Pioneering insights into deep groundwater movements in the Paraná Basin: Comparison with subsurface flows in the Amazon Region

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Abstract

We present results of a pioneering study that provide new insights into the characteristics of deep groundwater flow systems of the Paraná basin. The technique employed, based on geothermal methods, is capable of providing simultaneous estimates of both vertical and horizontal components of groundwater flows. The analysis makes use of bottom-hole temperature data from oil wells. Vertical velocities of subsurface flows are found to fall in the range of 10^{-10} to 10^{-9} m/s while the horizontal components are generally an order of magnitude higher, falling in the range of 10^{-9} to 10^{-8} m/s. The results obtained have allowed identification of three different regions of up flows and five different regions of down flows, at depths ranging from 1000 to 4000 meters. The geographic distribution of such flow pattern points to complex interplays of subsurface recharge and discharge systems of groundwater in the Paraná basin. This system is unlike that found in the basins in the Amazon region, where systematic lateral flows in the west – east direction is ubiquitous.

Introduction

Most hydrogeologic studies carried out in Brazil have dealt with problems of groundwater circulation at relatively shallow depths of no more than a few hundred meters. The absence of such studies has been a consequence of the difficulties in acquiring relevant experimental data, necessary for quantification of deep groundwater movements and for regional mapping of recharge and discharge zones. A classic example is the Paraná basin, where relatively good information is available on groundwater movements at shallow depths of less than a kilometer but very little information is available on groundwater flows in strata below the uppermost aquifers.

On the other hand, subsurface thermal regime is quite sensitive to heat transfer by advective fluid flows and there exists simple geothermal methods that can provide valuable information on the nature of groundwater movements. In recent decades, geothermal methods have emerged as a versatile class of geophysical methods in studies of groundwater hydrology. The main advantage of this approach is the ease with which it is possible to determine characteristics of advective fluid flows, at depths extending to several kilometers.

In this context, the focus of the present work is on analysis of bottom-hole temperature data for oil wells, for determination of subsurface flow systems of groundwater through the deep strata in the Parana sedimentary basin.

Hydrogeological Characteristics of the Paraná Basin

The Paraná basin covers an area of about one million km^2 in the Brazilian territory. It also extends into eastern Paraguay, northwestern Uruguay and northeastern Argentina. According to estimates by Rebouças (1976, 1994) and Araujo et al. (1999) the volume of water stored in these aquifer systems is of the order of 50000 km^3, and the rates of natural recharges are 234 km^3 per year. The outcrops on the borders of the Paraná sedimentary basin are considered responsible for most of the aquifer recharge.

The Paleozoic sediments of the Paraná basin host some of the important aquifers, such as the Furnas sandstone of Devonian age, the Aquidauana and Itararé sandy beds of Lower Permian, the Rio Bonito Formation of Middle Permian and Rio do Rasto Formation of Upper Permian. Aquifers at shallow depths of less than 500 meters are present along the eastern, southern and northwestern margins of the basin, where yields of wells are found to fall in the range of 10 to 50 m^3/h.

The Triassic-Jurassic deposits form a system of confined aquifers of regional extent, collectively known as the Guarani aquifer. It extends over an area of 839000 km^2 in Brazil and an additional area of 355000 km^2 in the eastern part of the Chaco-Parana Basin. The aquifer is capped by basaltic lava flows with thicknesses of up to 1500 meters. The sedimentary strata of the aquifer were deposited during the Jurassic and Triassic periods. The upper Botucatu Formation consists of well-sorted sandstones of aeolian origin. The lower Piramboia Formation consists of silty and clayish sandstones of aeolian and fluvial origins. The Triassic sandstones usually have a larger amount of clay in their lower layers, which diminishes their hydraulic efficiency. Artesian conditions prevail in about 70% of its confined area.

Data Sets Employed in the Present Work

Current understanding of the thermal field of subsurface layers in the hydrogeologic provinces of Brazil is based mainly on results of heat flow studies, analysis of thermal springs and assessments of geothermal resources, carried out since 1970. Parts of this information has been gathered and organized as a modern data base by the Geothermal Laboratory of the National Observatory in Rio de Janeiro. The data compilations reported in the earlier works include those reported by Meister (1973), Hamza et al (1978) and Hamza and Muñoz (1996). Supplementary data sets have also been reported studies of Oliveira et al (2006), Hamza et al (2005) and Hamza et al (2010). More recently, the geothermal data set available for Paraná basin has been examined in detail in by Gomes (2009). Significant parts of this data set refer to measurements in shallow boreholes, which are incapable of providing direct information on deep geothermal fields. Hence, the data set selected for purposes of the present work is limited to those obtained by the BHT method in deep oil wells, generally with depths greater than 1000 meters at 82 localities. The geographic distribution of this selected data set is illustrated in the map of Figure (1).

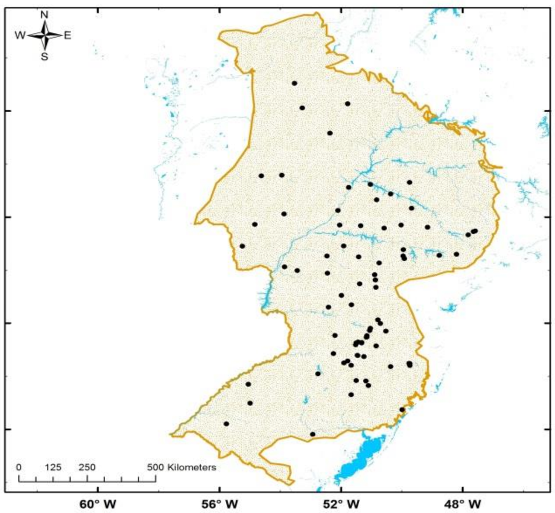

Figure (1) Locations of geothermal measurements in the Paraná basin, selected for the present work.

Methodology

The general principle of the geothermal method in studies of groundwater flows is based on considerations of the role of advection heat transfer on the conductive regime of subsurface layers. In relatively stable tectonic settings, changes in thermal regime take place on time scales that are large compared with time periods amenable for experimental measurements. Hence it is usual practice to assume steady state conditions and ignore time dependent changes in model simulations of advective effects on thermal fields. Under steady state conditions the equation for simultaneous heat transfer by conduction and convection in a porous and permeable medium of homogeneous thermal properties is (Carslaw and Jaeger, 1959; Stallman, 1963):

$$\lambda_s \left[\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right] - \rho_f C_f \left[\frac{\partial v_x T}{\partial x}+\frac{\partial v_y T}{\partial y}+\frac{\partial v_z T}{\partial z}\right]=0 \quad (1)$$

where T is the temperature at the position determined by the coordinates (x, y and z), λ_S the thermal conductivity of the medium, $\rho_f C_f$ the thermal capacity of the fluids in the pore space and v_x, v_y, and v_z velocity components of fluids in the directions *x, y* and *z* respectively.

A number of solutions of this equation have been discussed in the literature. Bredehoeft and Papdopulos (1965) considered the case where flow is dominantly in the vertical direction, which has been employed widely in hydrogeologic and geothermal studies (see for example Cartwright, 1970; Mansure and Reiter, 1979). Pimentel and Hamza (2012) presented a solution for the general case of a layered medium that takes into account explicitly the interior and exterior boundary conditions of the heat transfer problem and the fact that the solutions for individual layers are coupled.

Lu and Ge (1996) considered the case where the flow has both horizontal (x) and vertical (z) components. The simplified differential equation considered by Lu and Ge (1996), for a medium with thickness L, may be given as:

$$\frac{d^2T}{dz^2}=\frac{\beta}{L}\eta+\frac{\alpha}{L}\gamma \quad (2)$$

The quantities $\alpha = c_w \rho_w v_x L/\kappa$ and $\beta = c_w \rho_w v_z L/\kappa$ are dimensionless Peclet numbers, in which $c_w \rho_w$ is the specific heat and v_x and v_z the velocities of the circulating water in the x and z directions. The parameters γ and η are the temperature gradients (*dT/dx)* and (*dT/dz*) in the horizontal and vertical directions respectively. According to the sign convention adopted by Lu and Ge (1996) γ is taken as positive when the heat flux is leftward and negative when it is rightward. Also, the parameter α is considered positive when the fluid flux v_x is rightward (or negative when it is leftward) and the parameter β is positive when the fluid flux v_z is downward (or negative when it is upward).

Lu and Ge (1996) provided a solution of (2) for a homogeneous medium. For a layered medium this may be rewritten as:

$$\frac{T_i - T_0}{T_L - T_0}=\frac{\exp[\beta(z_i/L)]-1}{\exp(\beta)-1}+\frac{\alpha\gamma}{\beta\eta}\left[\frac{\exp[\beta(z_i/L)]-1}{\exp(\beta)-1}-\frac{z_i}{L}\right] \quad (3)$$

where the subscripts *0* and *L* indicate temperatures at the top and bottom of the medium where water flow occurs, while i is the temperature of the i^{th} layer at depth z_i within the medium.

Equation (3) allows use of curve-matching methods for determination of the parameter β and the product ($\alpha\gamma/\beta\eta$). This in turn may be used for determination of the velocity components v_x and v_z. Reiter (2001) pointed out that the solution presented by Lu and Ge (1996) may be reformulated, in deriving a relation for vertical gradient (η) as:

$$\eta = a + bz + cT \quad (4)$$

In equation (4) *a* represents the value of temperature gradient in the absence of fluid flows, *b* is related to the product of specific discharge in the horizontal direction and horizontal temperature gradient and *c* is related to vertical specific discharge. As demonstrated by Reiter (2001) equation (4) allows use of three-dimensional plots for determining the velocity components. Unfortunately, the formulation presented by Reiter (2001) has some dimensional inconsistencies. Hence, in the present work, data analysis by curve matching methods has been based on relations derived from equation (3).

In graphical representations of thermal profiles (with the depth axis pointed vertically downward and temperature on the horizontal axis) the effect of advection heat transfer manifests as a characteristic curvature in the vertical distribution of temperatures. The sign of the flow parameter (β), may be positive or negative depending on the direction of v_z. Thus, a plot of equation *(3)* should reveal the effect of advection heat transfer in the vertical temperature distribution. Positive values of β generates curvatures that are indicative of down flow, while negative values leads to curvatures that indicate up flow. It is clear that fit of observational data on temperature distribution may be used for determining the value of β and hence the velocity of ground water flows.

It is customary practice in hydro-geologic and geothermal studies to look for non-linear features in temperature logs as the first step in identifying thermal effects of groundwater flows. In cases where only bottom-hole temperature (BHT) data are available the method proposed by Pimentel and Hamza (2012) may be employed in the determination of groundwater flows. According to this procedure, the depth to the bottom boundary of the flow system is set on the basis of information available in regional hydro-geological studies. Following this, the bottom boundary temperature is calculated, based on regional geothermal gradients derived from BHT data. It then becomes possible to use equation (3) for deriving theoretical curves.

An example of the method used for determination of horizontal and vertical velocities of groundwater flow in the Paraná basin is presented in Figure (2). In this figure, the dashed line is the best fit of the model (based on equation 3) and the blue dots are observational data. The characteristic curvature in the temperature distribution indicates that this is a region of groundwater recharge. Note that, in this example, the horizontal component (v_x) of groundwater flow is nearly ten times greater than the vertical component (v_z).

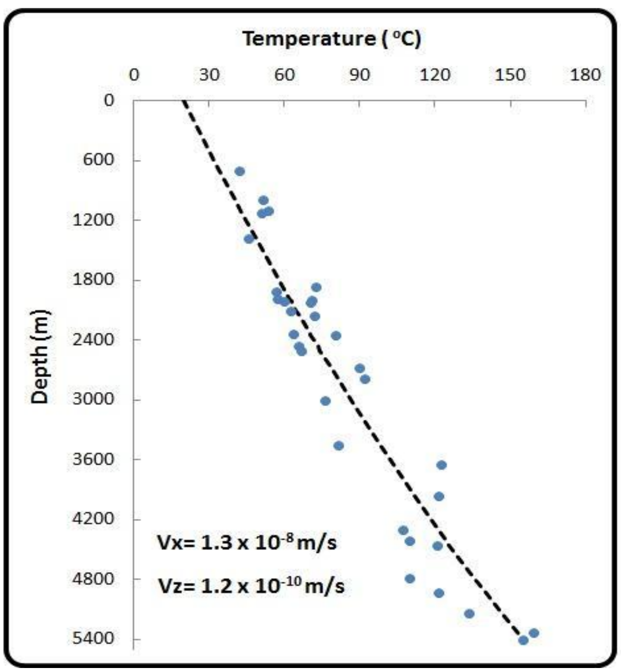

Figure (2) Example of the method used for determination of horizontal and vertical velocities of groundwater flow in a recharge region, on the eastern border of the Paraná basin.

An example indicative of negative flow parameter is illustrated in Figure (3), for a region in the Paraná basin. In this figure the dashed line is the best fit of the model (based on equation 3) and the blue dots are observational data. Note that, in this example, the horizontal component of groundwater flow is nearly one hundred times greater than the vertical component.

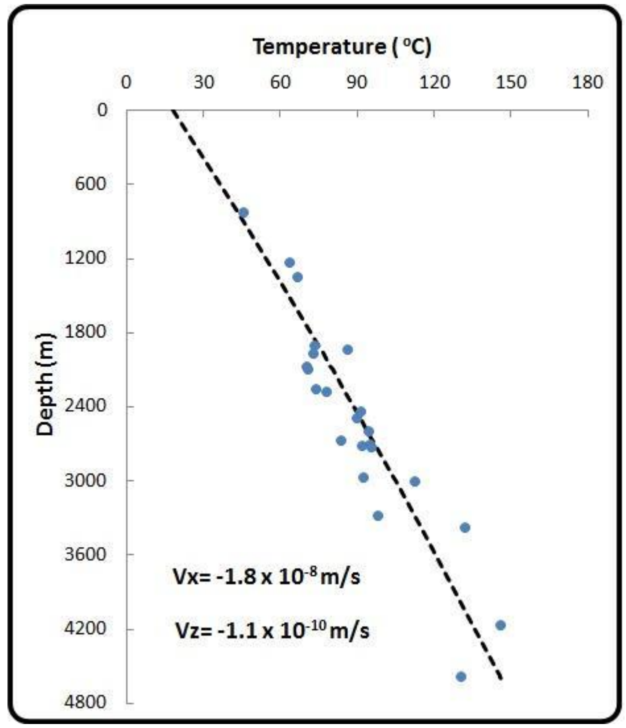

Figure (3) Example of the method used for determination of horizontal and vertical velocities of groundwater flow in a discharge region, in the northwestern part of the Paraná basin.

The main difficulty in applying the above mentioned procedure arises from geological uncertainties as to the depth levels of the top and bottom boundaries of the flow system. The availability of information on permeability of deep strata is, in general, limited. In addition, there are considerable uncertainties as to the lateral extent of lithologic units and stratigraphic sequences. Also, there are intra-basinal as well as inter-basinal variations in depth levels of deep aquifers. Fortunately, results of numerical simulations reveal that errors of up to 10% in the depth level of the bottom boundary has only a minor influence on the estimates of flow velocities.

Results Obtained

Separation of data sets with positive and negative values of the flow parameter was found to be convenient in analysis of the subsurface flow pattern. These are considered as localities of down flow and up flow of groundwater. Contiguous groups of such localities may then be considered as forming regions of recharge and discharge zones. A summary of well depths, flow depths and basal temperatures of such regions is given in Table (1).

Table (1) Well depths, flow depths and basal temperatures of recharge and discharge regions in the Paraná basin.

Flow System	Well Depth (m)	Flow Depth (m)	Basal T (^oC)
Recharge	1396-2792 East-central	2900	95.5
	702 - 1344 Eastern parts	1600	81.5
Discharge	1947-2105 Northern parts	2200	75.0
	3003 – 4162 Western parts	4300	139
	1902 - 3273 South-east	3400	108

A summary of the vertical (v_z) and horizontal (v_x) velocity components for the five different regions in the Paraná basin is given in Table (2).

Table (2) Vertical (v_z) and horizontal (v_x) velocities for the five different regions in the Paraná basin.

Region	Velocity (10^{-9} m/s)		Modal Parameters	
	v_z	v_x	β	α
East-central	1.0	40	4.87	194.8
Eastern parts	1.2	75	3.09	201.6
Northern parts	-1.2	-65	-4.44	-240.2
Western parts	-1.1	-50	-7.95	-361.2
South-east	-1.5	-80	-8.57	-456.9

Figure (4) indicates the zones of recharge (blue contours) and discharge (red contours) of groundwater in the Paraná basin, identified in the present work.

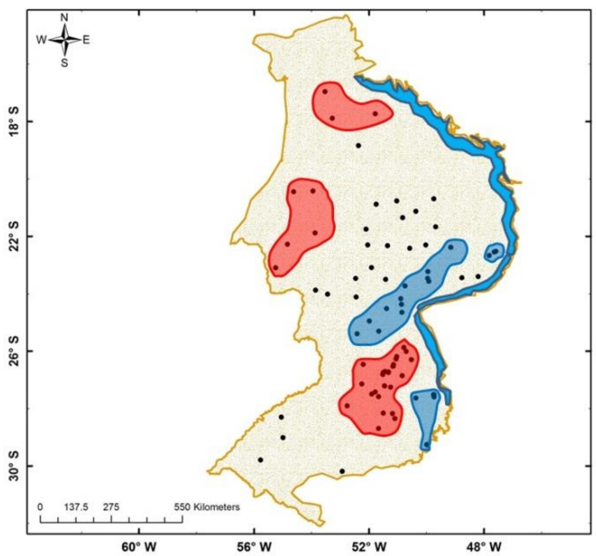

Figure (4) Zones of up flow and down flow of groundwater at depths of in the Paraná basin. The blue patches on the eastern border of the basin are recharge zones at depths less than 300 meters.

As can be seen in this figure it has been possible to identify three different zones of recharge and three additional zones of discharge. We conclude that the deep circulation system in the Paraná basin is characterized by a complex system of up flows and down flows of groundwater. However, for a number of localities model fits to BHT data sets are unable to identify any specific flow pattern. Such cases are considered indicative of data sets with poor resolution for identifying the nature of subsurface flows.

Recharge Flows at Shallow Depths

Additional indications as to the nature of movements in the zone overlying region of deep circulation systems can be found by considering the extrapolated segments of vertical distributions of bottom-hole temperatures at shallower depths. Examples of such distributions are illustrated in Figure (5). The continuous lines in this figure are least square fits to relevant BHT data sets, while the dotted lines indicate bounding (minimum and maximum) values of temperatures compatible with the observational data. For obvious reasons, the linear extrapolations of the least square fits to shallower levels have been terminated at depths corresponding to the values of mean annual surface temperatures, derived from local meteorological records. The vertical temperature distributions arising from applying this procedure are found to point to the existence of zones of abnormally low temperature gradients (LGZ) at shallow depths.

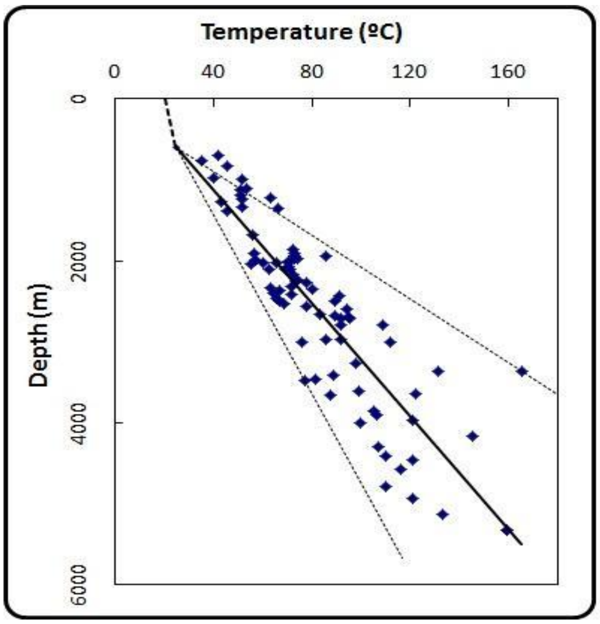

Figure (5) Temperature distributions illustrating water flow effects at shallow depths in the Paraná basin.

Note that the gradient values for the upper layer (LGZ) are in the range of 5 to $10^oC/km$, while those for the deeper levels are in the range of 23 to $31^oC/km$. The depths of the transition zones of gradients in the basins are found to be variable, approximately 600 meters.

Comparison with Flow Systems in the Amazon Region

At this point, it is convenient to make a comparative analysis of subsurface flows calculated for the Paraná basin with those reported by Pimentel and Hamza (2012) for basins in the Amazon region. Listed in Table (3) are the values of the velocity components and the model parameter δ for these two basins. Note that the vertical velocity components of subsurface flows in the Paraná basin are in general lower than those for the Amazon basin. It may be considered as indication that the recharge flow rates in the Amazon basin are relatively larger. The horizontal velocity components, however, reveal an opposite trend. The higher horizontal velocities in Paraná basin is a consequence of the relatively shorter distance for flow of groundwater from the recharge area to the zone of lateral flow. The relatively high values of the correlation coefficients in the last column of this table indicate that the respective model fits and conclusions as to the flow systems are robust.

Another interesting point is that the magnitudes of velocities decrease in the downstream direction in both regions. This is in general agreement with the expected trends of hydraulic gradients driving the regional flows. For example, the largest value of the horizontal velocity component for the Amazon region is found in the Acre basin, situated in the upstream side of the flow system. On the other hand, the lowest velocity is found for the Marajó basin, situated in the downstream side. A similar pattern is also observed for the Paraná basin, where both vertical and horizontal flow velocities are higher in its eastern parts (in the upstream side of regional flow), compared to those in the east-central parts (in the downstream side).

Table (3) Comparative analysis of flow velocities (V) for the sub-basins in the Amazon and Paraná.

Basins	V (10^{-9} m/s)		Modal Parameters	
	v_z	v_x	δ	R^2
Amazon Region				
Acre	1.4	49	-0.857	0.9903
Solimões	1.1	44	-0.818	0.9873
Amazonas	1.1	33	-0.784	0.9766
Marajó	0.9	30	-0.822	0.9879
Barreirinhas	0.9	22	-0.479	0.9116
Paraná Basin				
Eastern parts	1.0	40	-0.615	0.9524
East-central	1.2	75	-0.657	0.9744
Northern parts	-1.2	-65	-0.836	0.9997
Western parts	-1.1	-50	-0.646	0.9722
South-east	-1.5	-80	-0.806	0.9845

According to Pimentel and Hamza (2012) the lateral flow in the Amazon region is inferred to take place along a central belt, following roughly the same course as that of the Amazon River, the direction of flow being from west to east. In the case of Paraná basin, the inferred direction of lateral flow is from northeast to southwest, following roughly the course of the Paraná River in southern Brazil. As in the case of Amazon region the zone of lateral flow is wider in the upstream parts in the northeast and narrower in the downstream parts in the southwest.

However, unlike the basins in the Amazon region, where only recharge type movements have been identified, the Paraná basin is found to be characterized by the presence of both recharge and discharge zones. Occurrence of up flow zones seems to be a characteristic feature of the Paraná basin, which is distinctly different from that observed in the Amazon region.

The area extents of down flow zones are found to be quite large implying the existence of distributed recharge systems in both sedimentary basins.

Discussion and Conclusions

The focus of the present work has been to make use of geothermal methods for determination of groundwater movements in deep strata of the Paraná basin. The available BHT data from deep wells have allowed estimates of vertical groundwater movements at depths of up to 4000 meters.

Vertical velocities of subsurface fluid flows, calculated from model fits to observational data, are found to fall in the range of 10^{-10} to 10^{-9} m/s while the horizontal velocities are found to fall in the range of 10^{-9} to 10^{-8} m/s. The zones of down flows are situated in the east-central parts of the basin, a region identified as the recharge area of the main aquifers (Furnas, Aquidauana and Guarani). These are adjacent to the narrow belt of recharge zones along the eastern border, identified in large number of hydrogeologic studies (DAEE, 1974; Rebouças, 1976; Araujo et al, 1999; Rabelo and Wendland, 2009; Manzione et al, 2012). The overall geographic distribution of recharge zones is in accordance with the general pattern of hydraulic gradient in this basin, which is directed from the eastern parts towards its west central parts.

The zones of up flows occur in the northwestern region and also in the south-central region. It is important to point out that the up flow zones are also characterized by the presence of a large number of thermal springs and higher than normal heat flow, this latter one attributed to deep thermal refraction effects (Hurter, 1992).

Identification of recharge flows has allowed inferences as to the existence of regional-scale lateral movements of groundwater in the basal parts of sedimentary basins. The inferred zones of lateral movements are mostly in the central parts of the basins with the direction flow roughly coincident with the fluvial discharge systems at the surface. The influence of lateral flows on subsurface geotherms needs to be taken into consideration in assessments of geothermal resources.

We propose that the part of subsurface flow system with lateral movements in the Paraná basin be named “Guarani River”.

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