Three-dimensional modeling of steady-state flow in lake bank filtration – Brazil

Silvia Fernandes Rocha and Eduardo Antonio Gomes Marques

ABSTRACT

Lake bank filtration (LBF) is an alternative technique of water catchment. LBF has been used by several countries for more than 100 years as pre-treatment for water supply and hydrogeological characterization studies. LBF studies are still recent and essentially focus on water quality with little or no hydrogeological approach. The benefits obtained through this technique were the reason for the implementation of a pilot project on LBF on the lake banks of the 'lake' at the Federal University of Viçosa (UFV) in the city of Viçosa (MG), southeastern Brazil. Several hydrogeological studies were carried out in this research. In this article, we highlight the study by means of three-dimensional modeling of steady-state flow to learn the characteristics of the aquifer and its interaction with the 'lake'. The three-dimensional numerical model of steady-state flow was elaborated for interpretative and predictive purposes. The results demonstrated the potential of the LBF system and how it can be used as an alternative for the UFV campus. The exposed scenario can help groundwater management in the study area.

Key words | bank filtration, Brazil, groundwater flow, MODFLOW, numerical modeling

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INTRODUCTION

Bank filtration (BF) of a river (RBF) or a lake (LBF) is a technique that includes the implantation of pumping wells on the banks of the surface water body. Surface water flows through the porous medium into the production wells by pumping. The collected water is a mixture of groundwater and surface water: The removal of microorganisms is one of the benefits identified in BF, since the technique favors low operation costs in water treatment systems (Ray *et al.* 2003; Sharma & Amy 2009; Freitas *et al.* 2012). Another BF benefit is that it can be a low-cost alternative for communities' needs for water supply. Due to these benefits and given a reality of increasing demand for water quantity and quality, the RBF technique has been used for more than 100 years in the pre-treatment of water supply in several European countries (Ray *et al.* 2003; Schubert 2003; Shankar *et al.* 2009; Polomčić *et al.* 2013; Sprenger *et al.* 2017). Water from RBF systems supplies 45% of the population in Hungary, 16% in Germany, 5% in the Netherlands (Shankar *et al.* 2009), and 56% in Serbia (Polomčić *et al.* 2013). In the United States, it has been used as a low-cost alternative to remove pathogens in filtration systems (Hunt 2003). Recently in Brazil, pilot projects of RBF (Freitas *et al.* 2012) and LBF (Mondardo 2009; Rocha & Marques 2016) were performed. The authors Ray *et al.* (2003) and Shankar *et al.* (2009) described that BF system efficiency is related to knowledge of the favorable hydrogeological conditions to promote surface–groundwater interaction and to evaluate its influence on the quality of the raw water. However, studies on hydrogeological modeling for BF are still recent, both in Brazil (Freitas *et al.* 2012; Rocha & Marques 2016) and abroad (Brink & Zaadnoordijk 1995; Shankar *et al.* 2009; Yang *et al.* 2011; Polomčić *et al.* 2013).

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The lack of scientific knowledge in LBF studies carried out in Brazil motivated the implementation of an LBF pilot project at the Federal University of Viçosa, campus of Viçosa (MG), southeastern Brazil in 2013, as part of PhD research (Rocha & Marques 2016). The study area has physical characteristics (geology, geomorphology, pedology, hydrogeology etc.) that are representative of alluvium deposits and residual soils of a vast area of Brazilian territory. This system is composed of a pumping well ('well') and five monitoring wells (SP1, SP2, SP3, SP4, and SP5) and it was implemented between May 2013 and October 2013 from drilling to percussion SPT (standard penetration test) type. The study presented in this manuscript is part of a PhD thesis on lake bank infiltration (LBF). Potentiometric monitoring was performed during a hydrological year, from September 2013 to August 2014, based on data collected daily. In the present manuscript only an evaluation of the behavior of the LBF during a steady-state period is presented. This period, from 07/07/2014 to 07/28/2014, was chosen because a serious drought occurred in the area. Water pumped in the well during this period was used as a resource for research activities on some crops at UFV's campus. Other periods were also simulated during the PhD research in order to evaluate pumping influence in other periods of the hydrological year.

For the modeling, data from other pre-existing points located in the study area (SPA, SPB, and SPC) were considered. Several field studies were performed to generate data previously unknown in the study area, such as the water level position, which is important for the elaboration of the conceptual hydrogeological model. In addition, these field studies allowed determination of the main hydrodynamic parameters, such as transmissivity, hydraulic conductivity, storage, as well as the local recharge of the aquifer. The numerical model endorsed the hypothesis of a mixture of superficial and underground water flowing through the porous media into the pumping well. Uncertainties of this model are related to the absence of wells located in areas with higher heads. Data from the numerical model were compared with data measured in the field during a hydrological year. The numerical model has allowed the evaluation of underground water flow both during steady-state and transient conditions and its influence on bank filtration. This approach can be applied to any place in the world that has an alluvium porous aquifer at the border of a reservoir.

In this context, the main goal of the manuscript is to present a steady-state 3D flow model applied to a LBF system, based both on field observations and numerical modeling. The selected area has no other pumping systems that could influence the results, so that the results could unequivocally be the occurrence of the bank filtration technique. Future scenarios representing variations in flow rates were simulated for a 10-year period.

METHODS

Site description

The study area is located on the UFV campus between meridians of 42°52′00″ W and 42°52′20″ W, and between parallels of 20°45′55″ S and 20°46′05″ S. Moreover, it presents an area of approximately 40,000 m^2 and a perimeter of 4,165 m (Figure 1).

The study area is located in the municipality of Viçosa (MG), which has a predominantly strong corrugated and mountainous landform with altitudes varying between 660 m and 780 m. According to Köppen climate classification, the climate of the region is CWa, with average annual precipitation of 1,200 mm, which is very concentrated in the summer months. July and August are considered the driest and coldest months of the year. The average temperature in the coldest month is less than 18 °C and in the warmest month is over 22 °C.

The geology of the region of the study area has gneiss as the predominant rock, with a varied texture and different levels of weathering. Other high-grade metamorphic rocks, such as amphibolites and migmatites, also occur. The hydrogeology of the study area is represented by a porous groundwater aquifer formed by alluvial deposits of the Quaternary based on gneiss residual soils (Carvalho *et al.* 2014). Moreover, the basis of the simulated numerical model is a fractured aquifer of gneiss that occurs under these residual soils.

The LBF pilot project was constructed on the alluvial bank of the upstream reservoir of one of the UFV's dams hereinafter referred to as the 'lake', the location of which is partially shown in Figure 1. Data from bathymetry were

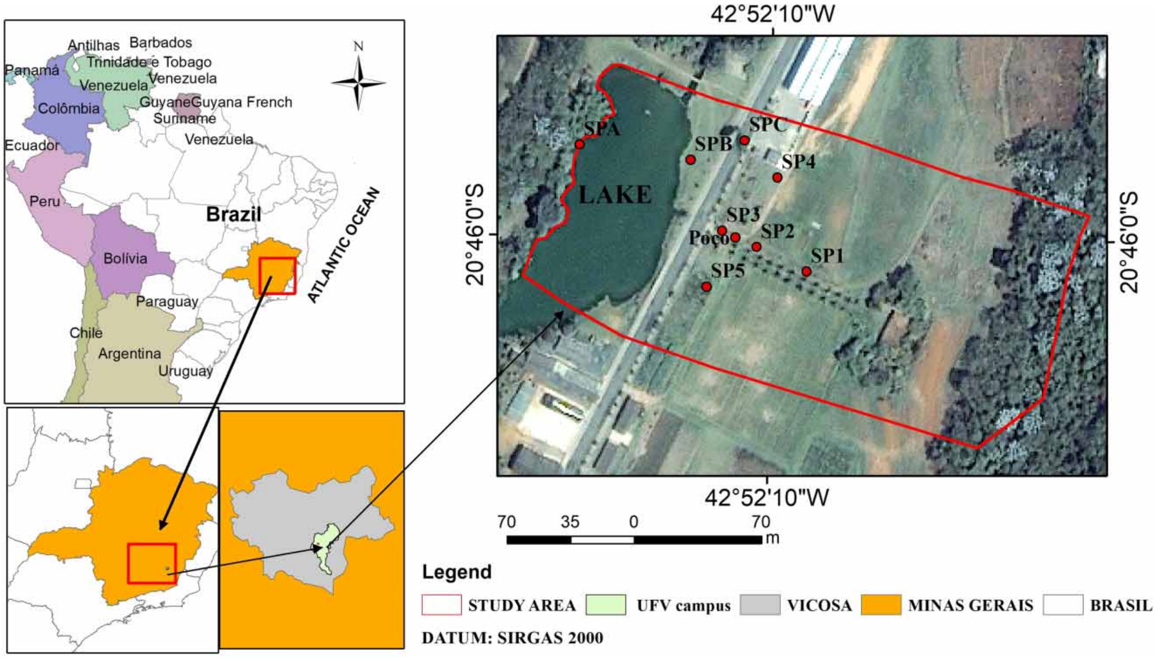

Figure 1 | Location of the study area in relation to the campus of UFV, the municipality of Viçosa, the State of Minas Gerais, and to Brazilian territory (Rocha & Marques 2016).

obtained by Ferreira *et al.* (2012), on a 1:500 scale. These authors have performed a detailed automatic bathymetric mapping of the same reservoir. In this research they have obtained data for the reservoir border and bottom elevation. Also, during field mapping the variations of reservoir border elevation were measured throughout the topographic survey for the rainy and dry seasons. Those data were used to solve boundary conditions through the *River* condition on Visual MODFLOW®.

The groundwater where the LBF system was implanted has an estimated average thickness of 21 m in the investigated stretch and pumped flows ranging from $4.5\ \mathrm{m^3{\cdot}h^{-1}}$ to $6.0\ \mathrm{m^3{\cdot}h^{-1}}$. Most of the monitoring wells fully penetrated the free aquifer with the exception of SP1, where the thickness of the alluvium was less than or equal to 11 m. The water table is located at approximately 4 metres. The submersible pump used in the 'well' is of the EBARA brand, with power of 372 to 2,237 W, 220 V, and flow capacity ranging from $5.0\ \mathrm{m^3{\cdot}h^{-1}}$ to $9.0\ \mathrm{m^3{\cdot}h^{-1}}$.

Potentiometric monitoring was carried out in the wells during one hydrological year (September 2013 to August 2014). Along with the numerical hydrogeological model, it allowed an evaluation of the lake–aquifer interaction in the implanted LBF system.

Steady-state flow modeling

The following methodological procedures were adopted:

1. Preparation of the conceptual model, involving the survey and data interpretation regarding the geological system and selection of the computational code.
2. Translation of the conceptual model into the numerical model, involving definition of the input parameters, discretization of the area, definition of boundary conditions, simulation condition, and processing of the model.

Conceptual model

The conceptual model consists of two predominant layers of soil. The first layer is limited by the terrain surface up to a depth of 4 metres and consists of clay–sandy silt soil from a landfill made in the UFV in the 1960s. The second layer occurs in the range of 4 to 25 m of depth as the impenetrable boundary, interpreted as being the rocky top. The maximum thickness of the alluvial aquifer was considered equal to 25 m. All wells were implanted in the alluvium. The wells' collection zones are found in this layer.

Potentiometric measures on all monitoring and on the pumping well were performed twice a day. The first measure was always done in the morning, before the beginning of pumping, in order to represent the natural flow; and a second one, late afternoon, after a pumping period. This was based on the results of the pumping test, previously performed, which showed that water-level recovery occurs in a 14 h period. Additionally, potentiometric measurements data have shown that, with no pumping, the reservoir presents effluent behavior.

Computational code

The modeled area was discretized by a grid consisting respectively of 44 rows, 57 columns, and two layers with 4 m and 25 m of depth, defining the model domain on Visual MODFLOW 2009.1. Other attempts were tested such as the consideration of three layers, but the best results for the modeling pointed to the domain of the model being separated in two layers, which is in agreement with the data collected in the surveys and with the elaborated conceptual hydrogeological model. After the discretization of the area, the topographic data were imported and the interpolation was performed using the inverse distance method.

For the period between July 7, 2014, and July 28, 2014, the model without pumping was considered as a steady-state flow, as no recharge had occurred during this period. This approach will be discussed in the Discussion section below.

Input data

All input data were collected during PhD field research by Rocha (2015). Each layer was considered initially as homogeneous and isotropic in the x and y axes. In the z-axis, conductivity was considered as being ten times smaller than the conductivity of the other axes (MODFLOW 2009). Two distinct hydraulic conductivity zones were defined in the model: layer 1 (soil with clay–sandy silt texture) and layer 2 (soil with sand–silt texture), for which the parameters shown in Table 1 were considered. The exploitable flow ranged from 4.5 $m^3 \cdot h^{-1}$ to 6.0 $m^3 \cdot h^{-1}$ during the simulated period. The topography was characterized by level curves with vertical equidistance equal to 0.20 m and scale 1:500. Recharge was equal to zero. Specific yield (S_y) was obtained from the pumping test. All other data were based on Betim (2013).

Table 1 | Input data in the steady-state model

Parameters	**Value**
Evapotranspiration (mm·year^{-1})	44.1
Recharge (mm·year^{-1})	0
Specific storage (S_s) (m^{-1})	1.0×10^{-5}
Specific yield (S_y)	0.14
Effective porosity	0.20
Total porosity	0.52
Kx, Ky, Kz (m·s^{-1}) (Layer 1)	1.77×10^{-6}; 1.77×10^{-6}; 1.77×10^{-7}
Kx, Ky, Kz (m·s^{-1}) (Layer 2)	5.0×10^{-5}; 5.0×10^{-5}; 5.0×10^{-6}

Boundary conditions

Two boundary conditions were considered: the Neumann condition (Type II) for the topographic divisor and the mixed condition (Type III) for the 'lake'.

Despite considering that pumping can change the groundwater divide, the pumping test and the field data obtained from monitoring wells has proved that the cone of depression did not reach the groundwater divide at the top of the hill. So, based on this fact, the underground flow divide was considered to be in the same place as the superficial water divide and defined as a no-flow boundary. This condition was inserted into Visual MODFLOW® by inactive cells that surround the modeled domain.

In this research the flow was considered dependent on the head. For this head-dependent flow condition, the *RIVER* module was used in Visual MODFLOW®, which simulates the water flow between surface waters and the aquifer in the cells of the domain to which this boundary condition was attributed.

Processing and calibration of the model

The numerical method to solve the system of linear equations generated by the spatial discretization of the groundwater equation in the area was WHS (Waterloo Hydrogeologic Solver), one of the four methods existing in the Visual MODFLOW® software. The parameters used were those adopted by the manufacturer with 200 iterations and residual criterion of 0.01, and the WHS solver considers both internal and external iterations (Ferrari 2006).

In the calibration, the normalized standard deviation (Normalized RMS) and the mean value of the well water level measurements for the simulated period were considered.

The WinPest® module (Visual MODFLOW®) was used for automatic model calibration, since the WinPest module defines a ϕ objective function, which consists of the sum of the squares of the differences between the measured and calculated values of the hydraulic heads in each well. In order to do the proper calibration, the values of the parameters of hydraulic conductivity, storage and recharge were manually changed, allowing WinPest® to estimate values of these selected parameters required to optimize (minimize) the objective function and thereby calibrate the model (Ferrari 2006).

RESULTS AND DISCUSSION

Conceptual model – potentiometric field data

Field measurements of water level position with and without pumping are presented on Figure 2, as potentiometric maps, during the steady-state period simulated (from 07/07/2014 to 28/07/2014).

The spacing of potentiometric curves in Figure 2 indicates the influence of the pumping well is higher for the SP2 and SP3 monitoring wells, as these are closer. At the static water level (NE), underground natural water flow is driven to the 'lake' with some small line inflections of the same hydraulic head, or in other words, before pumping the lake (reservoir) receives water from the aquifer (effluent behavior).

During pumping, the flow direction on the potentiometric map (Figure 2), shows that underground water flows towards the pumping well, as expected, due to the cone of depression, causing the reduction of the hydraulic head on the well and its influence on SP2 and SP3.

In the aquifer discharge zone, hydraulic gradients were of 10^{-3} m·m^{-1}, favoring aquifer storage. In the vicinity of higher terrain, where the recharge zones are located, there are no wells and because of that an estimate of hydraulic gradient in these areas was not possible.

Interpretative analysis of the water level in the steady-state period

Data of the static water level in all wells installed on the FML system for the steady-state period simulated (07/07/2014 to 28/07/2014) can be seen in Figure 3. During this period no precipitation occurred on the study area and recharge

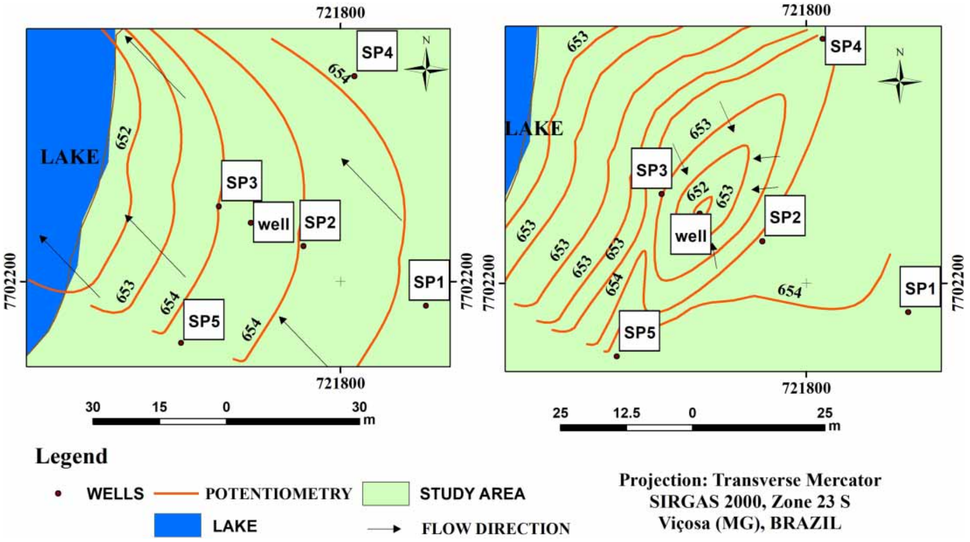

Figure 2 | Potentiometric maps based on field monitoring, representing static water level (on left) and dynamic water level (on right) during the steady-state period simulated.

was equal to zero. Despite that, the water level in the pumping well presented a maximum variation in water level close to 0.1 m during this period.

All wells installed in the studied LBF system were at similar elevation and did not dry during all the study, even during a severe dry season. Observation of other wells located at higher elevations on a similar watershed close to the one of the present study, on the other hand, dried during the dry season. This fact shows that the underground water contribution plays an important role in the behavior of the aquifer under study and can supply sufficient amounts of water to avoid depletion of its water level.

Interpretative analysis: calibration of numerical model

The automatic calibration process through WinPest was developed until Normalized RMS values no longer changed significantly. In all trials the model converged with less than 25 iterations, demonstrating its stability and reliability in its results. The numerical model presented a RMS of 28.11%. Other steady-state periods were simulated to evaluate the consistency of the model specifically for this area. However, as in the conceptual model, the difference between minimum and maximum hydraulic heads is small, and RMS values lower than 28% were not obtained. In order to decrease the RMS, the study area probably should present a greater difference between the minimum and maximum observed heads, which was not observed in practice. A similar situation was identified by Freitas *et al.* (2012) in numerical modeling of a RBF system in Brazil. These authors found a RMS close to 21% and the model also reproduced the hydrogeological characteristics identified in the conceptual model. Thereby, the numerical model used by MODFLOW has difficulty in converging with lower RMS when the difference of observed head is small.

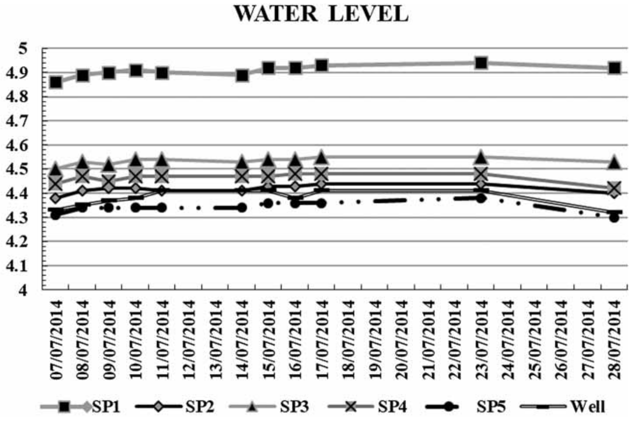

Figure 3 | Water level chart of field measurements during the steady-state period.

This result suggested the necessity for comparative analysis of the variations between the observed and calculated hydraulic heads. The observed hydraulic head values were obtained from the potentiometric monitoring performed in the wells during one hydrological year (September 2013 to August 2014). This analysis allowed a more accurate daily evaluation of the lake–aquifer interaction in the implanted LBF system and an evaluation of the variation of the water table and of the recharge. Figure 4 demonstrates that variations between observed and calculated hydraulic heads are of 0.2 m for SPC and up to 1.0 m for SP5, which can be considered high.

In the calibration process the values generated by the steady-state numerical model have represented a material transversely isotropic in each layer, with greater sensitivity in the horizontal conductivity (*Kx*) in the two layers. Therefore, this demonstrated that the heads observed within the modeled volume are controlled predominantly by horizontal flow (Table 2).

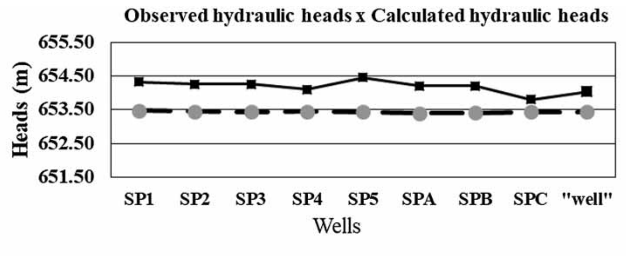

Figure 4 | Comparative chart between hydraulic heads observed in the conceptual model and hydraulic heads calculated by Visual MODFLOW ®.

Table 2 | Hydraulic conductivities obtained in the calibration of the steady-state model using the WinPest module (Rocha & Marques 2016)

Layer	*Kx* (m·s^{-1})	*Ky* (m·s^{-1})	*Kz* (m·s^{-1})
Layer 1	1.17×10^{-6}	1.77×10^{-6}	1.83×10^{-7}
Layer 2	5.0×10^{-6}	5.0×10^{-5}	5.0×10^{-6}

Carvalho *et al.* (2014) performed steady-state flow modeling for an area with similar physical characteristics as the one present in this study. After model calibration they found, for the alluvium, $Kx = 2.48 \times 10^{-5}$, $Ky = 2.56 \times 10^{-5}$ $\mathrm{m \cdot s^{-1}}$. The hydraulic conductivity values are of the same order of magnitude as the ones found in the present study for layer 2 (Table 2). The model has shown a higher sensitivity in horizontal hydraulic conductivity (*Kx*) for both layers, showing that observed heads in the interior of the modeled volume area are predominantly controlled by horizontal flow.

In relation to the *Kz* value, Visual MODFLOW® assumes for this parameter that 'underground water only flows vertically through these aquifer layers' (MODFLOW 2009). Necessarily, Visual MODFLOW® requires an input of *Kx*, *Ky* and that *Kz* has to be presented with a ten-time difference, as this is a condition of the software to run the modeling (MODFLOW 2009).

The knowledge of hydraulic conductivity zones and recharge areas could be improved if other wells were located in the study area. This situation was observed in the studies of Polomčić *et al.* (2013) and Shankar *et al.* (2009).

Interpretative analysis: potentiometry

Visual MODFLOW® presents an interpretation of the numerical model through the standard legend on the generated maps. This interpretation is given as velocity vectors and potentiometric curves. For the first case, the color scheme for the velocity vectors is: red (when the direction of flow goes out of the layer being viewed), blue (when the direction of flow goes into the layer being viewed) and green (when the direction of the flow occurs in the layer being viewed). For potentiometric curves, Visual MODFLOW® exhibits hydraulic heads ranging from highest to lowest potential.

In the LBF system, the model demonstrated velocity vectors in green in layer 2, demonstrating that there is flow in the saturated zone of the aquifer. The natural flow of groundwater occurs towards the 'lake', presenting small inflections of the lines of the same hydraulic head, i.e., the 'lake' receives water from the aquifer (effluent) before the pumping (Figure 5).

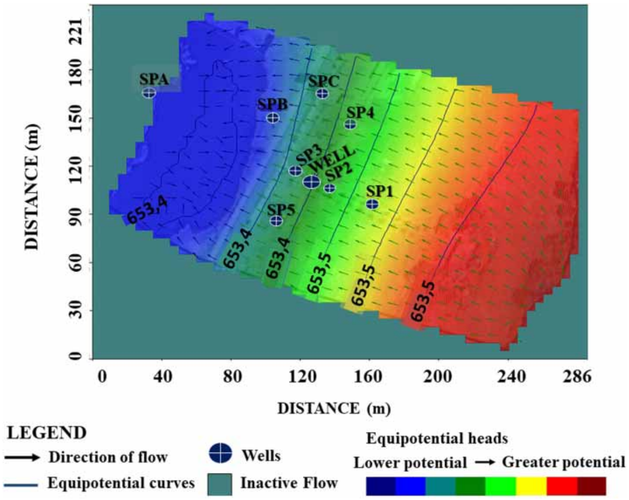

Figure 5 | Steady-state flow map from Visual MODFLOW® model without pumping.

Before steady-state flow modeling, information on flow direction and whether or not groundwater and surface water were mixed at that location was unknown. The results demonstrated that with LBF system implantation, these phenomena actually occur with great efficiency in the study area and this is directly related to the characteristics of the geology and local relief. The predominance of the alluvium layer in this area occurs due to the fact that in the 1960s, there was a section of the São Bartolomeu River where the 'lake' (dam reservoir) is currently located. Probably, it can be assumed that other LBF or RBF systems deployed in other locations with the same geological and relief characteristics may also be efficient in their operation.

When inserting the pumping well, its influence on the adjacent equipotential curves could be easily observed by generating an asymmetric drawdown cone, locally compromising the water flow that would drift to the 'lake' (Figure 6). These results are in accordance with the conceptual model and prove that LBF occurs with pumping.

The numerical model presented in Figures 5 and 6 is in line not just with the conceptual model but also with the information collected in the field (in monitoring wells), as presented in Figure 2. Before pumping, underground water flow moves towards the 'lake' (reservoir), and with the beginning of pumping, a depression cone is created, which inverts the flow direction, and water begins to flow from the reservoir to the wells, so creating bank filtration.

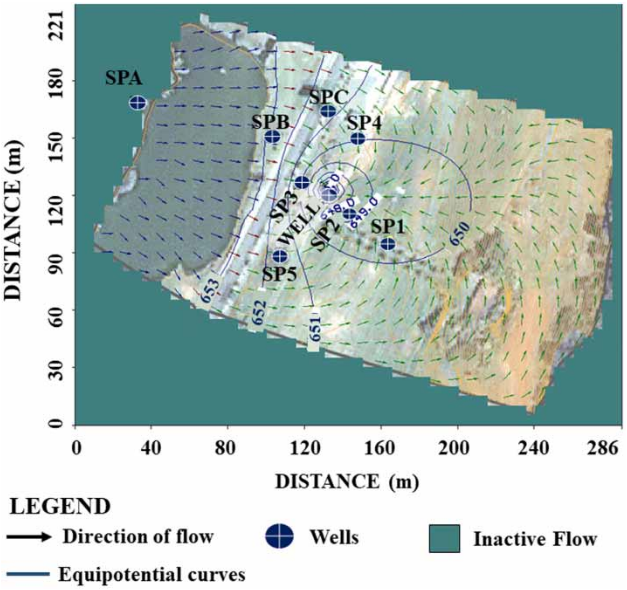

Figure 6 | Steady-state flow map from Visual MODFLOW® model with pumping.

With pumping, it was previously expected that there would be a cone that would induce water from the 'lake' to the 'well'. However, the hydrogeological characteristics of the aquifer that would control the cone size and shape and its relation with the 'lake' were unknown (Figure 7).

The 'well' presents influence on the potentiometric heads and in the horizontal flow of the 'lake'. Water from the 'lake' is induced to the 'well' during the pumping. However, it was not possible to determine the ratios in which this process occurs. Therefore, the underground flow is also controlled by the specified flow rate. This demonstrates that the collected input data has favored the construction of a model that represents the real situation of the LBF.

Predictive analysis

After one hydrological year of observed data based on field monitoring (Figure 2) and its comparison with numerical model data (Figures 5–7) a predictive analysis for future scenarios could be implemented.

For that, type II boundary conditions have been maintained for the topographic divisor of the study area, as the depression cone is far from this limit. Also, a mixed (Type III) condition was used for the 'lake'. Aquifer parameters (Kx, Ky, Kz, Ss, Sy, Eff. Por, Tot. Por) were attributed to each cell of the grid in the numerical model. The initial condition was set for simulation of steady-state flow so that, on Visual MODFLOW®, the recharge was considered null, and the charges initially attributed were the same as observed on the monitoring wells. In this contribution a simulation of a flow variation was performed for a 10-year period for the same steady-state period, during July. By considering the possibility of an increase in water consumed for this period, flow was varied between 5 and 9 $m^3 \cdot h^{-1}$, in accordance with the pump capacity currently in use.

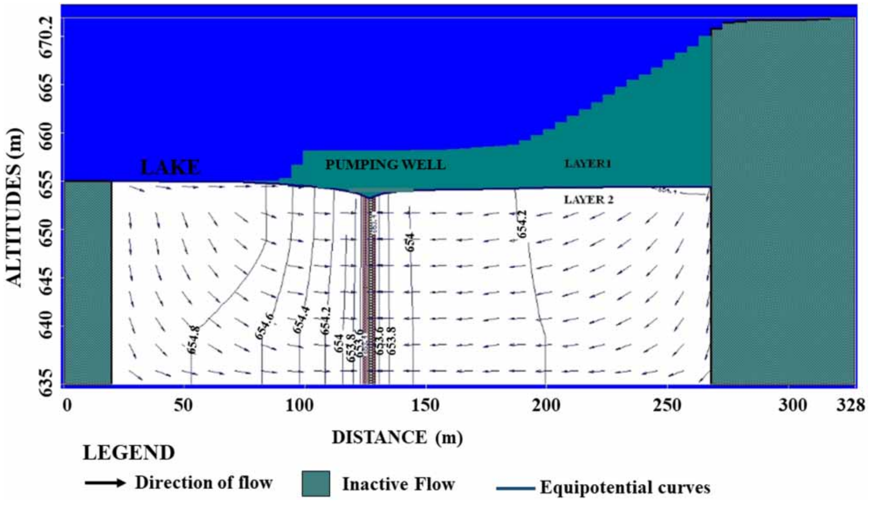

Figure 7 | Profile of the drawdown cone during pumping.

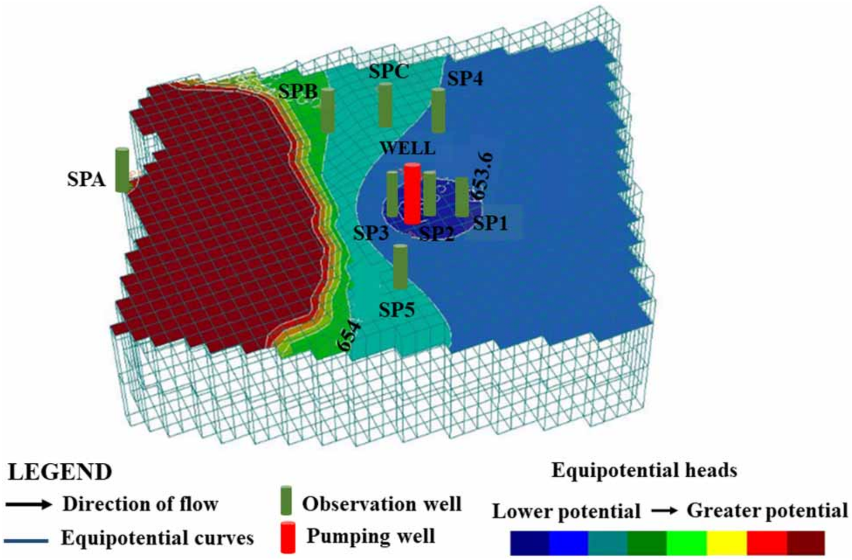

Figure 8 | Map of the steady-state flow model with pumping after 10 years.

The numerical model indicates that flow up to 9 $m^3 \cdot h^{-1}$ can be obtained with no significant impact on water level position. Also, above this value, the model shows that some cells and wells can dry.

In the predictive analysis for the drought period, the model was able to evaluate which could be the exploitable flows within the study area without resulting in expressive depression of the water level and so causing drying of the pumping well. LBF system utilization has proved to be a feasible and low-cost alternative for water supply on UFV's campus (Figure 8).

CONCLUSIONS

Based on the interpretative analysis, the model exhibited convergence with the data collected in the field, especially for the aquifer characteristics and flow coherence towards the 'lake'. In the study area there were no other wells besides those constructed for the research. Therefore, the possibility of interference from other wells in the pumping of the LBF system was not considered. For the conceptual model, the numerical interpretative model showed that the hydrogeological characteristics of the study area favor the operation of the LBF system. This result allows the suggestion that promising results should also be found in the implantation of other MLF systems in places with similar geological and physical characteristics to those of the study area.

In the predictive analysis during the drought period, the model was able to predict the exploitable flows in this area of study and the LBF system utilization as a feasible and low-cost alternative in a condition of low water supply in the UFV campus.

The LBF system was implemented as a pilot project to test its technical feasibility, both in a real case and in numerical model interpretation and its validation with real data.

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