Indications of an Underground River beneath the Amazon River: Inferences from Results of Geothermal Studies

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Abstract

Analysis of geothermal data for the basin systems of the Amazon region reveals non-linear features in the subsurface temperature distributions. Results of numerical simulations indicate that such features cannot be attributed to mechanisms other than advective heat transfer, originating from downward fluid flows. Velocities of such fluid flows were calculated using a steady state model of flow through porous media comprising the sedimentary basins. The depth ranges and area extent of such flows indicate the existence of generalized lateral flow in the basin systems of the Amazon region (Acre, Solimões, Amazonas, Marajó e Barreirinhas). The direction flow inferred from the basement topography fo the region is from the western to the eastern parts. Estimates of flow rates indicate that Amazonas basin has highest flow rate while the Marajó basin has the lowest. Overall flow rate is estimated to be in the range of 3900 to 4000m^3/s, substantially higher than the maximum flow rate of São Francisco river in eastern Brazil.

Introduction

Much of the area of the Amazon region is covered by sedimentary rocks. The major sedimentary basins are Acre, Solimões, Amazonas, Marajó and Barreirinhas. The map of Figure (1) illustrates the locations of these basins. It is estimated that nearly 24 % of the total area of the Amazon region is covered by sedimentary basins.

Amazon river system is one of the largest drainage systems on the surface of the Earth. The characteristics of this surface river discharge system have been the object of a large number of investigations over the last several decades (Jaccon and Cudo, 1987; Guimarães et al., 1993; Molinier et al., 1994). Nevertheless relatively few investigations have been carried in understanding the characteristics of recharge and discharge of groundwater and conditions of subsurface flow systems in this region. Much of the studies in groundwater hydrology has been carried out as part of evaluations of flow systems on local scales, there being very evaluations on regional scales. In the present work we examine in some detail the characteristics of geothermal data acquired in deep boreholes and wells and its use for determining regional scale subsurface fluid flows of groundwater in the Amazon region.

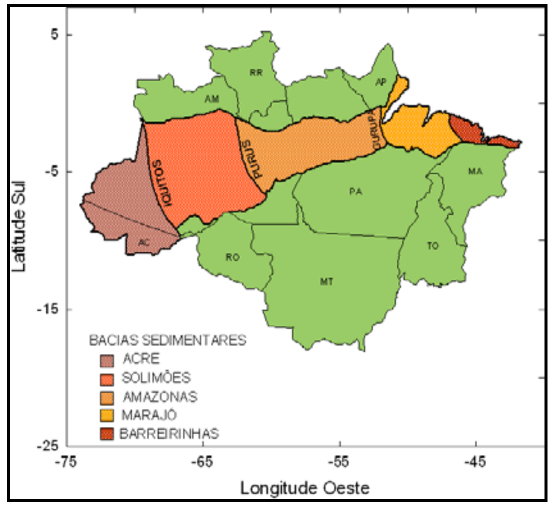

Figure (1) Sedimentary basins of the Amazon region.

Geological Characteristics of the Study area

The geologic context of the Amazon region is marked by the presence of large sedimentary basins (Acre, Solimões, Amazonas, Marajó e Barreirinhas) developed over cratonic basement rocks of Precambrian age. The cratonic nuclei outcrop in the north (Guiana shield) as well as in the south (Guaporé craton). The western border is limited by the sub-Andean structural units ((Marañon, Ucayali and Madre de Dios in Peru and Llanos in Colombia). In the eastern border on the continental platform is the Foz de Amazonas sedimentary basin.

The structural features of basement rocks are considered as indicative of the limits of the sedimentary basins. Thus Iquitos arc is considered as the dividing limit between Acre and Solimões basins, while Purus arc is considered as the dividing limit between Solimões and Amazonas basins. Similarly Gurupá arc is the dividing limit between Amazonas and Marajó basins. Most of the major sedimentary formations developed during Paleozoic and Mesozoic times. There has been relatively little tectonic activity during Cenozoic times.

Data base of the present work

Significant parts of data used in the present work is based on results extracted from results of the earlier works of Meister (1973), Zembruscki (1982), Carvalho et al (1987), Zembruscki and Kiang (1989) and Araujo (1999). Supplementary efforts in data acquisition have also been reported in relatively more recent studies of the Amazon region. These include data reported in studies of Carvalho et al (2006); Pimentel (2007) and Hamza (2008). According to the summary of the data base presented by Pimentel and Hamza (2010) geothermal measurements have been carried out in a total of 241 localities in the Amazon region. Of these 185 are located within the regions of sedimentary basins of Acre, Solimões, Amazonas, Marajó e Barreirinhas. The remaining 56 localities are situated outside basin areas.

Much of the data has been acquired using two different methods, classified as Bottom Hole Temperature (BHT) and Conventional (CVL). The main characteristics of such methods and their quality attributes are described in detail by Hamza e Muñoz (1996), Hamza et al (2005) and Gomes and Hamza (2006). A summary of the data base employed in the present work is reproduced in Table (1).

Table (1) Localities of geothermal measurements in the Amazon region.

Region / Basin	Number of Localities	Methods of Data Acquistion
Acre	12	BHT
Solimões	16	BHT
Amazonas	119	BHT and CVL
Marajó	20	BHT and CVL
Barreirinhas	18	BHT
Emb. Metamórfico	56	CVL
Total	241	

Methodology

The general principle of the geothermal method for the study of groundwater flows can be understood by considering the role of advection heat transfer on the conductive regime of subsurface layers. 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 (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 represents 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 e z respectively. In the case one dimensional flow of heat and and fluids the equation may be simplified as:

$$\lambda_s\left[\frac{\partial^2 T}{\partial z^2}\right]=\rho_f C_f v_z\left[\frac{\partial T}{\partial z}\right] \quad (2)$$

The solution of this equation for the boundary conditions that $T = T_0$ at $z = 0$ and $T = T_L$ at $z = L$ is (Bredehoeft and Papdopulos, 1965):

$$\frac{T_z - T_0}{T_L - T_0}=\frac{[\exp(\beta z / L)-1]}{[\exp(\beta)-1]} \quad (3)$$

where

$$\beta=\frac{\rho_f C_f v_z L}{\lambda_s} \quad (4)$$

Note that the term β represents the ratio of thermal energy transported by conduction to that by advection. The left hand side of equation (3) is the dimensionless temperature (θ) whose vertical distribution depends on the sign of the parameter β, which may be positive or negative depending on the direction of v_z. Thus a plot of dimensionless depth (z/L) versus dimensionless temperature (θ) should reveal the effect of heat transfer by vertical water flow in the temperature distribution. It usually appears as a characteristic curvature. A schematic illustration of the curvatures in temperature profiles, indicative of groundwater flows, is provided in Figure (2).

In usual graphical representations of temperature profiles (with the depth axis pointed vertically downward and temperature on the horizontal axis) the curvature is concave towards the temperature axis for down flow of ground water, while it is convex for up flows (see Figure 2). Fit of observational data on temperature distribution may then be used for determining the value of β and hence the velocity of groundwater flows.

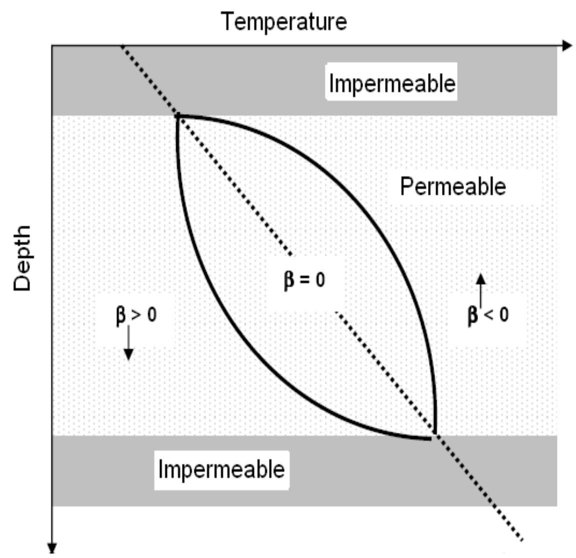

Figure (2) Schematic illustration of the effects of groundwater flows in temperature profiles.

Pioneering studies on the use of geothermal methods for obtaining information on groundwater flows were carried out by Cartwright (1970) and Mansure and Reiter (1979). Hamza (1982) presented an overview of the techniques used in data analysis and interpretation. This method has been used identifying ground water flows in the north eastern parts of Brazil by Hamza et al (1987). It has also been employed in identifying ground water flows induced by seismic activity in the region of Nuporanga (SP) by Yamabe and Hamza (1996) and in the region of Bebedouro (SP) by Assumpção et al (2010).

It is customary practice in geothermal studies to look for non-linear features in temperature logs of boreholes as the first step in identifying effects of groundwater flows. A major limitation of this approach is that it provides information only on water flows for the specific depth interval. In addition, the availability of boreholes with suitable temperature log data is, in general, severely limited. Such difficulties make this conventional approach inefficient for evaluation of basin scale flow systems.

In the present work we adopt a modification of this procedure that circumvents the difficulty of the conventional approach and allows determination of groundwater flows on regional scales. In the new procedure theoretical curves are fit to results of bottom-hole temperature data for a large set of boreholes and deep oil wells. In addition, the wide geographic distribution of oil wells and the large depth intervals of BHT data mean that the results are representative of basin scale flow systems. The main drawbacks with this approach are the relatively low precision of BHT measurements and the difficulty in setting the lower depth limit of the flow system. In the present work we have used corrected values of BHT data and results of geological studies were employed in setting physically reasonable limits for the bottom boundary of the flow system.

Results

The results obtained in data analysis are presented in the following items for the five different basins of the Amazon region. Within each basin the data have been separated into two different groups: one with depths less than ~ 2000 meters and another one for greater depths. Such grouping was done in view of the indications that flow systems in the upper parts of sedimentary basins have velocities different from those at lower levels. The choice of depth value is arbitrary, but it is convenient to relate it to overall differences in the stratigraphic sequences of the basins.

Acre Basin: BHT data are available for 12 sites in this basin. The geothermal gradients vary between 19.5 to 35.2°C/Km, the mean value being 21.13 ± 3.48°C/Km. Figure (3) illustrates the relation between dimensionless values of BHT and depth, for oil wells in the depth range of 960 to 1992 m in this basin. The square symbols in figure (3) indicate data and the dashed curve (in black color) represent the best fit model values for down flow of groundwater with velocity of 3.7×10^{-9} m/s. The blue curve is derived for the model case of down flow of ground water with velocity of 8×10^{-9}m/s. The line in red color indicates the case where down flow is absent.

Figure (4) illustrates the relation between dimensionless values of BHT and depth, for wells in the depth range of 2204 to 3747 meters. In this figure also the square symbols indicate the data, while the curve in black color represents the best fit model values for down flow velocity of 2.3×10^{-9} m/s. The color curves are the same as those in Figure (3), included here only for reference purposes.

Note that velocity of groundwater flow is higher in the upper parts (see Figure 3) relative to that for the lower parts (see Figure 4) in the Acre basin. Such a variation seems compatible with the normal trend of reductions of velocity of deep lying formations, arising from steady decreases in porosity of sedimentary rock formations with depth.

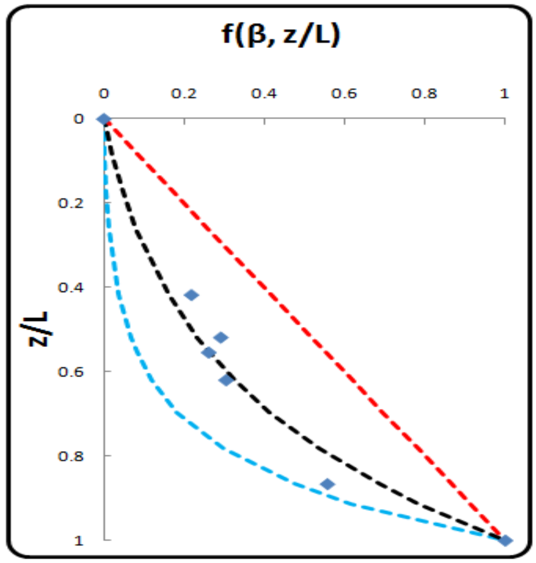

Figure (3) Relation between dimensionless values of BHT and depth, for oil wells in the depth range of 960 to 1992 meters, in the Acre basin.

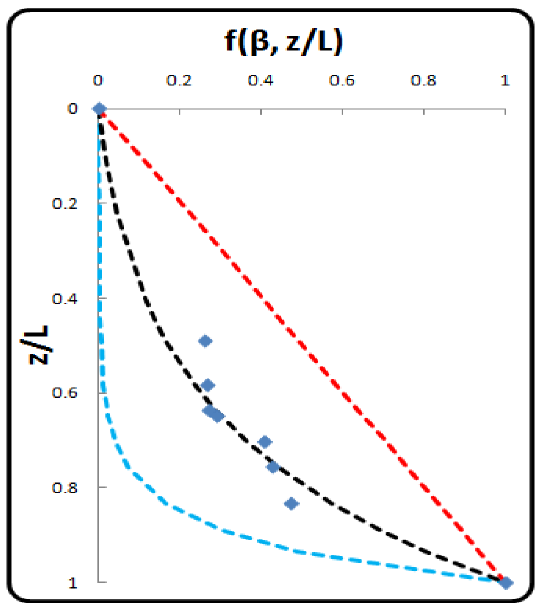

Figure (4) Relation between dimensionless values of BHT and depth, for oil wells in the depth range of 2204 to 3747 meters in the Acre basin.

Solimões Basin: BHT data are available for 16 sites in this basin. The geothermal gradients vary between 19.6 to 34.4°C/Km, the mean value being 31.04 ± 2.07°C/Km. The relation between dimensionless values of BHT and depth is illustrated in Figure (5), for wells in this basin, in the depth range of 1011 to 1992 meters. As in the previous case for the Acre basin, the square symbols in this figure indicate data and the dashed curve in black color represents the best fit model curve for down flow of groundwater with velocity of 3.8×10^{-9} m/s. The color curves are the same as in Figure (3), included here only for reference purposes.

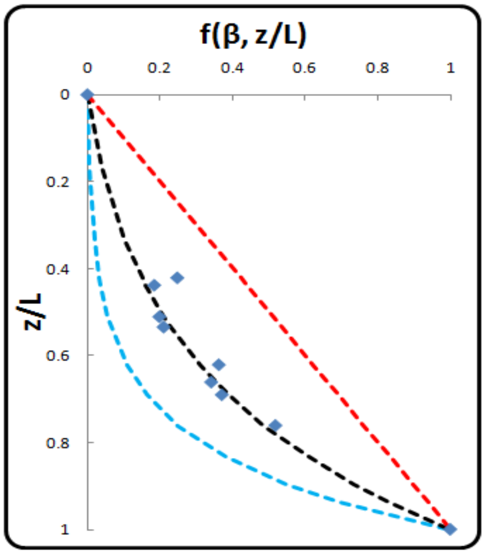

Figure (5) Relation between dimensionless values of BHT and depth, for oil wells in the depth range of 1011 to 1826 meters in the Solimões basin.

Figure (6) illustrates the relation between dimensionless values of BHT and depth in Solimões basin, for wells in the depth range of 2087 to 3066 meters. The best fit model curve in this case indicates a velocity of 2.6×10^{-9} m/s. This is significantly lower than the value encountered for the upper layer (see Figure 5). But the overall trend is similar to that encountered for the Acre basin.

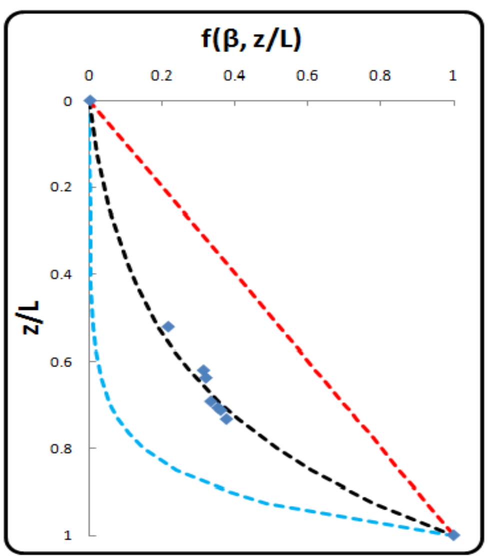

Figure (6) Relation between dimensionless values of BHT and depth, for oil wells in the depth range of 2087 to 3066 meters in the Solimões basin.

Amazonas Basin: BHT data are available for 119 sites in this basin. The geothermal gradients vary from 17.5 to 35.4°C/Km, the mean value being 25.68 ± 1.24°C/Km. Figure (7) illustrates the relation between dimensionless values of BHT and depth, for a selected set of wells, in the depth range of 815 to 1855 meters. The best fit model curve in this case indicates a velocity of 4.2×10^{-9} m/s. The color curves are the same as in Figure (3), and included here only for reference purposes.

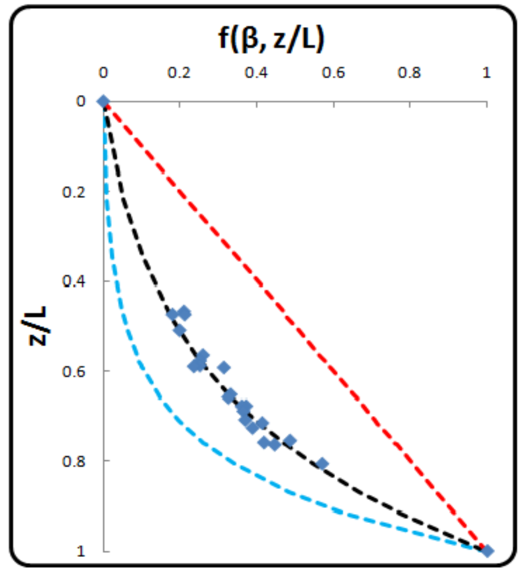

Figure (7) Relation between dimensionless values of BHT and depth, for oil wells in the depth range of 815 to 1855 meters in the Amazonas basin.

Figure (8) illustrates the relation between dimensionless values of BHT and depth in the Amazonas basin, for wells in the depth range of 1867 to 3871 meters. The best fit model curve in this case indicates a velocity of 2.8×10^{-9} m/s. This is lower than the value encountered for the upper layer (see Figure 7), but compatible with the value encountered for the adjacent Solimões basin.

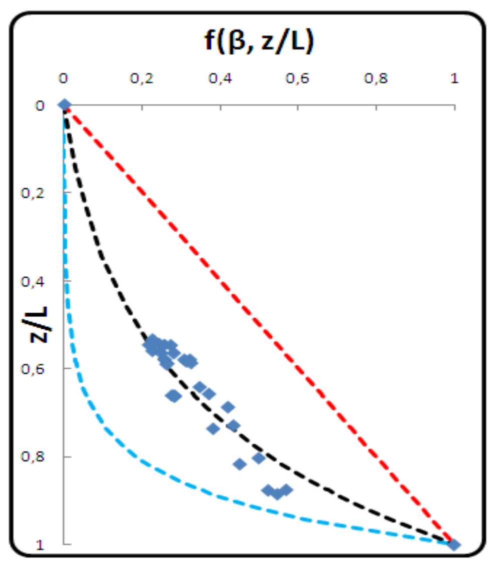

Figure (8) Relation between dimensionless values of BHT and depth, for oil wells in the depth range of 815 to 1855 meters in the Amazonas basin.

Marajó Basin: BHT data are available for 15 sites in this basin. The geothermal gradients vary from 16.6 to 34.23°C/Km, the mean value being 23.24 ± 1.77°C/Km. The curve fit for dimensionless values of BHT and depth in this basin indicates down flow of ground water with velocity of 3.1 x10^{-9} m/s, for the depth range of 430 to 1800 meters. For depths in the range of 1910 to 3762 m (see Figure 9) the velocity is found to be 1.8 x 10^{-9} m/s, which is in reasonable agreement with the value found for the Amazonas basin.

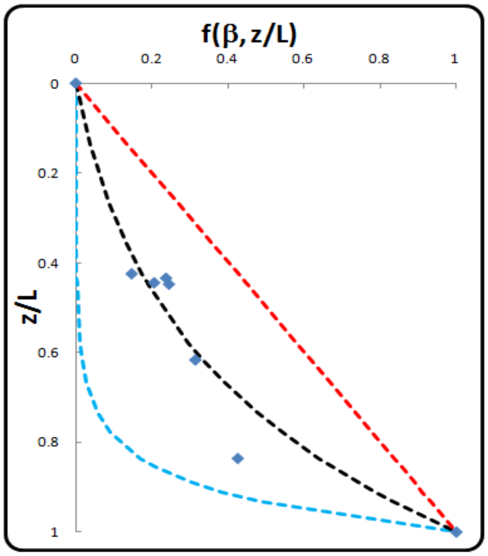

Figure (9) Relation between dimensionless values of BHT and depth, for oil wells in the depth range of 1910 to 3672 meters in the Marajó basin.

Barreirinhas Basin: BHT data are available for 18 sites in this basin. The geothermal gradients vary between 17.3 to 29.4°C/Km, the mean value being 28.23 ± 3.07°C/Km.

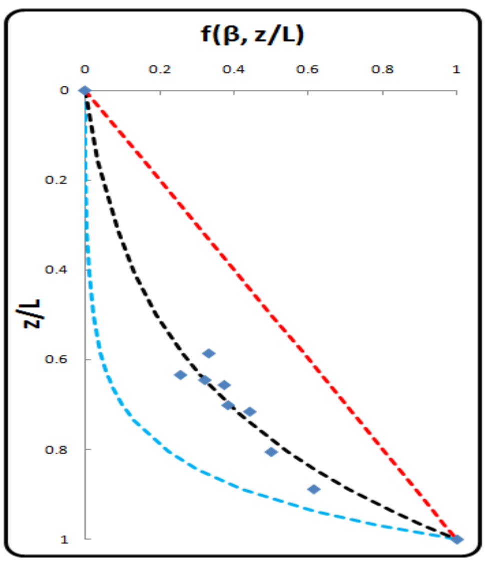

Figure (10) Relation between dimensionless values of BHT and depth, for oil wells in the depth range of 1874 to 2842 meters in the Barreirinhas basin.

The best fit curve for the relation between dimensionless values of BHT and depth in this basin indicates down flow of ground water with velocity of 3.0 x10^{-9} m/s, for the depth range of 1064 to 1723 meters. For the deeper depths in the range of 1874 to 2842 m the velocity is found to be 4.0 x 10^{-9} m/s (see Figure 10). This is slightly higher than the value for upper layer and constitutes an atypical situation.

Conclusions

Analysis of the relations between dimensionless values of BHT and depth in oil wells has allowed estimates of the vertical recharge velocities for groundwater flows in five distinct sedimentary basins of the Amazon region. The results obtained are summarized in Table (1) for two different depth intervals. At shallow depths of less than 2000m the velocities are systematically high compared to those for deeper depth levels. Relatively high velocities of 3.5x10^{-9} m/s were observed in the Amazonas and Barreirinhas basins. The lowest value of 2.4x10^{-9} m/s was found for the Marajó basin. Intermediate values of velocities were found for Acre and Solimões basins.

The systematic trends of down flows observed in these basins are possible only if large scale lateral flows occur in deeper layers of the Amazon region. Since the hydraulic gradient in these basins is in the general direction of west to east, the observed vertical recharge velocities are indicative of an extensive subsurface lateral flow system in the west to east direction in the Amazon region. The lateral flow rates may be estimated as the product of recharge area and vertical velocities of these basins. The values obtained are given in the last column of Table (1).

The overall subsurface lateral discharge rate estimated for the Amazon region is 3900 m^3/s. For comparison purposes we note that this value is much higher than the surface discharge (≈ 2850 m^3/s) of the São Francisco river system in the eastern parts of Brazil. We conclude that the impacts of such lateral flow patterns must be included in assessment of overall hydrological systems for the Amazon region.

Acknowledgments

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Table (2) Vertical recharge velocities and flow rates for the five different basins of the Amazon region.

Basin / Region	**Depth Range (m)**	**Velocity (m/s)**	**β**	**Mean Velocity (m/s)**	**Area (m^2)**	**Flow Rate (m^3/s)**
Acre	960-1992	3.70E-09	2.55	3.02E-09	1,50E+11	452.25
	2204-3747	2.33E-09	2.15			
Solimões	1011-1826	3.80E-09	2.74	3.20E-09	4,40E+11	1408.00
	2087-3066	2.60E-09	3.12			
Amazonas	815-1855	4.20E-09	2.90	3.50E-09	5,00E+11	1750.00
	1867-3871	2.80E-09	2.94			
Marajó	430-1800	3.10E-09	2.05	2.45E-09	5,30E+10	129.85
	1910-3762	1.80E-09	2.43			
Barreirinhas	1064-1723	3.00E-09	2.88	3.50E-09	4,60E+10	161.00
	1874-2842	4.00E-09	2.64			
Total						3901.10