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FINITE DIFFERENCE MODEL FOR EVALUATING THE RECHARGE OF THE GUARANÍ AQUIFER SYSTEM ON THE URUGUAYAN-BRAZILIAN BORDER

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Abstract. Part of the precipitation that falls over a region infiltrates through soil layers and eventually migrates deeper reaching the groundwater reservoir known as aquifer. The water that makes its way to the aquifer becomes recharge. The magnitude of recharge constitutes an upper bound to the amount of water that can be extracted from a groundwater reservoir without causing a major impact on it. The recharge can not be measured directly therefore it has to be determined by an indirect method, and as such, is one of the most difficult hydrological variables to calculate.

The Guaraní Aquifer System (GAS) is an international transboundary groundwater reservoir. Its area is about 1200000 km^2 distributed in Brazil, Argentina, Paraguay and Uruguay. This aquifer is contained within the pores and cracks of sandstones (rocks of mostly sandy nature). The Uruguayan-Brazilian border nearby the cities of Rivera (Uruguay) and Sant´Ana do Livramento (Brazil) is of special interest as this area receives a significant amount of recharge, both direct from precipitation and indirect from fractured basalts overlying the GAS, that compensates water abstractions. This study focuses in this particular area of the GAS, covering about 650 km^2 surrounding both cities.

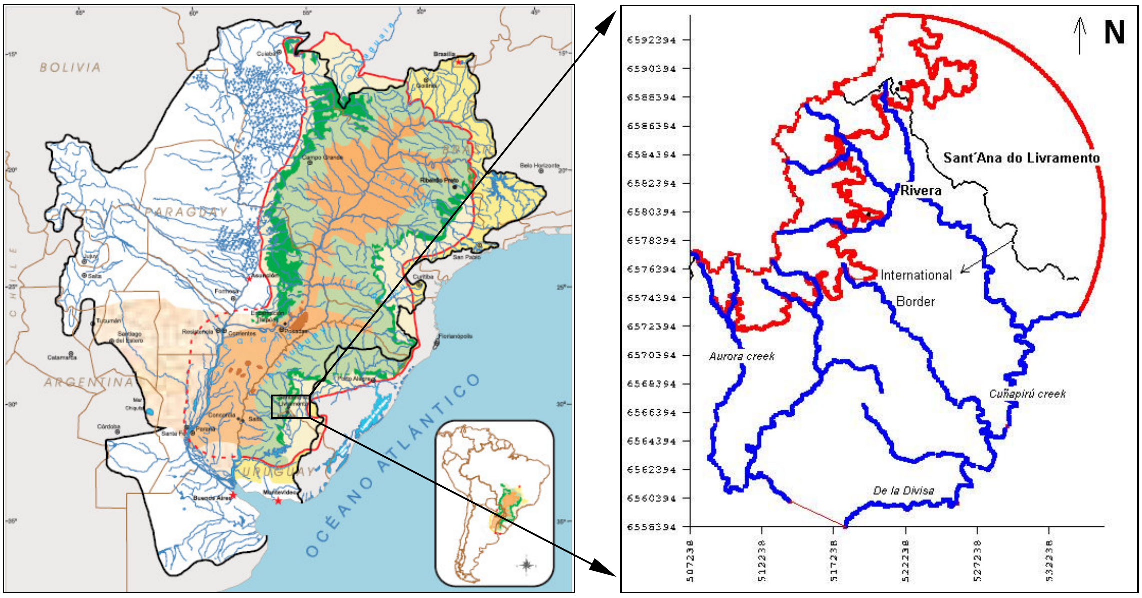
The well known numerical code MODFLOW that solves the parabolic groundwater flow equation by the finite difference method was used. A steady state condition was simulated representing the current hydraulic behavior of the groundwater system. The finite different grid consists of 135 rows and 156 columns, 250 m x 250 m in both, x and y directions. Vertically, the model contains three layers coincident with the aquifer units defined in the conceptual model, which are basalts, shallow sandstone aquifer and deep sandstone aquifer. The calibration was performed by the trial-and-error method, matching simulated hydraulic heads with the observed data. Boundary conditions, recharge rates, stream/aquifer interphase conductances and hydraulic conductivities were adjusted during the calibration process.

The conceptual model was correctly validated. Model results approximately match existing data, although they highlighted data scarcity and the dubious reliability on many available data. In the deep aquifer the model reproduces adequately the cone of depression detected near the two cities, surveyed in the field, caused by intensive groundwater pumping. Regarding flow directions, model results would indicate that most of the streams in the area drain the groundwater reservoir, in agreement with field evidence. Downward flows were simulated between model layers. In terms of the simulated recharge rates for the current calibration of the model, the rate over basalts resulted in a meager 1.3 mm/year, and the rate over the outcropping areas of sandstones resulted in 140.2 mm/year, equivalent to 0.08 % and 8.55 %, respectively, of the mean annual precipitation of 1639 mm estimated at Rivera.

1 INTRODUCTION

Part of the precipitation that falls over a region infiltrates through soil layers and eventually migrates deeper reaching the groundwater reservoir known as aquifer. The amount of water that makes its way to the aquifer is called recharge. The magnitude of the recharge is quite important because it constitutes an upper bound to the amount of water that can be extracted from a groundwater reservoir without causing a major impact on the reservoir. The recharge can not be measured directly therefore it has to be determined by an indirect method, and as such, is one of the most difficult hydrological variables to calculate.

The Guaraní Aquifer System (GAS) is a transboundary, international groundwater reservoir that in most of its extent overlaps with the Paraná River Basin. Its area is about 1200000 km^2 distributed as follows: 840000 km^2 in Brazil, 255000 km^2 in Argentina, 71700 km^2 in Paraguay and 58500 km^2 in Uruguay (Figure 1a). More than 15000000 people live in this area, where the aquifer is being increasingly exploited and constitutes the main source of freshwater for urban supply as well as for industrial and agricultural uses.



(a) (b)

Figure 1 – (a) Base map of the GAS and location of study area. (b) Model domain (source of base map http:// www.sg-guarani.org).

This extensive aquifer is contained within the pores and cracks of sandstones (rocks of mostly sandy nature). Water quality and depth to groundwater vary regionally. In the Northern part of Uruguay the aquifer outcrops to the surface, deepening in the East-West direction as it enters Argentinean territory. The Uruguayan-Brazilian border nearby the cities of Rivera (Uruguay) and Sant´Ana do Livramento (Brazil) is of special interest as this area receives a significant amount of recharge that compensates water abstractions for multiple uses. Direct recharge from precipitation and indirect recharge from fractured basalts overlying the GAS in vast areas, replenish the sandstone aquifer. This study focuses in this particular area of the GAS, and especially on how much recharge is potentially reaching the aquifer.

Groundwater flow modeling is one of the available methodologies to estimate recharge. The well known numerical code MODFLOW that solves the parabolic groundwater flow equation by the finite difference method was used in this study (Rodríguez et al. 2006). There were two main modeling objectives: 1) to validate the conceptual model of the flow system behavior; 2) to estimate an approximate value of the recharge rate in the study area.

Numerical results approximately matched existing data, although they highlighted the effect of scarce information and the dubious reliability on many available data.

Section 2 presents the mathematical model for groundwater flow while Section 3 describes the main characteristics and some numerical features of the computational code used to solve the problem. The steps followed for the model implementation are summarized in Section 4. Sections 5 and 6 are devoted to the discussion of model results and conclusions, respectively.

2 MATHEMATICAL MODEL

Groundwater flow of constant density through heterogeneous and anisotropic porous media is described by the following parabolic equation

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t} \tag{1}$$

where K_{xx} , K_{yy} , K_{zz} are hydraulic conductivity values along the x, y, z coordinate axes, assumed parallel to the major axes of hydraulic conductivity (LT $^{-1}$); h is the potentiometric head or hydraulic head of the aquifer (L); W is a volumetric flux per unit volume of aquifer representing sinks/sources of water ($W<0$ means water out of the groundwater system, $W>0$ means flow into the groundwater system) (L^{-1}); S_s is the specific storage of the porous material (L^{-1}); and t is the time (T). In Equation (1) the terms in parenthesis are nothing but the three components of the Darcy flux q_x, q_y, q_z , when the Cartesian axes are parallel to the major axes of hydraulic conductivity. Darcy's law is expressed as $\mathbf{q}=-\mathbf{K}\cdot\nabla h$ (Bear 1972), where $\mathbf{q}$ has units (LT $^{-1}$) and the gradient operador ∇ has units (L^{-1}).

The specific storage S_s and the hydraulic conductivity are space dependent physical parameters, while the source/sink term W may be a function of space and time.

When combined with appropriate initial and boundary conditions, Equation (1) describes transient, three-dimensional flow. Various analytical solutions to Equation (1) exist. However, numerical methods must be employed to obtain approximate solutions for engineering applications of practical interest.

3 ABOUT MODFLOW

This section describes some of the numerical and practical features of the computational code used in this work.

3.1 General characteristics

MODFLOW (McDonald and Harbaugh 1988; Harbaugh et al. 2000) is a three-dimensional finite-difference computational code with a modular structure that allows it to be easily modified to adapt the code to a particular application. Ground-water flow is simulated using a block-centered finite-difference approach. Layers can be simulated as confined (linear case) or unconfined (non-linear case) or as a combination of both, and may have spatially varying thickness. The modular structure consists of a MAIN Program and a series of highly independent subroutines. The subroutines are grouped into "packages." Each package deals with a specific feature of the groundwater system that is to be simulated, such as flow from rivers or flow into drains, or with a specific method of solving the set of simultaneous equations resulting from the finite-difference method discretization. The division of the program into packages permits the user to examine specific hydrologic features of the model independently. MODFLOW is currently the most used numerical model for ground-water flow problems.

3.2 Spatial and time discretization

The flow region is subdivided into blocks or cells in which the medium properties are assumed to be uniform. The cells location is described in terms of rows, columns and aquifer layers in a 3D setting. An *i, j, k* indexing system is used, where *i* is the row index, *j* is the column index and *k* is the layer or vertical index. Layers are numbered from top to bottom. Rows are considered parallel to the *x* coordinate axis so increments in the row index *i* correspond to increases in the *y* axis; and columns are considered parallel to the *y* coordinate axis, so that increments in the column index *j* correspond to increases in the *x* axis. Figure 2 illustrates a cell and its six adjacent aquifer cells.

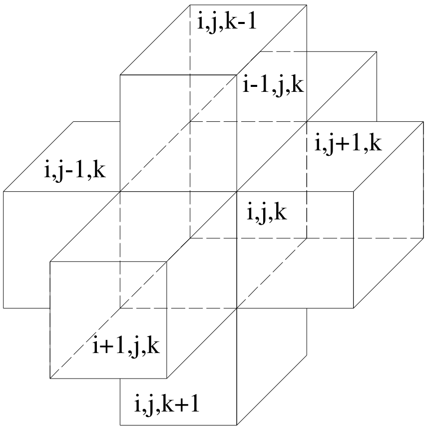


Figure 2: Model cells scheme (after McDonald and Harbaugh, 1988).

The spatial finite difference approximation to Equation (1) can be derived upon the application of the continuity equation in a cell. According to Darcy´s law (Bear 1972), the flow into cell *i,j,k* in the row direction from cell *i,j-1,k* is given by

$$Q_{i,j-1/2,k} = K_{i,j-1/2,k}\,\Delta C_i \Delta V_k \frac{(h_{i,j-1,k} - h_{i,j,k})}{\Delta R_{j-1/2}} \qquad (2)$$

where

$Q_{i,j-1/2,k}$: volumetric discharge through the face between cells *i,j,k* and *i, j-1,k* (L^3T^{-1}),

$K_{i,j-1/2,k}$: hydraulic conductivity along the row between nodes *i,j,k* and *i,j-1,k* (LT^{-1}),

$\Delta C_i \Delta V_k$: area of the cell face normal to the row direction (L^2),

$\Delta R_{j-1/2}$: distance between nodes *i,j,k* and *i, j-1,k* (L).

A similar expression to Equation (2) can be written to approximate the flow into cell *i, j, k* through the remaining five faces. To account for flows into the cell from external sources such as streams, drains, aerial recharge, evapotranspiration or wells, additional terms are required.

If there are N external sources/sinks affecting a single cell, the combined flow into or out of the cells is expressed as

$$QS_{i,j,k} = \sum_{n=1}^{n=N} p_{i,j,k,n}\, h_{i,j,k} + \sum_{n=1}^{n=N} v_{i,j,k,n} \tag{3}$$

where $QS_{i,j,k}$ is the flow into the cell from external sources/sinks (L^3T^{-1}); and $p_{i,j,k,n}$ and $v_{i,j,k,n}$ are constants ($L^2\,T^{-1}$) and ($L^3\,T^{-1}$), respectively, dependent on the sources/sinks characteristics.

The time derivative in Equation (1) is expressed with a backward difference approximation at time t_m as follows (Figure 3)

$$\left[\frac{\Delta h_{i,j,k}}{\Delta t}\right]^m = \frac{h^m_{i,j,k} - h^{m-1}_{i,j,k}}{t_m - t_{m-1}} \tag{4}$$

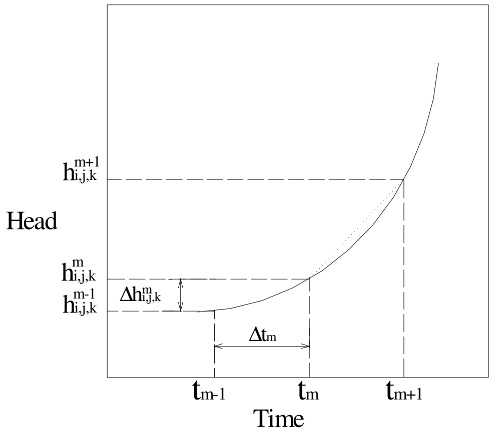


Figure 3 – Time discretization (after McDonald and Harbaugh, 1988).

In summary, the backward-finite-difference equation for cell *i,j,k* is

$$Q^m_{i,j-1/2,k} + Q^m_{i,j+1/2,k} + Q^m_{i-1/2,j,k} + Q^m_{i+1/2,j,k} + Q^m_{i,j,k-1/2} + Q^m_{i,j,k+1/2} + QS^m_{i,j,k} = S_{s\,i,j,k}(\Delta R_j\, \Delta C_i\, \Delta V_k)\frac{h^m_{i,j,k} - h^{m-1}_{i,j,k}}{t_m - t_{m-1}} \tag{5}$$

Equation (5) is nothing but the mass conservation equation. An equation such as (5) is written for every cell in the finite difference grid. A set of linear or non-linear equations may result depending on the type of aquifer considered. The system is solved with one of several solvers provided. Aquifer hydraulic heads, flow-rates and cumulative-volume balances from each type of inflow and outflow are computed for each time step.

3.3 Available solvers

MODFLOW-2000 includes direct, iterative and hybrid solvers : Direct Solution Package (DE4), the Strongly Implicit Procedure Package (SIP), the Slice-Successive Overrelaxation Package (SOR), the Preconditioned Conjugate-Gradient Package 1 (PCG1) and the Preconditioned Conjugate-Gradient Package 2 (PCG2), the Link-AMG Package (LMG), and the Geometric Multigrid Package (GMG) (Harbaugh et al. 2000).

It is well known that those three families of solvers differ in their main characteristics, and their performance is highly dependent of the problem size and the computational resources available for its solution. However, it is not the objective of this contribution to test the performance of every available solver in MODFLOW. The authors have used the PCG2 solver. Given the relatively small size of the problem and the computational resources available, no convergence problems were encountered.

Nonetheless, a brief review of some numerical testing performed by other authors was considered pertinent to overview some numerical aspects of this well known code.

The LMG solver typically is 2 to 25 times faster than the PCG2 solver. It is especially good for models with large grids or with a high degree of heterogeneity and where the initial heads are quite different from the final solution. However, it also typically uses 3 to 8 times as much more memory as the PCG2 solver (Mehl and Hill, 2001; Detwiler et al., 2002). For transient simulations, the initial heads for each time step are typically close to the final heads for the time step. In such models, the Link-AMG solver typically does not perform as well as the PCG2 solver.

Ideally the solvers would all give the same result. However, Osiensky and Williams (1996) explored the relative accuracies of the SOR, SIP and PCG2 solvers. For their test conditions, the SOR package performed miserably. The water budget error was approximately 200%. This illustrates the importance of checking the water budget before assuming that a MODFLOW simulation is correct. SIP did somewhat better; when the acceleration parameter was set to 1.8, the solution was essentially correct. For some other tested values, the errors were very large. High errors in the water budgets were associated with high errors in the computed solution. PCG2 performed well in all tests reported by these authors. This is probably because one of the convergence criteria for PCG2 is related to the water budget. The other solvers don't have a similar criterion. Then, in any model application is advisable to make sure that the water budget error is less that 1% before accepting the results of a MODFLOW simulation.

Hill (1990) reported that the "Modified Incomplete Cholesky" method of PCG2 usually requires the shortest time to find a solution. She also found that PCG1 and SIP are fairly similar in the amount of time they require but PCG1 found solutions for which no solution was found by SIP. The DE4 solver may sometimes be faster for small linear problems but problems will rarely be small enough for it to be as fast as other solvers. Even though it is slow it may also be useful for cases where other solvers can not reach a solution.

4 MODEL IMPLEMENTATION

Groundwater modeling includes a set of basic steps. First a conceptual model is constructed. The conceptual model is built upon field data and consists on the definition of the hydraulic behavior of the aquifer system, number of layers, flow directions, hydrological stresses, etc. Second, a numerical code is developed or selected and implemented according to its requirements. In this work, MODFLOW was run through the Graphical User Interphase GMS (Groundwater Modeling System, 2006). Third, a calibration is performed to validate the conceptual model postulated in the first place. Calibration is the process of varying appropriate model parameters and/or boundary conditions to obtain a good agreement, statistically speaking, between observed and simulated hydraulic heads and eventually, between observed and simulated flows. Once the model has been conveniently calibrated and the conceptual model validated, the model can become a prediction tool.

4.1 Study area

The study area covers approximately 650 km^2 of the GAS surrounding the cities of Rivera (Uruguay) and Sant'ana do Livramento (Brazil) (Figure 1b). In the figure, blue lines indicate modeled streams and the red line in the interior of the computational domain represents the boundary of basalts mapped on the field.

From a regional point of view, the GAS is formed by a collection of unconsolidated and fractured aquifers with geological-structural control. Shallow cracks and fractures are associated to basalt rocks overlying more permeable layers, i.e. the proper sandstone Guaraní aquifer. Deeper fractures are associated with vertical and horizontal movements of geologic units, of regional extent, that control not only the basaltic formation but also the sandstone aquifer at depth. A more detailed description of the geological and hydrogeological characteristics of such a large groundwater reservoir can be found in Rebouças (1976), Almeida (1983), Lavina (1991), Araujo et al. (1995), Kittl (2000) and Vives et al. (2000), among others.

In the study area the sandstones of the GAS outcrop to the surface, therefore it has been defined as a recharge area. Direct recharge originates in precipitation while an unknown quantity of water from fractured basalts is believed to contribute to indirect recharge to the GAS. The mean annual precipitation at the Rivera station is 1639 mm (DNM, 2006).

The landscape is generally characterized by gentle slopes. Maximum elevations reach 400 m above mean sea level. However, the transition between basalts and the adjacent sandstones can be identified easily in the field or in topographic maps by the presence of steep slopes.

4.2 Stratigraphic model/conceptual model

Stratigraphy is basically the study of rock layers and layering. Stratigraphc profiles surveyed at wells provide the key information to reconstruct geologic layers and later the conceptual model. Profiles from around 90 wells as well as geologic maps were used to numerically generate the "solid", i.e. a three dimensional reconstruction of the aquifer system interpolated from geologic formations and their thicknesses identified in each of the considered wells. From these point data cross sections were generated to later interpolate the solid (Figure 4).

Stratigraphic profiles and geologic maps combined with hydrogeoquemical data and water levels measured at 50 wells helped to define the conceptual model, i.e. the groundwater system hydraulic behavior (Oleaga 2002; Silva Busso 1999; Pacheco 2004).

Sandstones of the Tacuarembó Formation, basalts of the Arapey Formation and modern sediments aligned with streams are the predominant geologic units surrounding both cities. The transition between basalts and sandstones is noticeable in the field by the presence of steep slopes. Sandstones may have transmissivities between 25 and 300 m^2/d, while basalts are much less permeable, with hydraulic conductivities between 10^{-3} and 10^{-7} m/s.

From a hydraulic point of view, there exist different contributing water levels, one located within basalts several meters above water levels measured within sandstone. Underlying the basalt a shallow, permeable layer within sandstones has been detected which is hydraulically connected to the streams that cut across the landscape. This layer disappears in the Brazilian territory. Deep wells (depths > 100 m) allowed defining a deep aquifer located in very permeable sectors of the GAS. Its hydraulic parameters and water yield vary greatly from place to place, however this layer concentrates most of the water supply wells. Strong hydraulic differences exist between these two layers detected within the sandstone, as water level differences between shallow and deep layers may reach up to 24 m, creating a vertical gradient that may cause downward flow. Field data collected during this study suggest that there exist downward vertical flows between layers, whose magnitude is yet unknown.

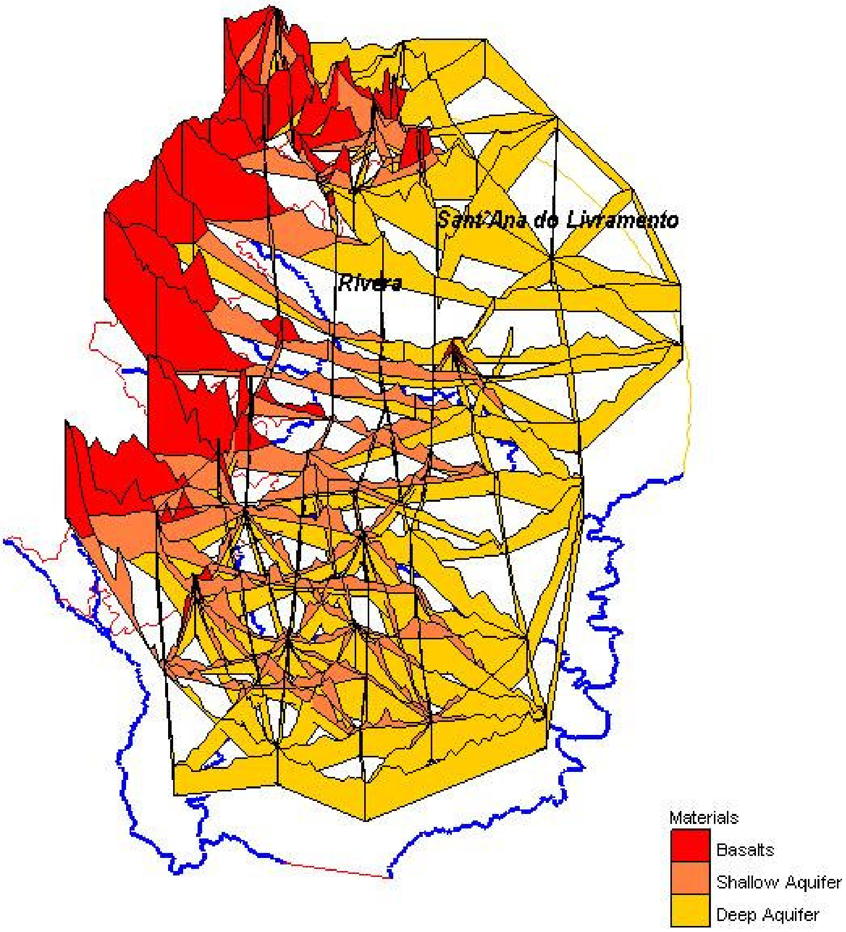


Figure 4 – Cross sections used to reconstruct the stratigraphy.

Therefore, the proposed water-bearing units for the aquifer system are: 1) upper aquifer: contained within altered basalts areas; 2) lower aquifer, Guaraní: contained within sandstones. This unit is a multilayer aquifer where several layers can be identified: a) shallow Guaraní aquifer; b) acuitard composed of sandstones with high clay content; c) deep Guaraní aquifer.

Figure 5 shows the location of two transverse profiles drawn through the area, while Figure 6 represents a schematic of the aquifer units identified.

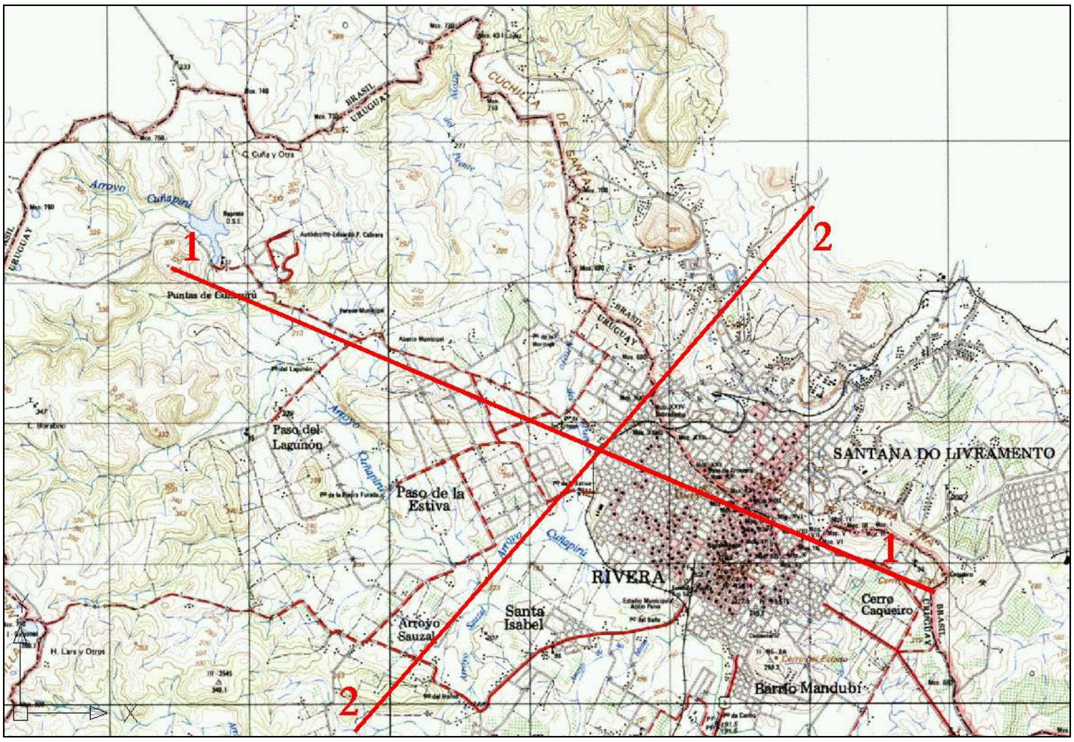


Figura 5 – Conceptual model, location of two transverse profiles constructed in the study area.

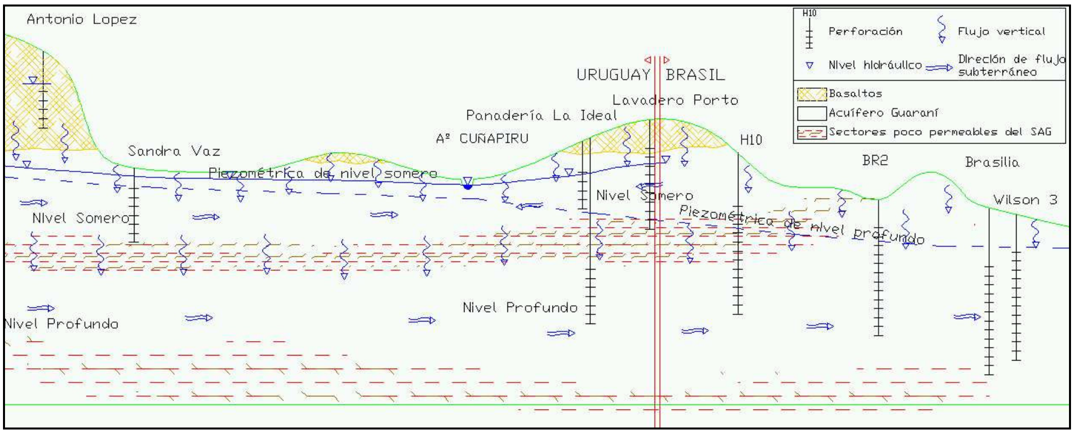


Figura 6 – Profile along 2-2 (blue arrows indicate flow directions as suggested from water levels measured at selected wells).

Figure 7 shows a 3D view of the interpolated stratigraphy. Basalts extend to the Northwest of the computational domain while the two sandstone formations develop underneath, outcropping to the East. The reconstructed aquifer system reproduces the conceptual model adequately; except that at this stage of the modeling process the acuitard was not explicitly modeled, its influence on the flow distribution was handled in an indirect way by means of the hydraulic conductivity values of the layers.

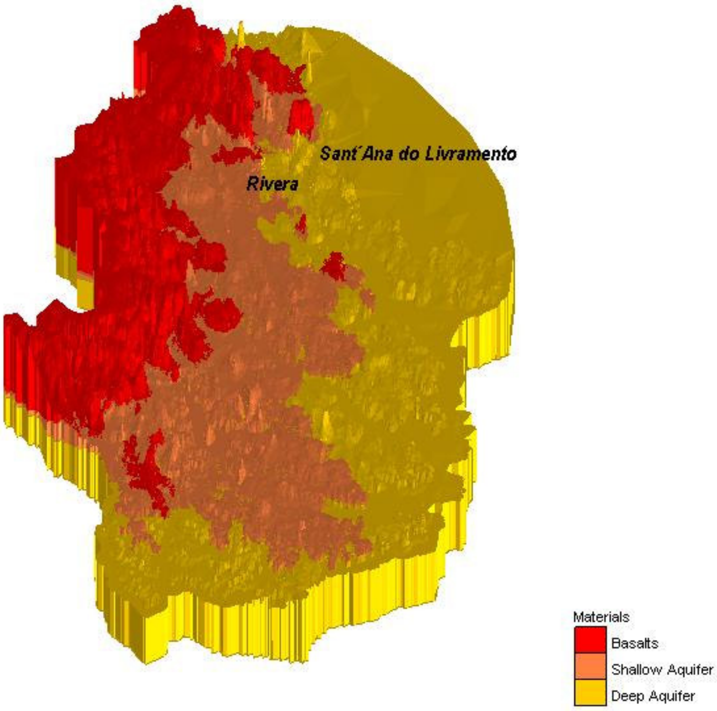
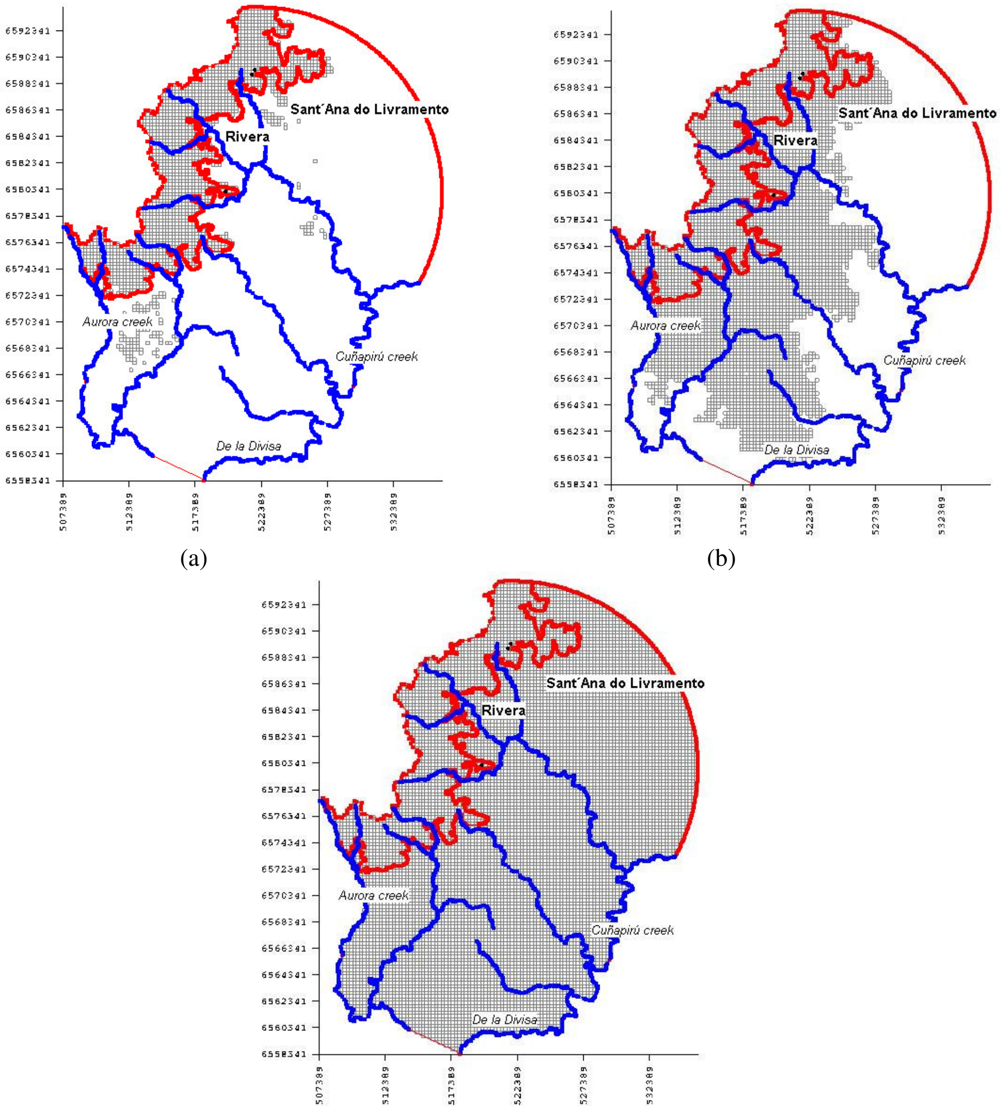


Figure 7 – Reconstructed 3D representation of the aquifer system.

4.3 Finite difference grid

The definition of the water-bearing units was the base for the construction of the finite different grid, which consisted on 135 rows and 156 columns, i.e. a total of 21060 cells of 250 m x 250 m in both, x and y directions. The grid size was considered appropriate according to field data availability. Vertically, the model contains three layers coincident with the aquifer units. The cell size in the z direction equals the thickness of the corresponding aquifer layer. According to the MODFLOW convention, cells located outside the model boundary (see Figure 1b for boundary definition) are deemed inactive, i.e. no solution is produced for those cells. As shown in Figure 8 a different number of active cells were used in each of the three simulated layers representing their different aerial extent. The basalt layer had 2049 cells or computational nodes, the shallow Guaraní aquifer layer had 5666 cells and the deep Guaraní aquifer layer had 10476 cells. Therefore, the active cells, i.e. calculation nodes, represent only 28.8 % of the total number of cells.



(a) (b)

(c)

Figure 8 – Finite difference grid. a) Layer 1: Basalts ; b) Layer 2: Shallow Guaraní aquifer; c) Layer 3: Deep Guaraní aquifer.

4.4 Boundary conditions, sources and sinks

The definition of an appropriate set of boundary conditions (BC) for each layer was part of the calibration process. This is a common scenario in groundwater flow modeling of natural systems where many uncertainties exist about the actual flow magnitudes and directions. Particularly critical was the border within Brazilian territory due to a complete lack of information regarding the hydraulic head distribution in that area. Along that portion of the model domain, a second type boundary condition was defined, with alternating positive and negative fluxes. The rest of the border in layer 3 was a combination of Dirichlet boundary conditions (prescribed-space variable hydraulic heads) and third type BC along streams. Figure 9 shows the BC on the deep aquifer layer. The border along the basalts (layer 1) was simulated as a no flow boundary. The shallow aquifer layer is not shown for brevity.

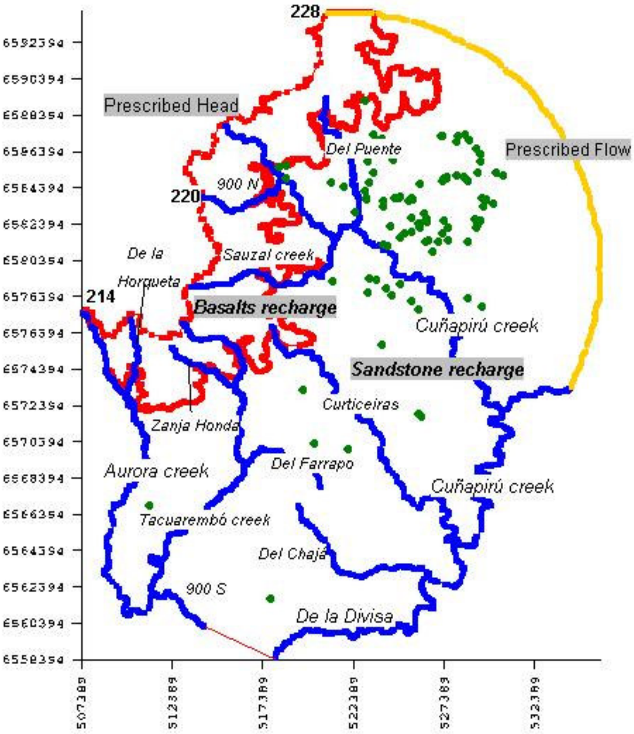


Figure 9 – Boundary conditions and sources/sinks for layer 3. Green dots represent wells. Numbers on the Northwestern boundary represent prescribed head values (in m). Simulated streams (in blue) run through the three layers depending on their planimetric location.

Aerial recharge was introduced in two different areas, one over basalts and the other over sandstones. As explained in the next section, recharge rates initially estimated were adjusted during the calibration process.

Rivers modeled inside and along some portions of the boundary simulated the stream/aquifer interaction process. The model assumes that a less permeable sediment layer, i.e. an interphase, separates the stream from the aquifer material. The flow between a stream and its adjacent aquifer is proportional to the hydraulic gradient between the stream and the aquifer, the proportionality coefficient given by the conductance of the interphase. This parameter varied in space and was set as a calibration parameter.

Water is being extracted from the aquifer system at high rates. In order to simulate this effect 25 point sinks, i.e. wells, were simulated on the shallow Guaraní aquifer layer and 104 wells were introduced in the deep aquifer. Figure 9 shows sinks and sources simulated in the deep aquifer.

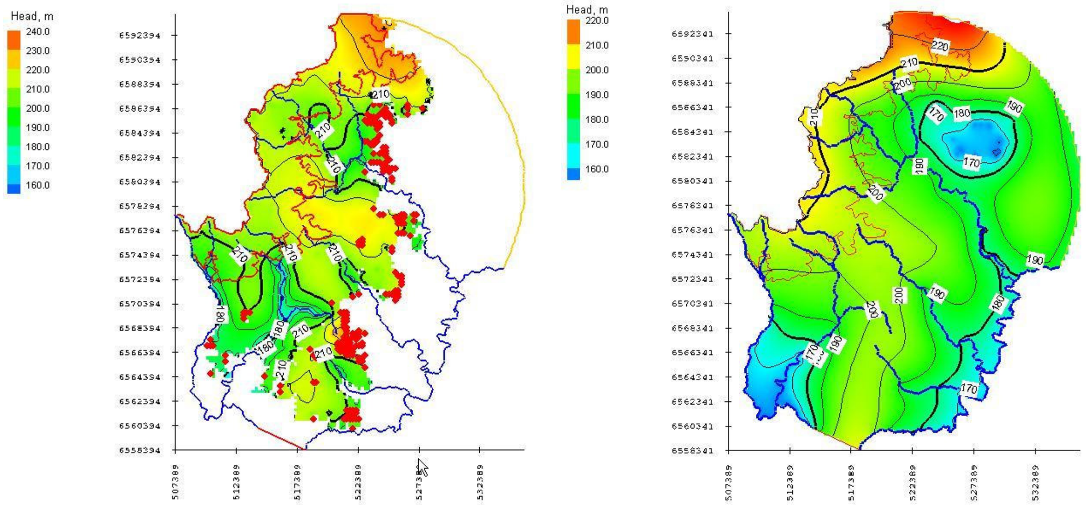
5 RESULTS

Calibration is the process of tuning model parameters and flows/heads at the boundaries with the purpose of getting a good agreement between observed and simulated aquifer heads in the interior of the computational domain and validating the conceptual model. After calibration, calibrated parameters must be within the range of observed or previously estimated values of the parameter. The set of model parameters can be adjusted automatically, using an optimization algorithm, or manually, by a trial-and-error procedure. A manual calibration was performed in this work aimed at validating the conceptual model previously defined and determining an approximate rate of recharge to the GAS in the study area. The model was run under steady state conditions.

Boundary conditions, recharge rates, stream/aquifer interphase conductances and hydraulic conductivities were adjusted during the calibration process

Basalt fractures and cracks were not explicitly represented. However, the hydraulic properties for that layer were selected to mimic the potential presence of vertical fractures that could transmit water to underlying formations. Vertical hydraulic conductivity values were 10 times greater than horizontal hydraulic conductivity.

Figures 10a and 10b show the distribution of simulated aquifer heads for layer 2 and layer 3, respectively. Both figures are qualitative as there is not enough field information to draw observed contour lines, particularly for layer 2. However, for the deep aquifer the model reproduces adequately well the cone of depression present near the two cities caused by intensive groundwater pumping. The cone has been detected in the field. In terms of flow directions, model results indicate that most of the streams in the area drain the groundwater reservoir, in agreement with field evidence. Red spots in Figure 10.a denote cells that became dry during the simulation process. This is consistent with the fact that those cells are located in the periphery of the shallow aquifer, where this layer has the smallest thickness in the transition zone toward layer 3.



(a) (b)

Figure 10 –Simulated hydraulic head. a) layer 2; b) layer 3.

A point-wise comparison between calculated hydraulic heads and hydraulic heads measured at selected wells shows adequate results in spite of some dispersion (Figure 11). This comparison should be analyzed with caution as in a finite difference grid the location of field data points rarely coincides with calculation nodes. Discrepancies can become large in case of local steep hydraulic gradients. Moreover, in a multi-aquifer system like this one, and due to certain construction characteristics of the wells, a hydraulic head reading may represent an integrated value across the entire hydrogeologic profile and not the hydraulic head of a particular layer. This makes the above comparison even more difficult.

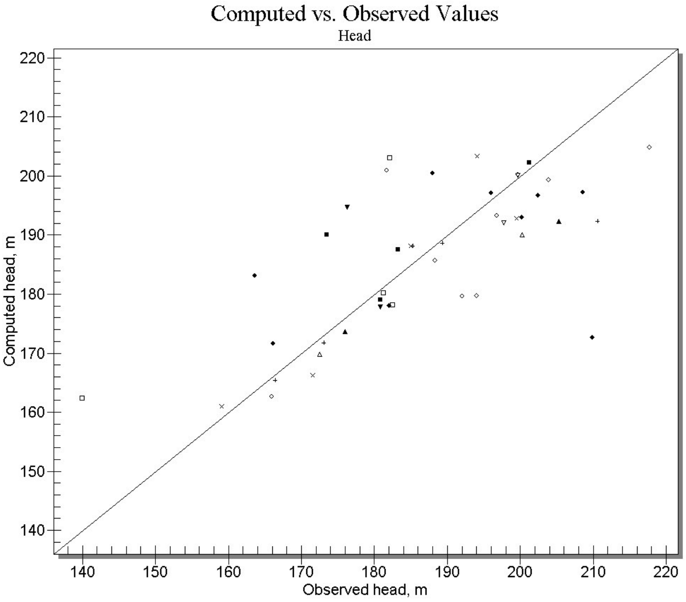


Figure 11 – Comparison between observed and simulated hydraulic head in Layer 3.

Model results would also indicate downward flows between layers, i.e. fractured basalts contribute to the shallow Guaraní aquifer, while this one contributes to the deeper Guaraní layer. Vertical hydraulic gradients, the driving force for downward flows, have been detected through field observations.

In terms of the simulated recharge rates for the current calibration of the model, the rate over basalts resulted in a meager 1.3 mm/year, and the rate over the outcropping areas of sandstones resulted in 140.2 mm/year, equivalent to 0.08 % and 8.55 %, respectively, of the mean annual precipitation of 1639 mm estimated at Rivera (DNM, 2006).

Sink/sources flows, border flows and inter-layer flows can be analyzed in terms of their directions. They are also instrumental in defining dominant flow terms of the model overall water balance. Figure 12 presents a schematic of flow directions and their simulated magnitudes.

According to model calibration, the results would indicate that recharge generated from precipitation is the main source of water entering the groundwater system. Its magnitude is small over basalts (recharge rate = 0.08 % of annual precipitation) and considerable over the outcropping sandstones (recharge rate = 8.55% of annual precipitation). All three layers combined receive an estimated 213,619 × 10^3 m^3/d. Recharge was represented by dashed arrows in Figure 12. Pumping is the main loss from the deep aquifer (layer 3) and a minor flow component from the shallow aquifer. It has been represented by solid, thick arrows with magnitudes in red. Dotted arrows represent flows through the river/aquifer interphase. The dominant simulated flow is from the groundwater system toward the surface water system.

One of the great uncertainties on the model is associated to boundary conditions. The model would simulate flow directions correctly, however the real magnitude of inflows and outflows through the model boundaries is not known.

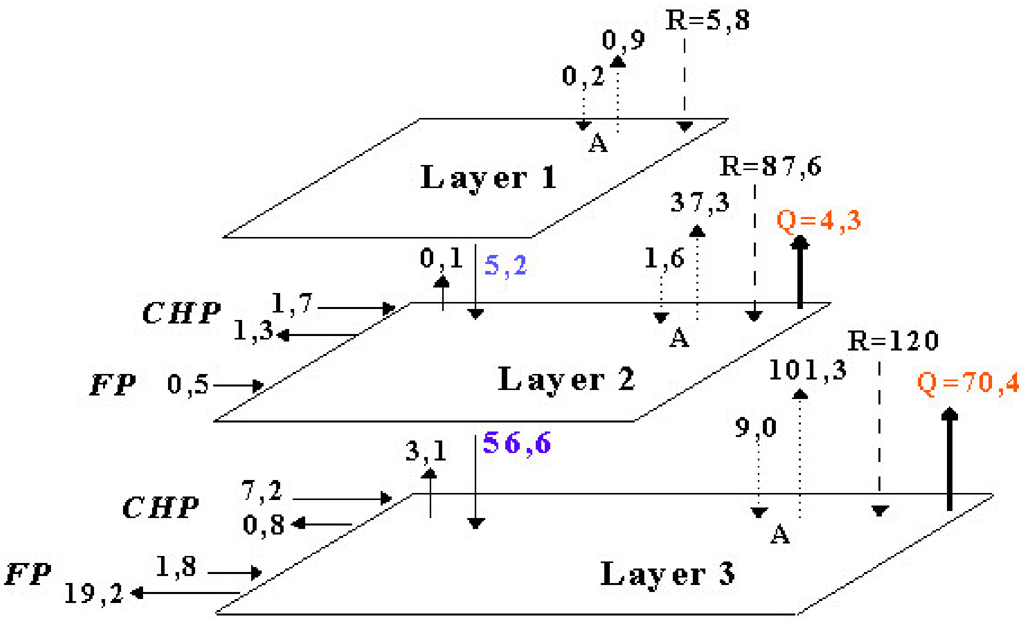
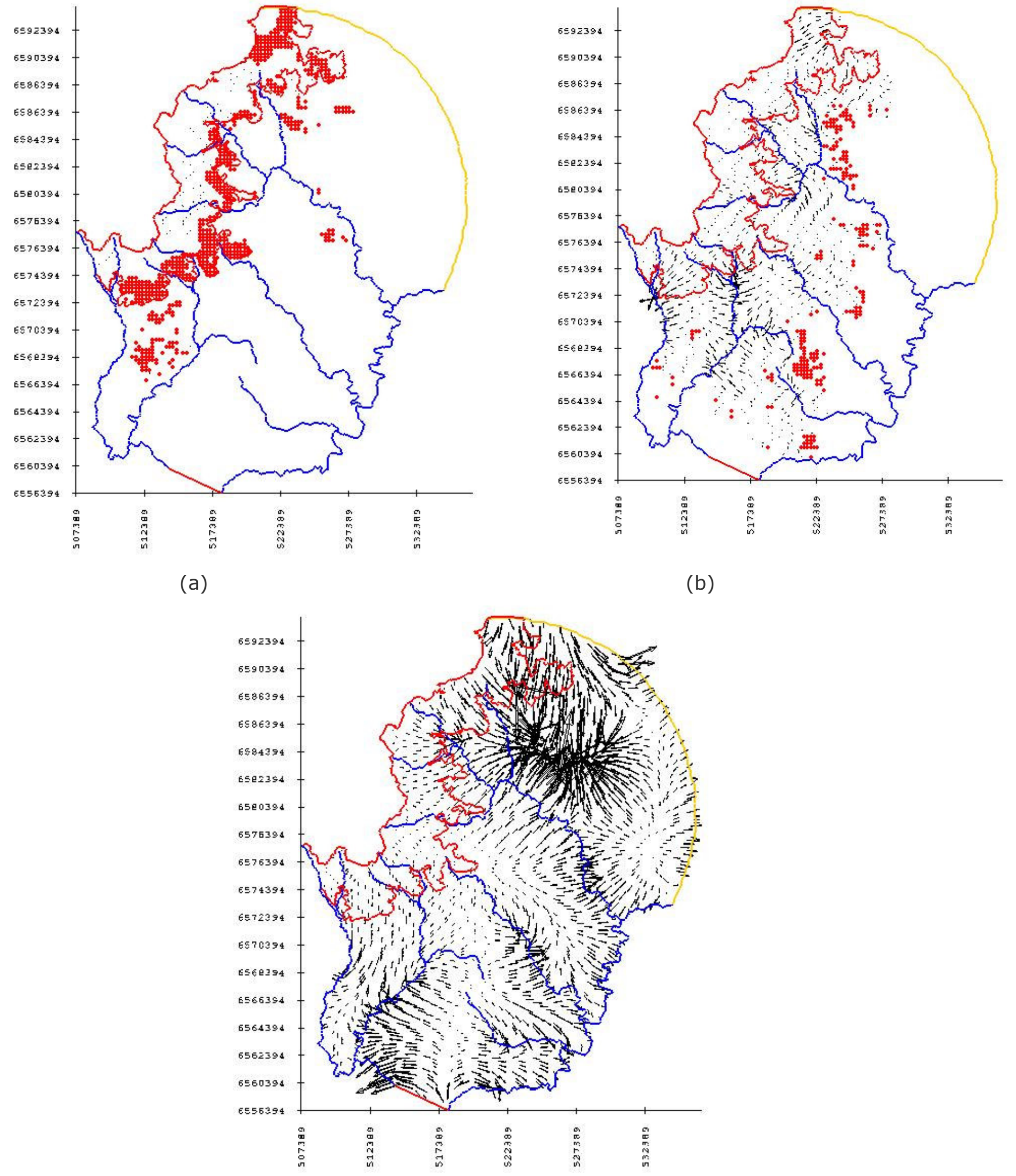


Figure 12 - Flows through all three model layers (R: recharge, Q: pumping, CHP: flow through portions of the border with Type I BC, FP: flow through portions of the border with type II BC) Arrows not drawn to scale, flows expressed in $m^3/d \times 10^3$.

One of the objectives of this work was the estimation of indirect recharge to the sandstone Guaraní aquifer from overlying fractured basalts. In this regard, the model simulates a downward flow from basalts toward the shallow Guaraní aquifer whose magnitude would be 5.112×10^3 m^3/d (blue numbers). This result would agree with the main hypothesis of this work. Also there would be a downward flow between the shallow and the deep layers whose magnitude would be 10 times higher. The simulated direction of inter-layer flows agrees what was postulated in the conceptual model based on field data.

MODFLOW computes flows through each cell wall in the grid (each term of the left hand side of Equation (5). A flow vector is generated at each cell center by computing a vector sum of the flows through the six walls of the cell. On an *xy* plane vector projections are drawn. Figure 13 shows simulated flow vectors in the three layers. Flow is virtually zero within basalts, this is reasonable given the low permeability of this geologic unit. Preferential flow may occur within fractures, but this effect is not being represented here. An equivalent hydraulic conductivity has been used instead. Flow vectors in layer 2 indicate that the streams cutting across this layer would discharge groundwater flow, verifying some of the postulates of the conceptual model and field observations. The same flow pattern between streams and the aquifer repeats in layer 3, with streams discharging groundwater. Inter-stream areas would constitute water divides. The boundary conditions implemented on the semi-circular portion of the boundary produced a stretch of approximately uniform outward flow. Inward flows would occur toward the North of the model domain. In the South of the area, flows concentrate toward streams, thought the magnitude of those flows is overestimated due to a poor calibration in that region. In layer 3 the flow concentration produced by intensive pumping is noticeable in the Northeast part of the computational domain.



(a) (b)

(c)

Figure 13 – Flow vectors . a) Layer 1; b) Layer 2; c) Layer 3. Note: even though no vector length scale is provided, the graphical length of vectors provides a good indication of the relative magnitude of flows in the three simulated layers.

Even though the calibration needs fine tuning in the future, overall the model represents the main flow directions adequately well. Flows magnitude and direction must be further verified by means of additional field data not currently available.

6 CONCLUSIONS

The GAS is an international transboundary groundwater reservoir that in most of its extent overlaps with the Paraná River Basin. The computational code MODFLOW was used to simulate groundwater flow within the multiaquifer system around the cities of Rivera (Uruguay) and Sant'Ana do Livramento (Brazil) in the Uruguayan-Brazilian border within the GAS. Two main objectives were pursued: validate the conceptual model of the hydraulic behavior of the multiaquifer system and estimate an approximate rate of recharge to the area.

Based on field data, the proposed conceptual model for the aquifer system is: 1) upper aquifer: contained within altered basalts areas; 2) lower aquifer, Guaraní: contained within sandstones. This unit is a multilayer aquifer where several layers can be identified: a) shallow Guaraní aquifer; b) acuitard composed of sandstones with high clay content; c) deep Guaraní aquifer. Field data collected during this study suggest that there exist downward vertical flows between layers, whose magnitude is yet unknown.

All layers were incorporated into the model constructing a 3D representation of the stratigraphy. Once the finite difference grid was defined over the 3D stratigraphy, a set of boundary conditions and sink/sources terms were introduced. The model was manually calibrated for steady state conditions with the following results:

- ✓ the proposed hydrogeological conceptual model was numerically validated.
- ✓ the calibration provided adequate results. Simulated hydraulic heads were in good agreement with observed hydraulic heads.
- ✓ In general, simulated flow directions agreed with flow directions identified in the field. Of particular interest is the presence of downward flows between the three layers. The basalt layer would recharge the shallow Guaraní aquifer layer, and that this one would recharge the deep aquifer. The real magnitude of those flows is yet unknown.
- ✓ Simulated recharge rates for the current calibration of the model resulted in a meager 1.3 mm/year over basalts, and 140.2 mm/year the rate over the outcropping areas of sandstones, equivalent to 0.08 % and 8.55 %, respectively, of the mean annual precipitation of 1639 mm estimated at Rivera.
- ✓ In spite of the good results obtained so far, uncertainties persist on the definition of boundary conditions on the three layers due to lack of enough field data. The magnitude of the flows should be verified by means of additional field data not currently available.
- ✓ The introduction of a more detailed zoning of hydrogeologic parameters may improve the regression between simulated and observed hydraulic heads.

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