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3D Numerical Modeling for Analyses of Pumping Tests and Its Application on Pumping Well Systems Design

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Abstract. Traditional analytical solutions for the evaluation of pumping tests under non-steady state conditions are applicable when the aquifer can be simplified as constant horizontal strata of infinite extension and homogeneous soil. Nevertheless, when such conditions are not representative of the study area, analytical solutions present considerable limitations. This paper discusses the application of 3D numerical modeling as a powerful tool to evaluate complex pumping well systems when it is mandatory to represent topography and variable thickness stratigraphic conditions of the study area. Furthermore, application of the analytical solutions is highlighted as a previous analysis to characterize the hydraulic properties of the aquifer (permeability, transmissivity and storage coefficient) and be took into account in the numerical analyses. The practical application presented in this paper utilized data from the northeastern part of the Valley of Mexico, particularly from the area of the former Texcoco Lake, where the construction of a new airport was planned. At the end some conclusions are given about the design and analysis of pumping well systems.

Keywords. Pumping test, non-steady condition, Theis solution, 3D numerical modeling, pumping well system design, pumping well system evaluation.

1. Introduction

The high-compressibility and low-shear-strength lacustrine clays that characterize the former Texcoco Lake subsoil need to be stabilized and improved before building any new construction or civil project. The soft ground improvement by using the preloading technique, complemented with vertical drains, was implemented to accelerate the consolidation soil process of a large work area at the study site. The implemented soil improvement technique included the following elements (Table 1, Figure 1): (a) 2-meter-thickness permeable volcanic material, locally known as *tezontle*, which will be part of the permanent pavement structure (lower preloading layer); (b) 2-meter-thickness basalt or andesite, which is a temporary load that must be removed once the desired soil consolidation is achieved (upper preloading layer); and (c) prefabricated vertical drain system. As expected, the ground settlement caused by the soil improvement technique has also triggered the planned settling of the preloading system. Due to the shallow water

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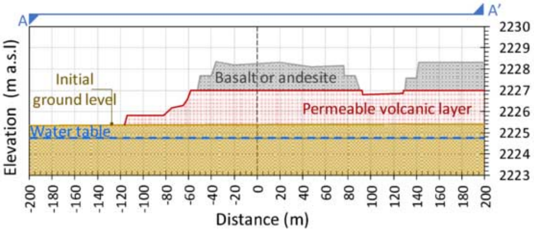
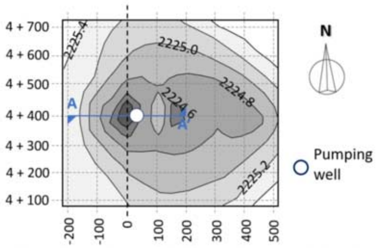
table (approximately 1 m below the original ground level), the preloading system has remained partially submerged (Figure 1c). Given this circumstance, the option to complement the preloading technique with a shallow pumping well system in the *tezontle* (permeable volcanic material) was considered to increase the soil effective stress. Pumping from a permeable layer and the resulting drawdown of water table would let to improve preloading technique efficiency regarding to time and magnitude of induced settlements [1, 2].

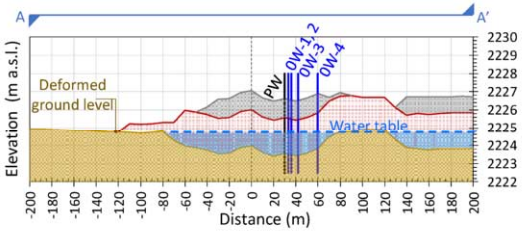
In order to design an adequate pumping well system, a 14-hours pumping test at a constant pumping rate of 6.0 l/s was conducted to characterize the hydraulic properties of the lower preloading layer (permeable volcanic material, *tezontle*). Figure 1 shows the deformed ground level curves in the study site at the pumping test date, the preloading system configuration, and the location of observation wells (OW) at 3, 6, 12 and 30 meters from the pumping well (PW).



a) Initial ground level



b) Plan view of deformed ground level (February 14, 2018)



c) Deformed ground level (February 14, 2018)

Note:
PW=Pumping well
OW=Observation well
m.a.s.l.=Meters above sea level

Figure 1. Section A-A': configuration of preloading system at pumping test date (February 14, 2018).

Table 1. Permeable materials of the preloading system and upper stratigraphy in the study area.

Soil unit	USCS classification	Description	Thickness (m)	Permeability (m/s)
Basalt or andesite	GW	Upper preloading material constituted by well-graded gravel with sand	0.0 – 2.0	---
Red permeable volcanic material (*tezontle*)	SW-SM	Lower preloading material constituted by well-graded sand with silt	0.5 – 2.0	---
Surface Crust (SC)^(*)^	CH	Light brown fat clay of soft consistency [3, 4, 5]	0.8	1.34×10^{-5}
Upper Clay Formation (UCF)^(*)^	CH	Soft lacustrine clay of high compressibility interspersed with thin seams of volcanic ash and sandy silt [4, 5]	21-34	3.88×10^{-9}

(*) References [3, 4, 5] can be consulted for further details.

2. Pumping theory

The analytical methods applied to estimate the aquifer hydrogeological parameters from pumping tests data under non-steady flow conditions are briefly described below.

2.1. Theis equation with Jacob's correction

The Theis equation that describes the time-drawdown theoretical behavior under non-steady-state conditions applicable to confined aquifers, can be expressed as follows:

$$s = \frac{Q}{4\pi T} W(u) \tag{1}$$

where s is the drawdown from field measurement in m, Q is the pumping rate in m^3/day, T is the transmissivity in m^2/day, and $W(u)$ is the well function defined by [6, 7]:

$$W(u) = \int_u^{\infty} \frac{e^{-u}}{u} du = -0.5772 - \ln u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} - \frac{u^4}{4 \cdot 4!} + .. \tag{2}$$

The Eq. (2) is an exponential integral represented by a Taylor series where u is an auxiliary function expressed as follows:

$$u = \frac{r^2 S}{4Tt} \tag{3}$$

where r is the observation distance from pumping well in m, S is the dimensionless storage coefficient and t is the time in days.

The equation 1 is valid for the case of confined aquifers and constant pumping rate. However, this equation can also be applied to the unconfined aquifers if drawdown is corrected by [6, 8]:

$$s^* = s - \frac{s^2}{2H} \tag{4}$$

where s^* is the corrected drawdown proposed by Jacob [6, 8] in m, and H is the original saturated aquifer thickness in m.

In addition, the transmissivity is estimated as follows:

$$T = kH \tag{5}$$

where k is the horizontal permeability in m/day.

2.2. Papadopulos and Cooper's correction

In the particular case of a large diameter well, the storage effect at the early process of water extraction needs to be taken into account. Papadopulos and Cooper (1967) [9] analyzed this problem by considering that drawdown depends on $W(u)$ well function, the aquifer hydraulic parameters transmissivity T and storage coefficient S, and the radius of the well casing r_c. The storage capacity of a large diameter well can be negligible for a time $t > 250r_c^2/T$ [10]. When time t becomes sufficiently large, drawdown values are representative of hydraulic properties of the aquifer. Figure 2 shows the case of a large diameter pumping well where the field data are fitted after the time proposed by Papadopulos and Cooper (1967) [9].

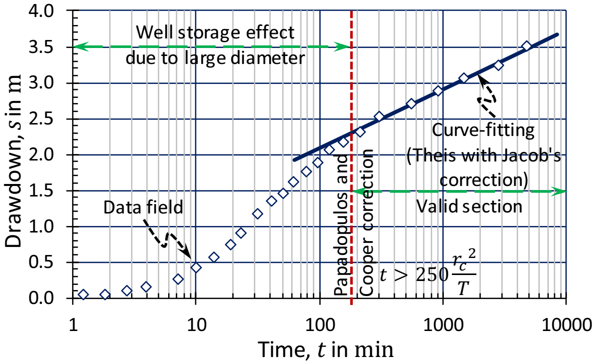


Figure 2. Drawdown-Time curve with storage effect in a large diameter well [11].

3. Analysis of the performed pumping test

3.1. Description of the pumping test

The pumping well has a casing of 1.58-meters diameter, which was installed at 5-meter depth, penetrating the upper and lower preloading layers (4 m) and 1 m into the natural ground. The water enters into the well through the slotted tubing section on the 2-meter thickness of the lower preloading layer (*tezontle*, Figure 3). Pumping and observation wells were equipped with vibrating wire piezometers to measure the water table variation during the pumping test, recording every minute with a 0.0001-meter precision.

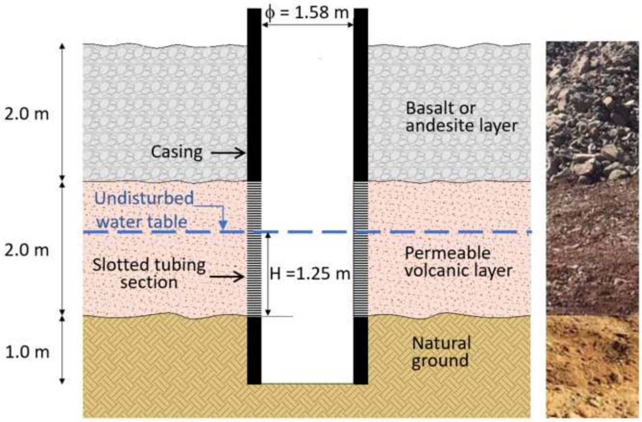


Figure 3. Simplified pumping well scheme.

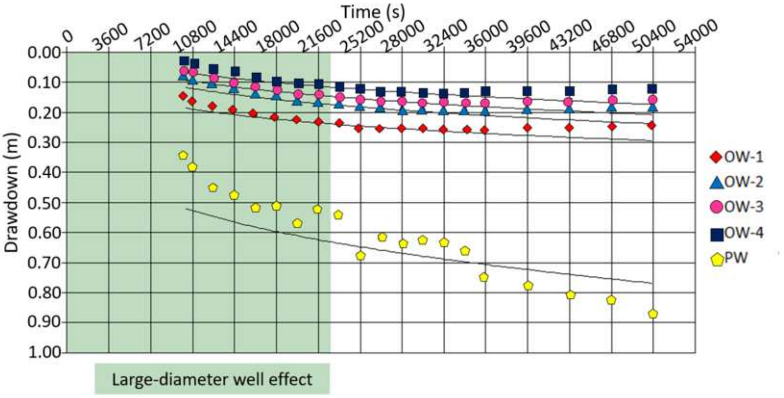
3.2. Estimation of hydraulic properties using analytical solutions

The theoretical curve obtained from the Theis solution with Jacob's correction should be the best match with the field data at every point of observation. In addition, taking into account the Papadopulos and Cooper's correction for large-diameter well effect (in this case 1.58-meters well diameter), it is assumed that under a time longer than 6.29 h ($t >$ 22645 s) the *in situ* drawdown measurements are representative of the aquifer properties (i.e. the volcanic permeable layer, *tezontle*). The specialized software *AquiferTest* [12] is used to obtain the hydraulic parameters by applying an algorithm that minimizes the sum of squared errors between field data and the analytical solution (Figure 4). Table 2 summarizes the parameters obtained from analytical solutions of Theis with Jacob's correction [13].

Table 2. Hydraulic properties obtained from analytical solutions of Theis with Jacob's correction.

Hydraulic property	PW	OW-1	OW-2	OW-3	OW-4
Transmissivity T (m^2/s)	6.30×10^{-3}	8.65×10^{-3}	6.89×10^{-3}	6.89×10^{-3}	6.89×10^{-3}
Permeability k (m/s)	5.04×10^{-3}	6.92×10^{-3}	5.51×10^{-3}	5.51×10^{-3}	5.51×10^{-3}
Storage coefficient S (dimensionless)	0.99	0.99	0.99	0.36	0.09

Note: PW=Pumping well, OW=Observation well.



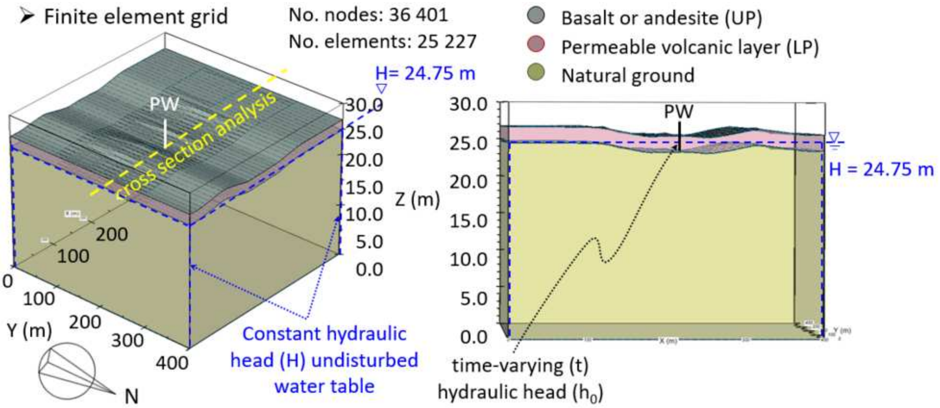
Note: PW=Pumping well, OW=Observation well

Figure 4. Best match of field data and theoretical curve obtained using Theis solution with Jacob's correction through the specialized software *AquiferTest*.

3.3. Pumping test evaluation using finite element method (FEM)

Unlike analytical solutions, the 3D numerical modeling using the finite element method (FEM) allows representing the complexity of strata configuration. This type of analysis requires the hydraulic properties of every soil unit as input to perform a pumping test evaluation and defined boundary conditions at the pumping well (Figure 5).

The model assumes a study area of 400×400 m, a 20-meter thickness of natural ground, and a constant thickness of 2 m for each upper and lower preloading layer (Figure 5). Table 1 summarizes the permeability of upper stratigraphy in the study area, while the assumed permeability of basalt or andesite layer is representative of a well-graded gravel ($k_{UP} = 1 \times 10^{-2}\ m/s$) [7]. In addition, taking into account the permeabilities estimated by analytical solutions, a parametric analysis was proposed in order to determine the most representative permeability of tezontle for numerical analyses. Consequently, three different values of permeability are analyzed for the volcanic permeable layer (*tezontle*): (a) $k_{LP} = 1.0 \times 10^{-3}\ m/s$, (b) $k_{LP} = 5.0 \times 10^{-3}\ m/s$, and (c) $k_{LP} = 1.0 \times 10^{-2}\ m/s$.



a) 3D view b) X-Z plane view

Figure 5. 3D numerical modeling of the pumping test: boundary conditions and main characteristics.

The specialized software SVFlux V2009 [14] is used for the 3D numerical model evaluation, considering the three aforementioned scenarios. The outputs of the model are the hydraulic head h at a distance r of 3, 6, 12 and 30 meters from the pumping well, as well as the estimated pumping rate Q. Figure 6 shows the comparison between drawdown profiles from the modeled hydraulic heads and field measurements at time $t = 14.0$ hours. The assessment of the previous results allows establishing that the modeled profile that fits better with field measurements and the pumping rate at which the pumping test was executed ($Q = 6.0\ l/s$) is the one obtained with a permeability value of $k_{LP} = 5.0 \times 10^{-3}\ m/s$.

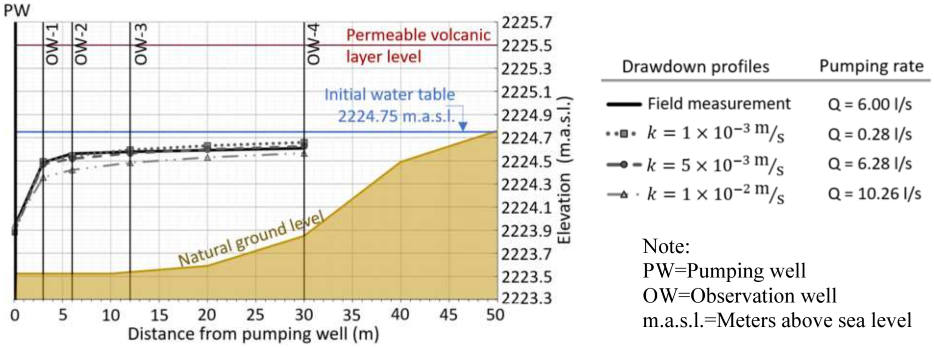


Figure 6. Comparison of drawdown between field data and 3D numerical modeling for three different permeability values.

Figure 7 shows the methodology implemented in this study to design and analyze a pumping well system. This methodology considers the application of the analytical solution that represents better the case-study according to the type of aquifer and flow conditions of the pumping test (steady-state or non-equilibrium), as well as the complementary evaluation with 3D numerical modeling using the finite element method (FEM). The results obtained from the pumping test analysis are useful to characterize the hydraulic properties of the aquifer (in this case the permeable volcanic material, *tezontle*), and they are took into account for the design of an appropriate pumping well system and the evaluation of its efficiency, as described in the following section.

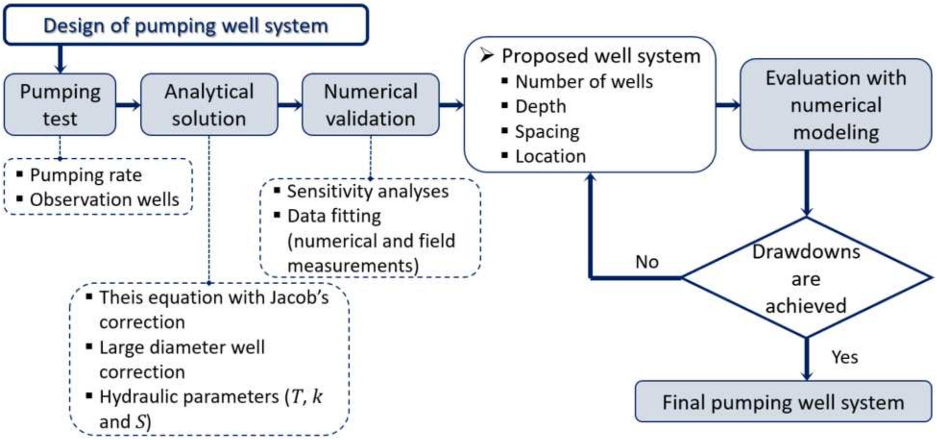


Figure 7. Methodology implemented to design and analyze a pumping well system.

4. Application to a pumping well system design

4.1. Characteristics of the pumping well system and 3D numerical modeling

In this study, the main purpose of the implementation of a pumping well system is to complement the preloading technique by reducing the surface water level in an estimated area of 700 × 5000 m (Figure 8). The pumping well system proposed for the case study has the following characteristics:

- The results obtained from the pumping test analysis were considered to evaluate the efficiency of the system under steady-state flow conditions.
- The settlement profiles of the natural ground level achieved by the soil improvement technique are represented in the 3D model, as well as the variation of surface water levels (Figure 8).
- The scheme of the pumping wells considers a total penetration of 4 m that reaches the base of the permeable volcanic layer (*tezontle*).
- The largest number of pumping wells corresponds to areas where the greatest settlement of the natural ground level occurs and the water table is higher. In addition, there were identified areas of minimum settling where there is no need to place wells.
- The optimum separation of pumping wells ranges from 70 to 120 m. Accordingly, the proposed system consists of 120 pumping wells (Figure 9).

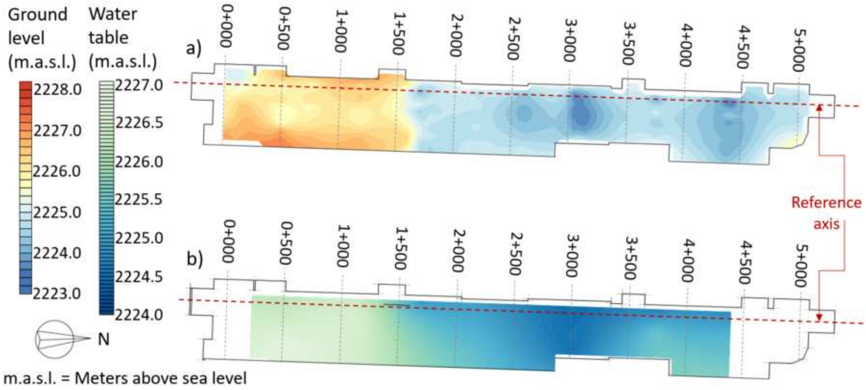
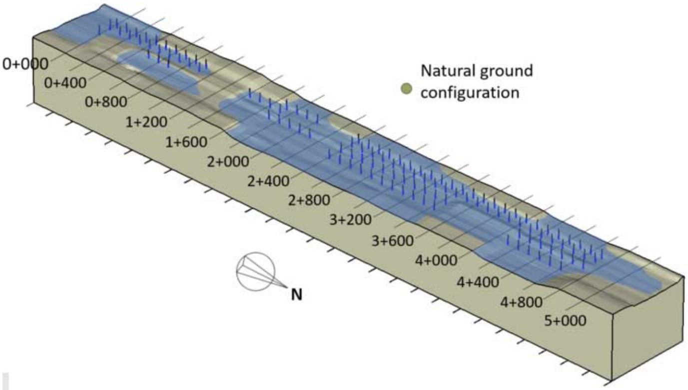
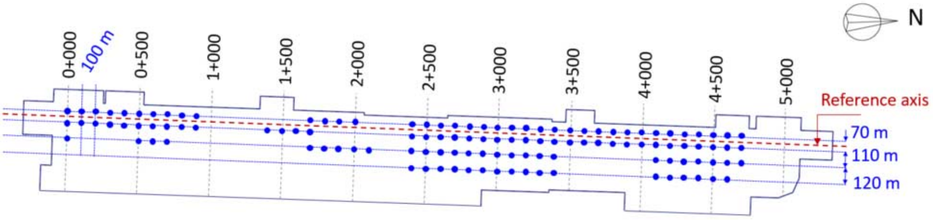


Figure 8. a) Ground level and b) water table maps (m.a.s.l.) at the area of interest.



a) 3D view



b) Plan view

Figure 9. Location of pumping wells.

4.2. Assessment of the pumping well system

The presented analysis is focused on wells number optimization and their location on critical zones, pumping rates estimation, and performance evaluation of the system when water table is lowered once the steady-state condition is achieved, as can be seen in the average drawdowns of Figure 10.

Special emphasis is placed on the importance of 3D numerical modeling that allowed a complete analysis of the entire proposed system, evaluating the pumping conditions in individual wells and the interaction between each well of the system to define the appropriate separation and optimize its operation. Besides, the 3D numerical modeling allowed to capture regional context complexity, regarding to settlement profiles of the natural ground level achieved by the soil improvement technique, as well as the variation of surface water levels. Additionally, the obtained results (average drawdown and average pumping rate) allowed identifying the zones where the highest efficiency of the system is achieved (Figure 10).

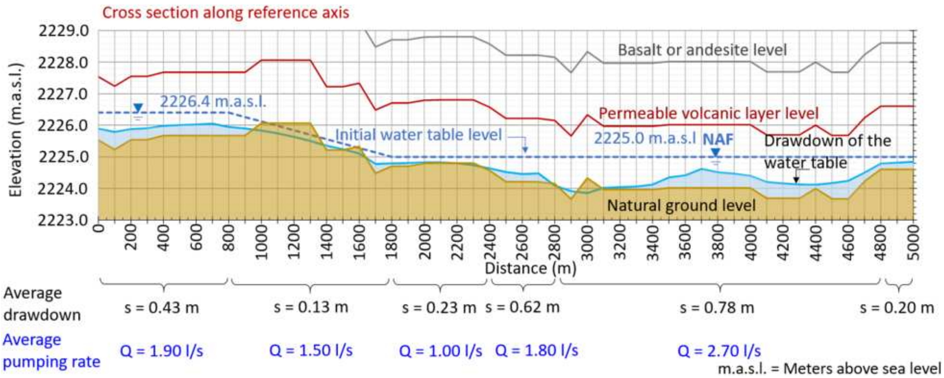


Figure 10. Results of the assessment of the pumping well system.

5. Conclusions

The main purpose of the implementation of the pumping well system studied herein, was to complement the preloading technique. This technique was used for the ground improvement of the site, for the construction of airport structures of a new airport in the zone of the former Texcoco Lake (the northeastern part of the Valley of Mexico).

With this objective, a methodology to design and analyze a pumping well system was implemented. The results obtained from the analysis of a pumping test executed in the former Texcoco Lake were useful to characterize the hydraulic properties of the aquifer (permeable volcanic material, *tezontle*) of the preloading system. These data were took into account for the design of an appropriate pumping well system and the assessment of its efficiency. The evaluation was carried out by numerical modeling.

According to the results of the performed analyses, the relevance of applying 3D numerical modeling based on finite element method (FEM) to analyze pumping tests or pumping well systems is justified when: the capabilities of analytical solutions are limited, the boundary conditions related to the water table are variables, and when water flow analyses under steady and transient state conditions are required with a regional context (including topography of the study site, heterogeneous materials and complex boundary conditions). Particularly, the 3D numerical modeling allowed evaluating the pumping conditions in individual wells and the interaction between each well of the system to define the appropriate separation and optimize its operation.

The proposed methodology can be extended to the groundwater lowering for excavations.

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