eastern parts of the state of Goiás are characterized by relatively higher thermal power outputs compared to the western parts.

Discussion and Conclusions

Available data on heat flow and hydraulic characteristics of wells were used in obtaining estimates of resource base and recoverable resources. 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.

On the other hand the results of computational schemes indicate that the conventional approach for determining recoverable resources is likely to lead to unrealistically high estimates of resources. For example, in the present case conventional approach is found to produce an estimate of 8,1 x 10^{21} J, an unrealistically high value as it implies a thermal power output incompatible with those found in known geothermal areas in the state of Goiás.

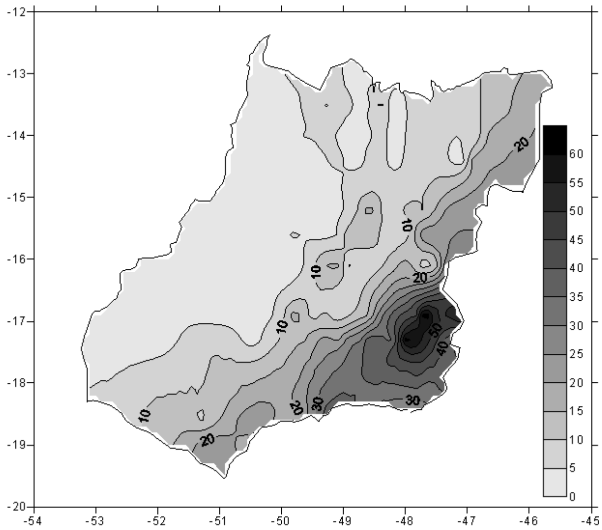

Figure (4) Contour map of thermal power output according to HS-3 scheme. The contours are in units of 10^4 W.

Heuristic schemes in which power output is tied to values of flow rates and depths of groundwater wells are found to produce estimates much lower than the conventional ones. In the present case these are found to fall in the more reasonable range of 18 to 7000 MW. A summary of the final results are presented in table (5).

Table (5) Estimates of recoverable resources obtained from heuristic schemes proposed in this work.

1st HS (*)	2nd HS	3rd HS
8,1 x 10^{21}J	7,1 GW or ~6,7x10^{18}J in 30 years	17,9 MW or ~17 x10^{15}J in 30 years

(*) HS = Heuristic Scheme

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