Subsurface Ramifications of the Paraiba River System: Similarities with the Deep Groundwater Flow Systems of the Amazon Region

*Elizabeth T. Pimentel and Valiya M. Hamza, Observatório Nacional, Rio de Janeiro, Brazil.

Abstract

The nature of groundwater flow systems in the Taubate basin and in the continental part of the Campos basin has been determined on the basis of analysis of geothermal data. The results obtained point to near vertical flow systems in the Taubate basin. The flow system in the Campos basin is dominantly lateral. The general conclusion compatible with such results is that large scale groundwater flow systems, similar to those found in the Amazon region, operate in sedimentary basins along the course of the Paraiba River.

Introduction

The Paraiba river region covers an area of about 57.000 square kilometres. It rises in the highland areas near the southeastern parts of the state of São Paulo and covers a distance of about 1.120 km before draining into the Atlantic Ocean. The main river and its tributaries form one of the largest drainage systems in Southeastern region Brazil.

The characteristics of the Paraiba fluvial discharge system have been the object of a large number of investigations over the last several decades (Almeida, 1976; Fernandes, 1993; Teissedre and Maraino, 1976; Capucci, 1988; Caetano, 2000). The main focus of investigations has been the evolution and characteristics of fluvial discharge systems at the surface. Relatively few studies have been carried out for examining subsurface flow systems and characteristics of recharge and discharge of groundwater in this region. Also, much of the studies in groundwater hydrology have been carried out as part of evaluations of flow systems at shallow depths on local scales. Practically no efforts have been made for examining regional scale flow systems in deep strata. In addition, very little information is available on the interactions between the river and the deep seated flow systems.

The absence of studies on regional scale flows has been a consequence of the difficulties in acquiring relevant experimental data, necessary for quantification of deep flows and in regional mapping of recharge and discharge zones of sedimentary basins. Subsurface thermal regime is however quite sensitive to heat transfer by advective fluid flows and there exists simple methods of analysis that can provide information on the nature of groundwater flows. In the present work we examine characteristics of temperature data acquired in water wells of the Taubaté and Campos basins and its use for determining subsurface flows along the course of the Paraiba River.

The study area is indicated in Figure (1), derived from the map of the Cenozoic rift zones of southeast Brazil identified in the work of Zalan and Oliveira (2005). The main tectonic units along the course of the Paraiba do Sul River are the Taubaté basin in the western part, rift zones of the Basement Complex of Southeast Brazil in the middle part and Campos basin in the eastern part.

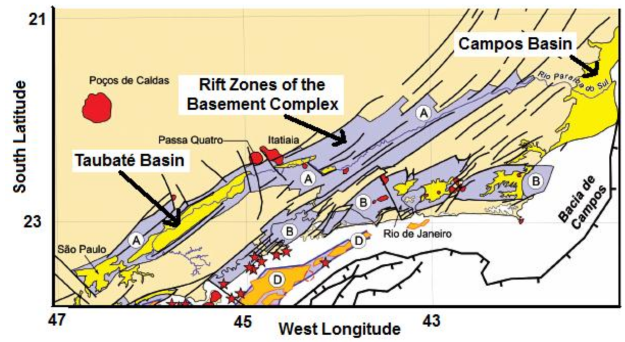

Figure (1) Map indicating the geologic context along the course of Paraiba do Sul River, derived from the map of the Cenozoic rift zones of southeast Brazil identified in the work of Zalan and Oliveira (2005).

Methodology

The 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 (Stallman, 1963). Recently, Pimentel and Hamza (2012) presented a solution relating temperature with depth for flow in layered permeable medium. We do not reproduce the mathematical details of their solution here but note that a plot of dimensionless values of temperature (θ) versus depth (z/L) may be used in outlining subsurface fluid flow. This procedure allows identification of the direction of subsurface flow and the flow velocity. Persistent trends of up flow or down flow may then be employed in outlining regions of recharge or discharge of groundwater.

Recharge Flow: Results of numerical simulations indicate that areas of down flow are characterized by values of dimensionless temperatures lower than the model results for the case in which flow is absent. As example of the case of down flow of groundwater we present in Figure (2) the results of model fits to temperature log data for well P-22 in the municipality of Lorena, located at the eastern sector of the Taubaté basin. In this figure the square symbols indicate observational data while the dashed curves in red color represent the best fit model for a down flow velocity of 9.5×10^{-8}m/s. The dashed line in black color indicates distribution of model temperatures for the case in which the flow velocity is zero. It is clear that Lorena is located in a zone of groundwater recharge.

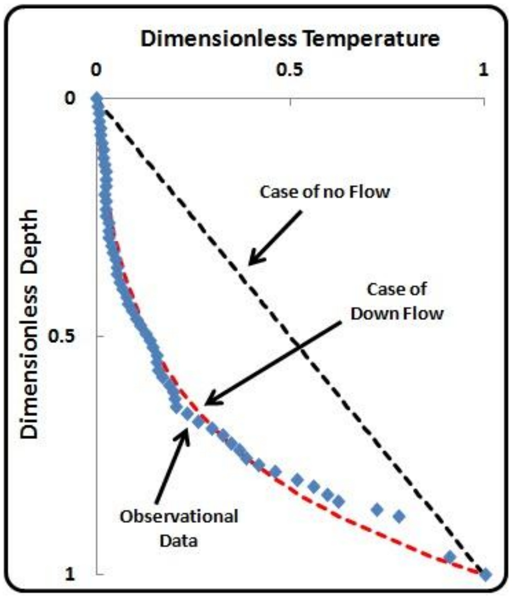

Figure (2) Model fit to geothermal data for well located in Lorena (eastern part of Taubaté basin), illustrating the case of down flow of groundwater.

Similar recharge flow patterns are also seen in model fits to bottom-hole temperature data from 22 wells in the municipalities of Jacareí, São José dos Campos and Caçapava. This case is illustrated in Figure (3), where the overall mean value for down flow velocity is 6.3×10^{-8}m/s. The conclusion is that recharge flows are dominant in both the eastern and western parts of the Taubaté basin.

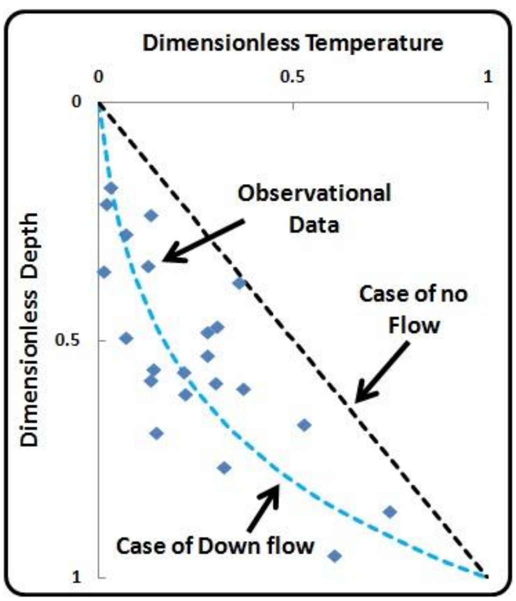

Figure (3) Model fit to bottom-hole temperature data for 22 wells located in the western parts of the Taubaté basin, illustrating the case of down flow of groundwater.

Discharge Flow: Results of numerical simulations indicate that areas of up flow are characterized by values of dimensionless temperatures higher than the model results for the case in which flow is absent. An example of the case of up flow of groundwater is presented in Figure (4) for bottom-hole temperature data for nine wells in the central parts of the basin, in the municipalities of Taubaté, Potim and Pindamonhagaba. In this figure the square symbols indicate observational data while the curve in blue color represent the best fit model for up flow velocity of -1.5×10^{-8}m/s. The line in black color indicates the case in which the flow velocity is zero.

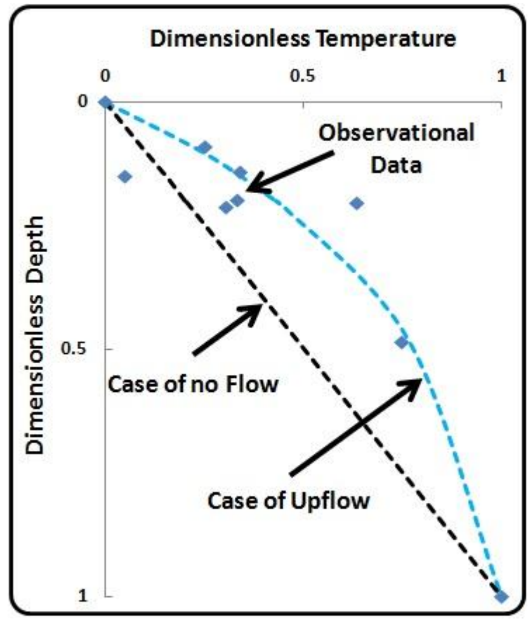

Figure (4) Model fit to bottom-hole temperature data for nine wells located in the central parts of the Taubaté basin, illustrating the case of up flow of groundwater.

Absence of detailed temperature logs of wells in this part of the basin prevents us from providing better examples of the up flow patterns. Temperature logs of wells in the municipality of Guaratinguetá presents a complex pattern with intercalating intervals of up and down flows. As a result attempts to interpret the logs on the basis of the models of the present work have not lead to useful results. Nevertheless, the obvious conclusion is that the central part of the Taubate basin is a zone of groundwater discharge.

Lateral Flow: Characteristics of lateral flow systems are generally determined on the basis of hydrological data of wells and subsurface structural features identified in geological studies. As an example we present in Figure (5) the area segment of lateral flow identified in studies of Capucci et al (2001) and Capucci (2003), in the region of São João de Barra in the Campos basin. According to estimates of Capucci (2003) the amount of water in the subsurface lateral flow system in the coastal area of Campos basin is higher than the fluvial discharge of the Paraiba do Sul River.

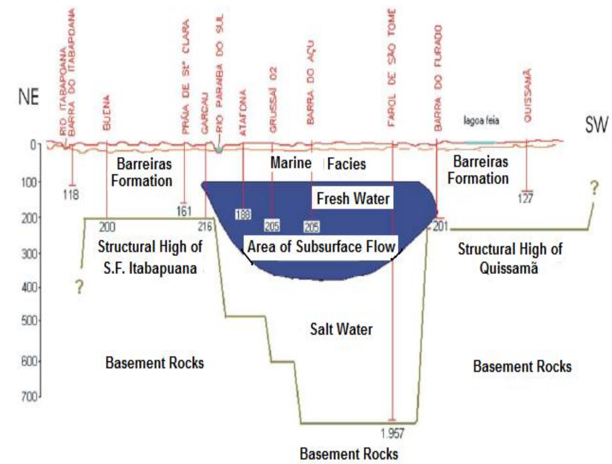

Figure (5) Lateral flow system inferred from hydro-geologic studies of the coastal area of the Campos Basin (Adapted from Capucci, 2003).

Thermal signatures of lateral fluid movements cannot easily be identified in geothermal data acquired in wells. However, in cases of regions with significant lateral fluid movements up flow of water takes place through the wells intersecting deep aquifers. An estimate of the magnitude of water flow necessary for maintaining the unusual distributions of temperatures in wells can be obtained on the basis of relevant heat transfer relations for fluid flows in cylindrical geometry. We make use of the solution, proposed initially by Ramey (1962), where the temperatures variation (*T*) with depth (*z*) in flowing wells is given by:

$$T(z,t) = T_0 + \Gamma z - \Gamma A + \left[T_f(t) + \Gamma A - T_0\right] e^{-z/A} \quad (1)$$

where T_0 is the surface temperature, Γ the geothermal gradient and $T_f(t)$ the temperature of fluid entering the well. In the above equation *A* is a parameter related to advective heat transport for in-hole flows, given by:

$$A \approx r_1^2 v \, \rho c \, f(t) / 2\lambda \quad (2)$$

in which r_1 is the radius of the well, *v* the velocity of fluid flow, *ρ* the density of fluid, *c* its specific heat, *f(t)* is a time function related to the period elapsed since the fluid flow was initiated and *λ* the thermal conductivity of wall rocks. Comparisons of the measured temperatures with model values calculated with equations (1) and (2) may be employed in setting reasonable limits for velocities of in-hole fluid flows.

As an illustrative example we present in Figure (6) results of temperature log data for the depth range of 50 to 188 meters in the well Açu along with model curves calculated on the basis of equations (1) and (2) for different flow velocities. It is fairly simple to note that flow velocities in excess of 10m/h are needed for maintaining low temperature gradients in the depth interval of 50 to 188 meters. For reasonable values of the parameters in equations (1) and (2) the corresponding minimum value for the in-hole flow rate is about 10 m^3/h.

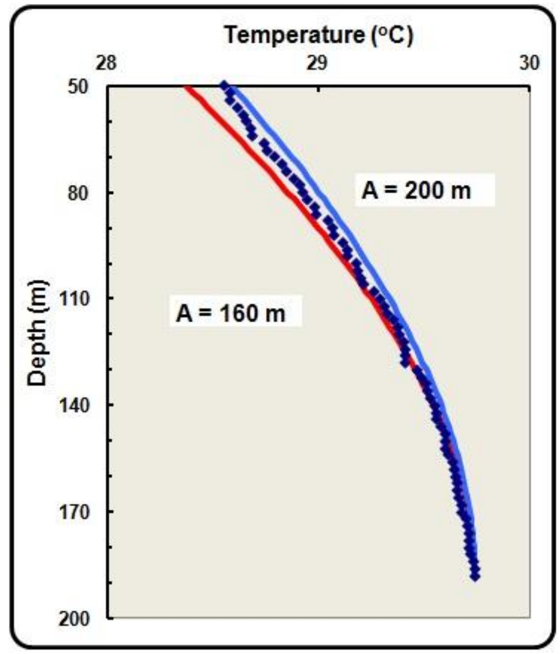

Figure (6) Example of model fit for geothermal data in well Açu for the case of in-hole flow.

Data Sets Employed in the Present Work

The data sets employed in the present work are based primarily on results of temperature measurements in wells drilled for groundwater in the basins of Taubate and Campos. In Taubate basin much of the geothermal data for this basin was acquired during the decade of 1980 as part of a geothermal exploration work of Hamza et al (1981). Detailed discussions of these data sets can be found in the works of Gomes and Hamza (2004), Hamza et al (2005) and Rodrigues and Hamza (2007). No suitable geothermal data are available for the areas where Paraiba River flows along graben systems in the metamorphic basement rocks at the border between the states of Rio de Janeiro and Minas Gerais. More recently results of bottom-hole temperature measurements have been made in a number of wells (Nascimento Filho, 2012). In the Campos basin geothermal data was acquired during the decade of 2000 as part of a geothermal exploration work of the state of Rio de Janeiro (Gomes and Hamza, 2005). More recently temperature measurements have also been made as part of a geothermal climate change study by Hamza et al (2007).

Model Results

In discussing model results it is important to point out that not all data sets are suitable for determining groundwater flow patterns. Temperatures at shallow depths are in general affected by changes in soil types, vegetation cover and climate changes of the recent past. Thus care should be taken in analysis of shallow borehole log data to avoid misinterpretations based on thermal models. Corrections are also necessary in dealing with bottom-hole temperature (BHT) data, in cases where measurements are made soon after the completion of drilling. Thus, in the case of BHT data reported by Nascimento Filho (2012) we have applied the AAPG correction procedure (AAPG, 1976). The results obtained in analysis of temperature logs of selected wells are summarized in Tables (1) and (2) for the Taubaté and Campos basins respectively.

Table (1) Summary of results of model fits to selected sets of data for Taubaté basin.

Locality	Depth Interval (m)	Groundwater Flow	
		Velocity (10^{-8}m/s)	Type
Caçapava	216	4.2	Recharge
Caçapava	200	4.3	
Guaratinguetá	197	13.0	
Guaratinguetá	207	4.0	
Jacareí	268	3.0	
Jacareí	169	6.5	
Lorena	214	9.5	
Lorena	256	5.5	
S.J. Campos	232	8.5	
Pinda	250	-3.1	Discharge
Pinda	732	-1.3	
Potim	285	-5.4	
Potim	290	-2.7	
Potim	282	-3.2	
Taubaté	221	-3.5	
Taubaté	254	-1.7	
Taubaté	442	-2.6	

Table (2) Summary of the results of model fits to selected sets of data for Campos basin.

Locality	Depth Interval (m)	Groundwater Flow	
		Velocity (10^{-8}m/s)	Type
Boa Vista	100	-3.5	Lateral with in-hole flow
Baixo Grande	108	-9.0	
Açu	232	-4.0	
Grussaí	214	-2.1	

Discussion and Conclusions

Analysis of geothermal data acquired in water wells of the southeastern parts of Brazil point to the existence of subsurface ramifications of the Paraiba do Sul River. Three distinct groundwater flow systems have been recognized. Recharge type flows are dominant in the western (municipalities of Jacarei, São José dos Campos and Caçapava) and eastern (municipality of Lorena) parts of the Taubaté basin, while discharge type flow is present in its central parts (municipalities of Taubaté, Potim and Pindamonhagaba). The observed pattern of recharge and discharge systems is in agreement with the results of hydro-chemical studies of ground waters carried out by Vidal and Chiang (2002). It is also compatible with the patterns of occurrence of thermal springs in the central parts (Taubaté and Potim) and absence of the same in the eastern and western parts.

Analysis of hydrological data of ground water wells in the coastal area of Campos basin reported by Capucci (2003) and Martins et al (2006) along with the analysis of geothermal data provided in the present work indicate that the subsurface flow system in this region is dominantly lateral. According to Capucci (2003) the quantity groundwater being discharged into the Atlantic Ocean along the coastal area in the municipality of São João da Barra is several times larger than the fluvial discharge rate of Paraiba do Sul River. The area affected by lateral flow is indicated in the map of Figure (7). It is bounded between the fault systems associated with the structural highs of S.F. de Itabapuana on the east and Quissamã on the west.

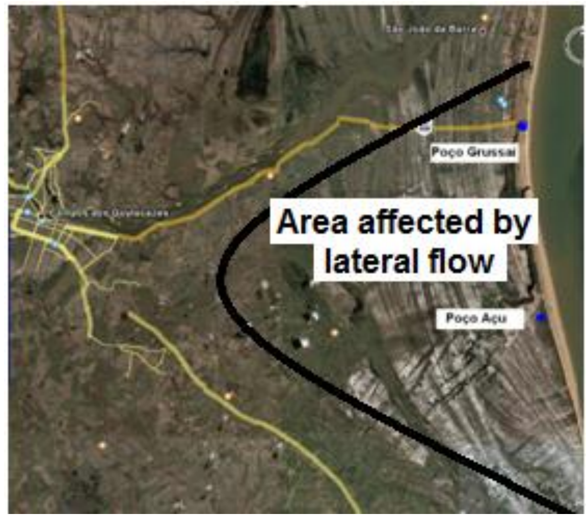

Figure (7) Satellite image of the coastal area of the Campos basin. The black curve is the approximate outline of the region of lateral subsurface flow.

This flow system has considerable similarities with the proposed subsurface flow system of the Amazon region (Pimentel and Hamza, 2012). We suggest that the subsurface flow system in the coastal area of the Campos basin be designated as the "Goytacaz *River*", in honour of tribal group that inhabited the estuary of the Paraiba do Sul River, during pre-colonial times.

Acknowledgements

The first author of this work is recipient of a scholarship granted by the Fundação de Amparo à Pesquisa do Estado do Amazonas – FAPEAM.
Financial support was provided by Fundação Amparo á Pesquisa do Estado do Rio de Janeiro - FAPERJ, for the project "Caracterização Físico-Química das Emanações provenientes das Falhas Geológicas na área Costeira do Estado do Rio de Janeiro" (Processo No. E-26/ 111.342/2010).

References

Almeida F.F.M. de, 1976. The system of continental rifts bordering the Santos Basin, Brazil. An. Acad. Bras. Ciênc.,48 (supplement): 15-26.

American Association of Petroleum Geologists, 1976. Basic data from AAPG Geothermal Survey of North America. University of Oklahoma, Norman.

Caetano, L.C., 2000. Água subterrânea para o Município de Campos do Goytacazes: uma opção para o abastecimento. M.Sc. Thesis, Universidade Estadual de Campinas, Instituto de Geociências. Campinas, SP.

Capucci, E.B., 1988. Mapa de Potencialidades Médias de Água Subterrânea no Estado do Rio de Janeiro. DIN/INX, CEDAE.

Capucci, E.B., Martins, A.M. and Mansur, K.L., 2001. Poços Tubulares e Outras Captações de Águas Subterrâneas – Orientação aos Usuários. Projeto PLANÁGUA SEMADS/GTZ de Cooperação Técnica Brasil-Alemanha, SEMADS, SEINPE, DRM-RJ.

Capucci, E.B., 2003. Água Subterrânea na Baixada Campista. In: I Simpósio de Hidrogeologia do Sudeste. Petrópolis, RJ. – ABAS.

Fernandes, F.L., 1993. Arcabouço estrutural e evolução da Bacia de Taubaté - SP. M.Sc. Thesis, Escola de Minas, Universidade Federal de Ouro Preto, Ouro Preto, 147p.

Gomes, A.J.L., and Hamza, V. M., 2004. Mapeamento de Gradientes Geotérmicos no Estado de São Paulo. In: Primeiro Simpósio Regional de Geofísica, São Paulo, v. 1: 1-4.

Gomes, A. J. L. and Hamza, V. M., 2005. Geothermal gradients and heat flow in the state of Rio de Janeiro. Rev. Bras. de Geof., 23 (4): 325-47.

Hamza, V.M. and Eston, S.M., 1981. Assessment of Geothermal resources of Brazil - 1981. Zbl. Geol. Palaontol, v. I: 128-155, Stuttgart.

Hamza, V.M., Gomes, A.J.L. and Ferreira L.E.T., 2005. Status report on geothermal energy developments in Brazil. In: Proceedings of the World Geothermal Congress, Antalya, Turkey, 24-29.

Hamza, V. M., Cavalcanti, A. S. B. and Benyosef, L. C. C., 2007. Surface thermal perturbation of the recent past at low latitudes – inferences based on borehole temperature data from Eastern Brazil, Climate of the Past Discussions, 3: 501-548.

Martins, A. M., Capucci, E., Caetano, L. C., Cardoso, G., Barreto, A. B. C., Monsores, A. L. M., Leal, A. S. and Viana, P., 2008. Hidrogeologia do Estado do Rio de Janeiro. Sintese do Estado Atual do Conhecimento. In: XIV Congresso Brasileiro de Águas Subterrâneas-ABAS, Natal-RN.

Nascimento Filho, M., 2012. Avaliação do Potencial Geotermal da Bacia de Taubaté. Unpublished M.Sc. Thesis, Univ. Estadual de Campinas, Campinas, SP.

Pimentel, E. T. and Hamza, V. M., 2012. Indications of regional scale groundwater flows in the Amazon Basins: Inferences from results of geothermal studies. Journal of South American Earth Sciences, v. 37: 214-227.

Ramey, H.J., 1962. Wellbore heat transmission, J. Petrol. Technol., 14: 427-435.

Rodrigues, I. F. and Hamza, V. M., 2007. Estrutura termal da crosta sob a bacia de Taubaté. In: International Congress of the Brazilian Geophysical Society, Rio de Janeiro, v.1: X01-X06.

Stallman, R.W., 1963. Computation of groundwater velocity from temperature data. U.S. Geol. Surv., Water Supply Pap., 1544-H: 36-46.

Teissedre, J.M. and Mariano, I.B., 1978. Possibilidades hidrológicas da Bacia de Taubaté. In: Proceedings SBG. 6: 3003-3011.

Vidal, A.C. and Chiang, C.H., 2002. Caracterização hidroquímica dos aqüíferos da bacia de Taubaté. Revista Bras. Geociências, 32: 267-276.

Zalan, P.V. and Oliveira, J.A.B., 2005. Origem e evolução estrutural do Sistema de Riftes Cenozóicos do Sudeste do Brasil. B. Geoci. Petrobras, Rio de Janeiro, v. 13 (2): 269-300.