

Environ Earth Sci (2013) 70:337–351
DOI 10.1007/s12665-012-2131-z

ORIGINAL ARTICLE

Groundwater optimization model for sustainable management of the Valley of Puebla aquifer, Mexico

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Received: 25 January 2012 / Accepted: 17 November 2012 / Published online: 9 January 2013
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Abstract The Valley of Puebla aquifer (VPA), at the central region of Mexico, is subject to intensive exploitation to satisfy the urban and industrial demand in the region. As a result of this increased exploitation, a number of state and federal agencies in charge of water management are concerned about the problems associated with the aquifer (decline of groundwater table, deterioration in water quality, poor well productivity and increased pumping and water treatment costs). This study presents a groundwater management model that combines “MODFLOW” simulation with optimization tools “MODRSP”. This simulation–optimization model for groundwater evaluates a complex range of management options to identify the strategies that best fit the objectives for allocating resources in the VPA. Four hypothetical scenarios were defined to analyze the response of the hydrogeological system for future pumping schemes. Based on the simulation of flow with the MODFLOW program, promising results for the implementation of the optimization of water quantity were found in scenarios 3 and 4. However, upon comparison and analysis of the feasibility of recovery of the piezometric level (considering the policy of gradual reductions of pumping), scenario 4 was selected for

optimization purposes. The response functions of scenario 4 were then obtained and optimized, establishing an extraction rate of 204.92 millions of m³/year (Mm³/year). The reduction in groundwater extraction will be possible by substituting the volume removed by 35 wells (that should be discontinued) by the same volume of water from another source.

Keywords Optimization model · Groundwater management · Overexploitation · Simulation

Introduction

Satisfying water demands continues to be a challenge for society due to the growth of urban-industrial centers and the environmental deterioration of the resource, which limits its use. The water supply problem has most recently focused on the deterioration of surface and groundwater quality, in addition to the exhaustion of aquifers (Waller-Barrera et al. 2009).

While groundwater has played an important role in the social support and economic growth of many geographic areas (Kemper et al. 2004), the management of aquifers has lacked a vision that promotes their sustainable development. In seeking sustainable management of aquifers, it is vital to know where the water originates and to implement a new approach for its management. Nevertheless, these issues are complicated by the scarcity of information about aquifers. Therefore, a new groundwater management policy requires scientific assessment of the potential of hydrological resources and the application of analytical tools for its sustainable use (Gárfias et al. 2010).

Thus, sustainable groundwater management requires a broad understanding of the processes that determine: the

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quantity and quality of this resource, its interaction with the environment, the potential impacts of the use of these systems and the application of techniques that support decision-making (Waller-Barrera et al. 2009).

The application of this new management policy is one of the most urgent endeavors in Mexico to solve environmental problems. The case of the Valley of Puebla aquifer (VPA) system is presented as an example of this urgency. This is one of 100 overexploited aquifers in the country (CONAGUA 2004) and is located in one of the most highly populated and economically active zones in central Mexico. Groundwater is the main source of the potable water supply in the region, and because of the condition in which, it is found it has been the subject of several studies (Geotecnología 1997; Flores-Márquez et al. 2006; Gárfias et al. 2010) that have made it possible to calculate a water deficit of approximately 22 Mm³/year (Flores-Márquez et al. 2006).

Some of the most notable damaging effects that can be detected in this aquifer are: a drawdown in groundwater levels, cones of depression of about 80 m, reduction in well productivity and the deterioration of groundwater quality due to the migration of sulfurous water (geothermal water) from natural origins at greater depths (CONAGUA 2003; Flores-Márquez et al. 2006; Gárfias et al. 2010).

In addition, the overexploitation of the aquifer has changed the regional hydrology and groundwater flow patterns over the past 20 years (Geotecnología 1997; Gárfias et al. 2010) and has caused an increase in the hydraulic gradients in some areas of the valley (Flores-Márquez et al. 2006).

Most of the studies developed cited above have focused on the analysis of hydrogeological conditions and the evaluation of water availability in aquifers, rather than studies that implement techniques to support decision-making related to the sustainable management of aquifers.

Groundwater flow models developed using the MODFLOW platform are some of the techniques that support decision-making (Gorelick and Remson 1982; Gorelick 1983; Das and Bithin 2001; McPhee and Yeh 2004) since they can perform predictive simulations of cause and effect when correctly calibrated and applied in a specific area (McPhee and Yeh 2004). This process normally involves comparing the results of a series of prediction scenarios with the results of a baseline model representing current conditions. Then, these base line conditions are projected toward expected future conditions in accordance with each case. These flow models have become useful tools which, in combination with optimization techniques, often provide excellent support for the development of management guidelines and decision-making (Zhou et al. 2003; McPhee and Yeh 2004).

The primary purpose of optimization for this strategy to support management is to achieve a determined objective to the greatest degree possible given established constraints. This is due to the necessary management limitations and considerations as well as the physical behavior of the aquifer to ensure that the final solution does not alter the physical laws of the system. Since the flow model simulates the behavior and response of the system, it is possible to incorporate the results of this modeling into an optimization model. Once the optimization objective function is established, an appropriate method of obtaining the solution can be applied (Das and Bithin 2001).

One of the methods most frequently used to obtain this solution is called the response function (Maddock 1972; Harou et al. 2009), which has been used to represent groundwater flow based on stationary or transitory regimens, pumping optimization, speed of groundwater flow and decline of groundwater levels (Heidari 1982; Elwell and Lall 1988; Nishikawa 1998; Larson et al. 2001; Harou and Lund 2008).

Due to the complexity of solving the response function matrices, computational tools have been developed to perform this task. One of the most frequently applied tools is the MODRSP program developed by Maddock and Lacher (1991), which solves response functions using finite-difference discretization. MODRSP is a modular program in which the users only need to specify which type of response functions they want to calculate, without the need of making a numerous calculations (Maddock and Lacher 1991).

Response functions can be generated using multiple MODFLOW simulations or just one simulation in the MODRSP program. It is important to remember that if the application of a combined simulation model and response function is valid, it can become a very useful tool for water management (Maddock and Lacher 1991).

Considering what has been presented above and given the strategic importance of these resources in the region of Puebla, the objective of the work herein is to calculate the optimal sustainable extraction volume for the aquifer, using the combination of a groundwater flow model and optimization techniques.

Description of the study zone

The Valley of Puebla is located in the central part of the Trans-Mexican Volcanic Axis and extends from the east, from the capital city of the state of Puebla, to the Sierra Nevada. It is surrounded by three volcanoes—the Malinche, Iztaccíhuatl and Popocatepetl—(Fig. 1). The region is located between 18°54' and 19°30'N latitude and 98°00' and 98°40'W longitude and has an average altitude of

2,160 m above mean sea level (mamsl) (Fig. 1). The principal rivers that run through the Valley of Puebla are the Atoyac, Zahuapan and the Alseseca. It has a temperate climate with moderate precipitation during the summer. The annual mean temperature is 16.6 °C, with a maximum of 21.3 °C in May and a minimum of 10.8 °C in February. Annual precipitation in the basin varies between 650 and 900 mm/year, with maximum of 1,000 mm/year in the basin’s eastern and western volcanic zones (Flores-Márquez et al. 2006).

Hydrogeological setting

The area of the Puebla aquifer encompasses two states—Tlaxcala and Puebla—and covers a surface area of approximately 4,060 km², of which 2,151 km² are in Puebla and 1,909 km² are in Tlaxcala. Three hydrogeological units can be distinguished in the VPA: upper, middle and lower (Flores-Márquez et al. 2006).

The upper unconfined aquifer is made up of granular sedimentary and fractured rock Quaternary formations, resulting from erosion and lava flows from the different volcanic cones in the Sierras. This unconfined aquifer, in general, has high hydraulic conductivity, with a thickness varying from few meters at the mountain front up to 200 m at the center of the valley. The groundwater of this aquifer is of very good quality, acceptable for human consumption. This upper aquifer overlies Pliocene lacustrine deposits of very low permeability, working as an aquitard between the

upper and middle aquifers (Fig. 2). This upper aquifer receives its recharge from the surrounding volcanoes.

The middle aquifer (semiconfined) is made up of andesites, basalts, igneous tuff and conglomerates of the Balsas Group; fracturing reveals secondary porosity (Fig. 2). This middle aquifer overlies an aquitard that is made up of folded limestones, marls and shales of the Mezcala Formation (Upper Cretaceous age). The lithology of the Mezcala Formation is practically impermeable; however, zones of high fracture produce hydraulic connection between the lower and upper aquifers. The recharge of this aquifer is subterranean, coming from the regional recharge areas represented by the Tarango Formation (Malinche and Sierra Nevada ranges). Groundwater flows into the VPA, where the sulfur concentrates, and a higher temperature—possibly related to volcanic activity—is measured. The natural discharge is manifested by springs and an ascendant recharge through the aquitard. Induced discharges have been caused by some wells, most of which abandoned or closed off due to the poor water quality.

The lower confined aquifer, composed of Lower Cretaceous sea deposits of the Tecomasuchil and Atzompa Formations (both made of reef limestone) and the Tecocoyunca Group (sandstone, gypsum, shales), is found under these rocks. These geologic units were affected by dissolution and tectonic fracturing, resulting in secondary permeability (Fig. 2) (Flores-Márquez et al. 2006). These rocks contain high concentrations of sulfate and sulfur constituents (Gárfias et al. 2010).

Fig. 1 Location map of study area of the Puebla Valley aquifer, showing principal features and the major volcanoes and mountain ranges. Also shown are the three observation pumping wells in the urban-industrial polygon zone of the state of Puebla (optimization area)

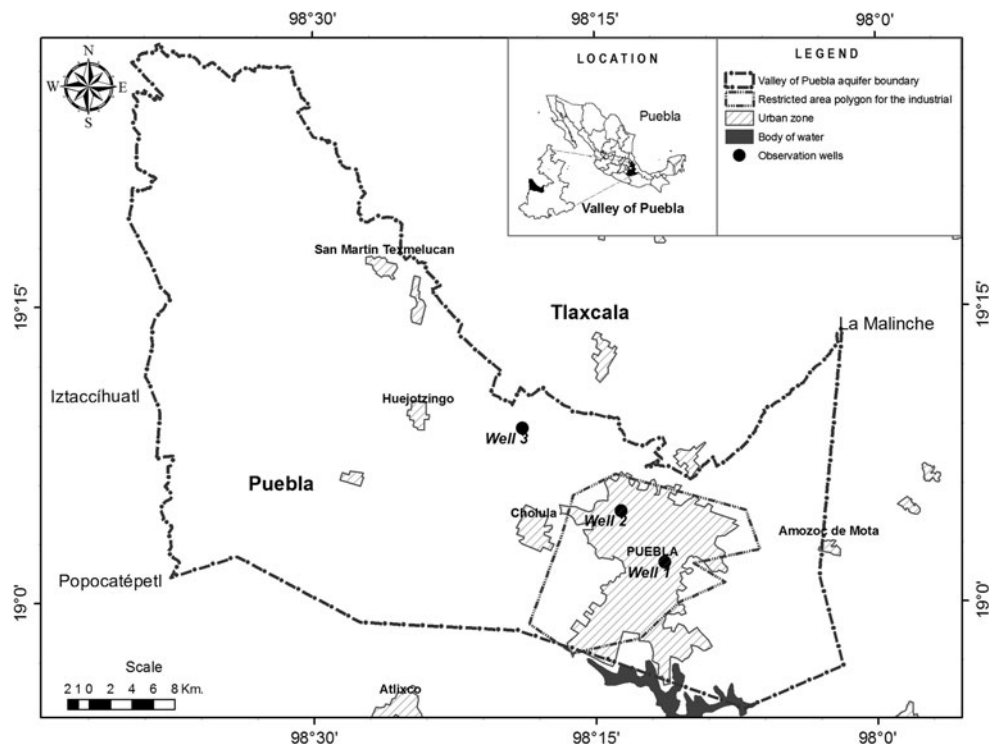
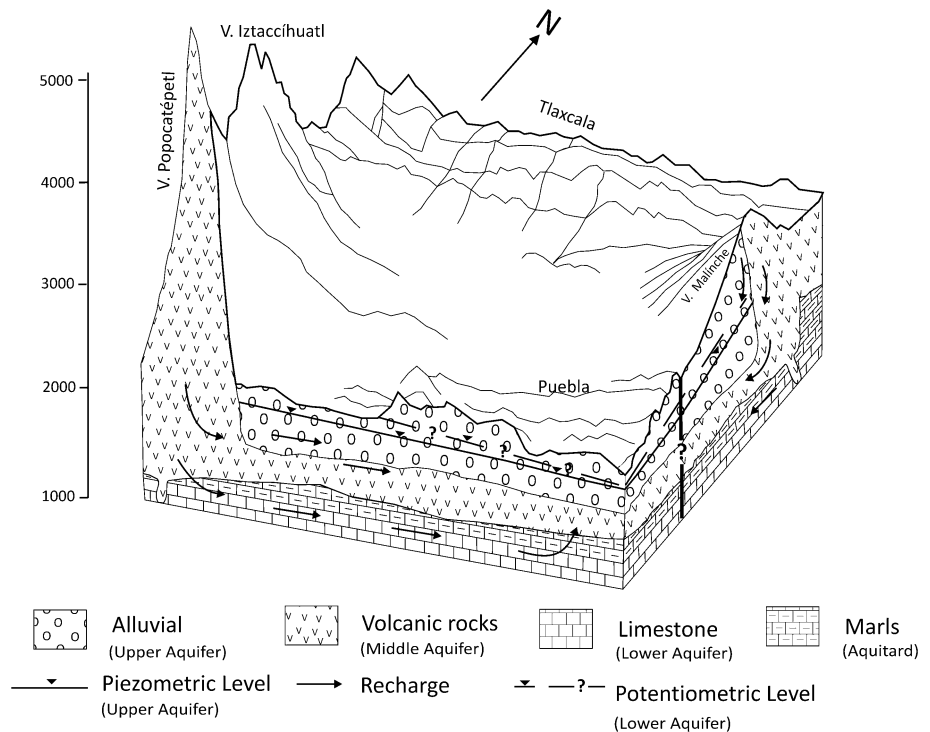


Fig. 2 Conceptual model of the Valley of Puebla aquifer included generalized geologic composition through the three-dimensional model; it also indicates the three hydrogeological units: upper, middle and lower. The *arrows* indicate the groundwater flow



These materials, in turn, lie over an aquiclude made up of a folded marine formation from the Upper Cretaceous age, (Mezcala F.) which is characterized by impermeable marl, limestone and shale. Under this aquiclude can be found the Tecocoyunca group as well as marine formations from the Lower Cretaceous age such as Tecomasuchil and Atzompa. The former is affected by tectonic fracturing and the latter affected by dissolution holes, both exhibiting secondary permeability.

Groundwater head elevation

The groundwater head distribution for the VPA indicates the existence of two recharge zones: (1) the recharge coming from the Iztaccíhuatl and Popocatepetl volcanoes on the Western side of the valley and (2) the recharge coming from the La Malinche Volcano on the Eastern side of the valley. The former originates a groundwater flow direction NW–SE, starting at the 2,400 mamsl elevation. The latter has a main component on the W–E direction, starting at about the 2,230 mamsl elevation (Fig. 6a).

The recharge coming from the Tlaxcala State, at the North of the study area, has a main direction of NE–SW, corresponding to the 2,300 mamsl elevation that matches the Zahuapán riverbed elevation. This groundwater flow joins the component from the Iztaccíhuatl and Popocatepetl volcanoes at Nativitas and Santa Isabel Tetlatlahuaca, where the elevation curve is about 2,190 mamsl. At Xoxtla and Ocotlán the flow takes a Western direction, and then

the groundwater moves mainly towards the South, following the Atoyac river direction up the Valsequillo Dam at the very end of the basin.

Methodology

The goal of groundwater management in the VPA is diminished groundwater withdrawal to equilibrate the total amount of recharge and preventing the geothermal (sulfurous) water intrusion.

Groundwater modeling

Mathematical simulation models are some of the most important tools that exist to understand the quantitative behavior of groundwater flow. Because of this, they enable the comprehensive evaluation of an unlimited number of parameters and/or variables interacting in an aquifer system and can thus provide an overview of its functioning.

A groundwater flow model that considers the conceptual model of the VPA in three dimensions was developed. Such a model considers that geological material is as a “representative volume”; which is described by the macroscopic Darcy’s law. Considering the above, the groundwater flow is assumed valid for a rigid saturated, heterogeneous and anisotropic medium described by the differential partial equation, complemented by initial and boundary conditions (McDonald and Harbaugh 1988):

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

where x, y, z are cartesian coordinates along the hydraulic conductivity components [L], K_{xx}, K_{yy}, K_{zz} are the principal components of the hydraulic conductivity tensor [LT⁻¹], h is the hydraulic head [L], W^* is the volumetric flow per unit volume, representing sink and sources of water [T⁻¹], S_s is the storage coefficient of the porous media [L⁻¹] and t is the Time [T].

The above equation should satisfy the initial and boundary conditions given by

$$h(x_i, 0) = h_0(x_i)$$

$$h(x_i, t) | \Gamma_1 = h_0(x_i, t)$$

$$V_i n_i | \Gamma_2 = -Vn(x_i, t)$$

where h_0 is the initial hydraulic head, h is the prescribed hydraulic head Dirichlet Γ_1 , N is the (n_1, n_2, n_3) unit vector normal to a Neumann Γ_2 boundary and Vn is the prescribed lateral flow per unit area of boundary Γ . If Vn is positive, flow enters the domain; if Vn is negative flows exits the domain.

The conceptual model for the groundwater systems in the VPA (Fig. 2) was transferred to a mathematical model using the VISUAL MODFLOW platform, version 4.0.; which solves the partial differential equations by finite difference methods, Table 1 shows the characteristics of this model.

Calibration process

The calibration process consists on adjusting the hydraulic parameters to the observed hydraulic heads with those calculated by the model. This process is repeated until a good fit of the heads is achieved. The fit of the heads was

analyzed by the Mean Absolute Error (MAE) and the Root Mean Squared Errors (RMSE) (Anderson and Woessner 1992).

The MAE is given by the equation

$$MAE = \frac{1}{n} \sum_{i=1}^n |(h_{oi} - h_i)|, \tag{2}$$

where MAE is the mean absolute error, n is the number of observation, h_{oi} is the modeled hydraulic head and h_i is the measured hydraulic head.

The RMSE algorithm is given by

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n [(h_{oi} - h_i)]^2}, \tag{3}$$

where RMSE is the root mean square errors, n is the number of observations, h_{oi} is the modeled hydraulic head, h_i is the measured hydraulic head.

The response functions

Response functions describe the response of an aquifer system to a unit stress (e.g., pumpage). The formulation presented here follows the work of Maddock and Lacher (1991). Drawdown response functions describe the drawdown at a particular location and time due to a unit pumping stress at another location and time. If $q(\hat{x}t)$ is the instantaneous discharge from a well at location \hat{x} in the l th aquifer at time t , and N_{wl} is the number of pumping wells in the l th aquifer, then the drawdown in the m th aquifer at point \hat{x} at time t is given by the following equation:

$$S_m(\hat{x}, t) = \sum_{l=1}^M \sum_{j=1}^{N_{wl}} \int_0^t G_m(\hat{x}\hat{x}, t - \tau) q(\hat{x}_l \tau) \tag{4}$$

For all $\hat{x} \in D_m$, where M is the number of aquifer layers, D_m is the domain of the m th aquifer layer and

Table 1 Characteristics of the flow model for the Valley of Puebla aquifer

Characteristics of the flow model for the Valley of Puebla aquifer	
Simulated surface	9,600 km ² (Puebla and Tlaxcala)
Length	80 km
Width	120 km
Spatial discretization	Finite differences grid on a geological map, scale 1:50,000
Rows	120
Columns	80
Vertical discretization	3 Units (variable thickness)
Boundary conditions	Constant flow (Newmann boundary)
Initial conditions	Hydraulic head configuration for the year 1979 (for the calibrated model) Hydraulic head configuration for the year 2010 (for the parametric scenarios)
Hydraulic properties	$K_1 4 \times 10^{-5} - 1 \times 10^{-7}$ m/s $S_1 0.15$ upper aquifer $K_2 6 \times 10^{-6} - 5 \times 10^{-6}$ m/s $S_2 1 \times 10^{-5}$ middle aquifer $K_3 2 \times 10^{-6} - 7 \times 10^{-6}$ m/s $S_3 1 \times 10^{-5}$ lower aquifer

$G_m(\hat{x}\hat{x}_j, t - \tau)$, $m = 1, \dots, M$ are the instantaneous drawdown response functions.

Consider a design horizon consisting of N_e consecutive stress periods. If the $q_l(\hat{x}_l, \tau)d\tau$ is the pumpage in well j at location \hat{x} in layer l at time t , and this pumpage varies from stress period to stress period but is constant within a stress period (pulse pumping), then the drawdown at the k th observation point in the m th aquifer layer at the end of the n th stress period, written as $s(m, k, n)$, is given by the equation

$$s(m, k, n) = \sum_{l=1}^M \sum_{j=1}^{N_{wl}} \sum_{i=1}^n \beta_d(m, k, l, j, n - i) q(l, j, i) \quad (5)$$

for $k = 1, \dots, N_{om}$; $n = 1, \dots, N_{ei}$; and $m = 1, \dots, M$, where N_{om} is the number of observation points for the m th aquifer, $q(l, j, i) = q(\hat{x}, l, j)$ for the j th pumping point in the l th aquifer, j_i is the duration of the i th stress period and

$$\beta_d(m, k, l, j, n - 1) = \int_{n_i}^{n_i} G_m(\hat{x}_k, \hat{x}_j, n_n - \tau) dt. \quad (6)$$

The β_d are the drawdown response functions and are constants independent of the quantity of pumping and drawdown (within limits of linearity). They are functions of the form of partial differential equation, the boundary conditions, the initial conditions, the model parameters and the geometry or location of the pumping. Each β_d describes the drawdown at a given location and time in response to unit pumping at another location and time ($i \leq n$).

The above equations are solved by the MODRSP program in a multilayer aquifer system. The response functions are obtained according to the external stresses of the system under study for a specific case.

Planning and scenario development

The proposed simulation of different parametric scenarios allows for varying extractions from the PVA. These scenarios represent probable conditions and illustrate the properties of the aquifer, which contributes to envisioning different operational policies and system behaviors. Four hypothetical scenarios were proposed in the study herein, for 2015, 2020 and 2025. The water levels of 2010 are used as initial values.

- Scenario 1: Continue the current extraction trend to meet supply (inertial)
- Scenario 2: Eliminate extractions from the city of Puebla polygon
- Scenario 3: Reduce VPA extractions and nullify extractions in the city polygon.

- Scenario 4: Gradually reduce the extraction of groundwater in the restricted area polygon for Puebla's urban-industrial zone without exceeding a safe yield of 339 Mm³/year (CONAGUA 2004).

Each scenario is developed according to the problem in the zone. Scenario 1—inertial trend—represents no management policy, and extraction is based only on the population's demand for water. Scenarios 2 and 3 are based on the problem being located primarily in the urban zone of the city of Puebla, since extraction from the aquifer is concentrated in that region. In scenario 3 the extraction volume is reduced by 30 %, which corresponds to the amount of treated wastewater in the study zone, representing a viable reutilization alternative for the various uses required. Scenario 4 considers the urban-industrial zone's restricted area polygon—as defined by management authorities—to be a critical extraction zone due to the existing problem (decline of the levels of groundwater, reduction in well productivity and deterioration of water quality in the exploited aquifer due to the migration of sulfurous water).

Calculation of extraction volumes

Extraction volumes were estimated based on the review of information reported by different authors over different years, from 1973 to 2010, as presented in the Fig. 3 (Agrogeología 1973; Lesser and Asociados 1982; CONAGUA 2000, 2010; Geotecnología 1997; CONAGUA-IMTA 2007). Figure 3 clearly shows the evolution of extraction from 1979 to 2010.

The reported volumes were used to obtain an equation representing the trend of hydrogeologic unit extraction (inertial tendency), which in this case is represented by a linear equation: $Y = 12.815X - 25184$ with a $R^2 = 0.96$. The tendency was also associated with the expected growth of the population at the study area.

Formulating the management model

The water pumping rate in all the cells is defined as decision variables and expressed as $Q(i)$, $i = 1, 2, \dots, n$, where n is the total number of cells to be optimized. Therefore, the objective function of the management model—which represents the maximization of the sum of the rate of groundwater pumping—can be expressed as a linear function:

$$\text{Max } Z = \sum_{i=1}^n Q(i), \quad (7)$$

where $Q(i)$ is the groundwater extraction volume for each cell i , and n is the number of cells. The objective function

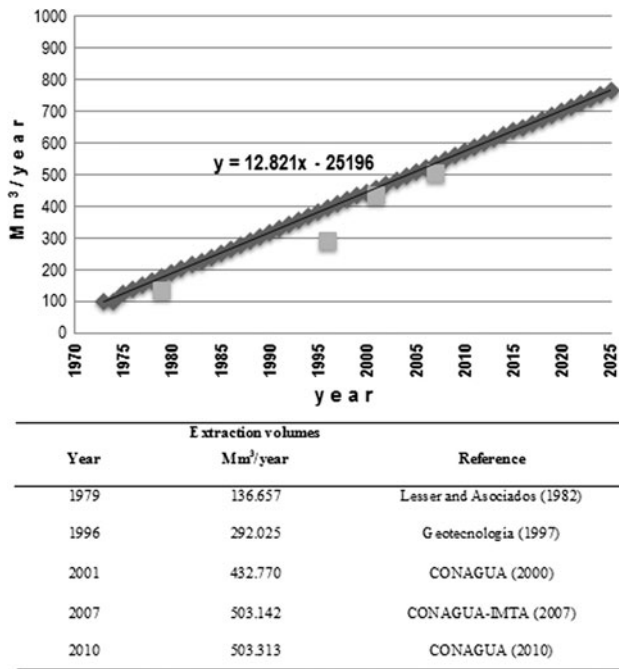


Fig. 3 Groundwater extraction from 1979 to 2030. This graph shows the volumes extracted at Valley Puebla hydrogeological system, for estimating the trend function of inertial extraction rate

is subject to a set of constraints that may include pumping rate reductions or limitations (Zhou et al. 2003). For this case in particular, the following are considered constraints:

- Maximum drawdown of 60 m (based on 9 control points randomly selected from the results of the flow model run), corresponding to the maximum allowable depth required to avoid the intrusion of sulfurous water.

$$\sum_{i=1}^n \beta(i,j)Q(i) \leq s_m(j), \quad j = 1, 2, \dots, m \quad (8)$$

where $s_m(j)$ is the maximum allowable drawdown level at point j (in this case, 60 m) at the end of the management period i , $\beta(i,j)$ is the drawdown resulting from pumping at point j (obtained from the MODRSP response function) for each optimization cell i and m is the number of points, in this case, 9).

- Constraints for pumping rate in the optimization cell i (in this case 10 Mm³/year) can be expressed as

$$Q(i) \leq Q_i(i) \quad (9)$$

where $Q_i(i)$ is the maximum pumping rate specified for each cell.

- An optimal extraction volume that does not exceed 339 Mm³/year (safe yield) for the aquifer area located in the state of Puebla, indicating that the result will be considered valid when the result of the solution of the sum of extractions is less than 339 Mm³/year:

$$\sum_{i=1}^n Q(i) < Q_T, \quad (10)$$

where Q_T is the sum of all the extractions, $Q(i)$ for each cell i that contains x number of wells, not to exceed Q_T to be valid.

Once the maximization problem is set up (objective and constraint functions), it is then solved using an optimization method. The speed at which it is solved depends on the number of cells and wells; in this case, the LINDO (Linear Interactive Discrete Optimization) program was used for the optimization of linear equations (Lindo Systems Inc 2011).

Results and discussion

Hydrogeologic simulation

After the scenarios were determined and extraction volumes simulated, a file of wells was created according to the current extraction information from 2,315 wells located in the aquifer zone and inventoried by the REPDA (Public Registry of Water Rights) (CONAGUA 2010). The volume was then weighted for each well to obtain the total extraction for each scenario (Table 2). It is important to clarify that while total extraction in the aquifer zone takes into account the two states where the aquifer is located (Puebla and Tlaxcala), the management policy that was analyzed focuses on the area located in the former (Fig. 4).

The initial conditions correspond to those of the year 2010 of the calibrated model. The components of the water balance were considered according to those values reported by CONAGUA-IMTA (2007) in the Table 3. The recharge (total inflow) was assumed constant over time since no other source of recharge is available for the study area.

The results of the scenarios provided by MODFLOW were evaluated and compared using three observation wells within the study zone to identify which scenario defines the best conditions for the aquifer based on recovery of the groundwater level.

Table 2 Extraction volumes to be simulated for each scenario

Scenarios	Simulation volumes (Mm ³ /year)			
	2010	2015	2020	2025
Scenario 1	503.313	592.707	624.695	707.862
Scenario 2	–	573.741	604.705	685.211
Scenario 3	–	479.613	505.497	572.795
Scenario 4	–	536.597	535.630	534.663

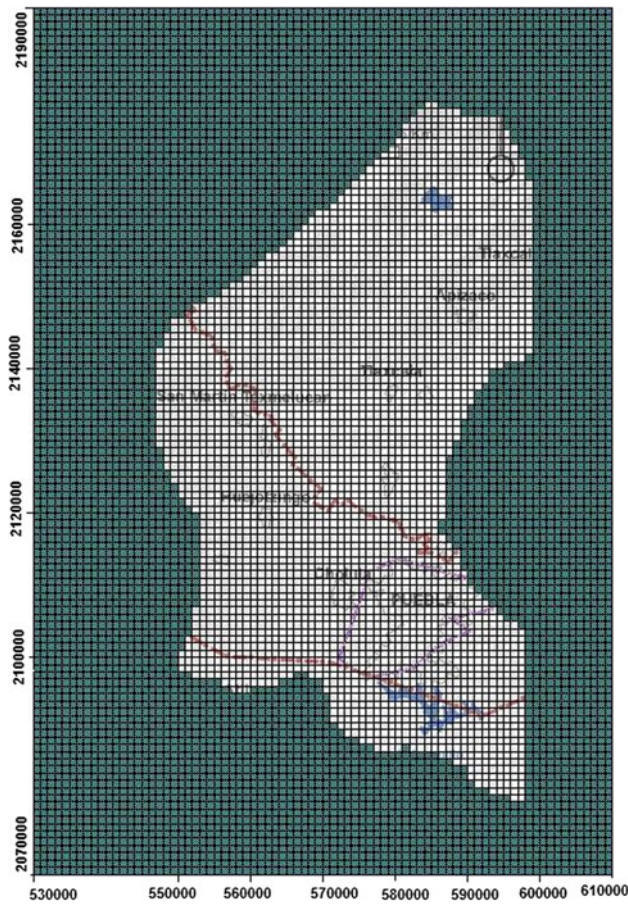


Fig. 4 Flow model grid for simulation MODFLOW represents the entire area of Tlaxcala and Puebla states

In the Fig. 5 the calibration curve for the year 1997 is presented. The RMSE obtained was 7.65 m and the MAE of 3.69 m. This figure shows that the system is well represented by the model. Thus, the calibrated model was used as the initial conditions for the management scenarios described in the next section.

After determining which scenario provides the greatest recovery of aquifer’s groundwater level, the response function was defined and the MODRSP model was applied, making necessary an adjustment to the MODFLOW input files. The files requiring modification are those that include

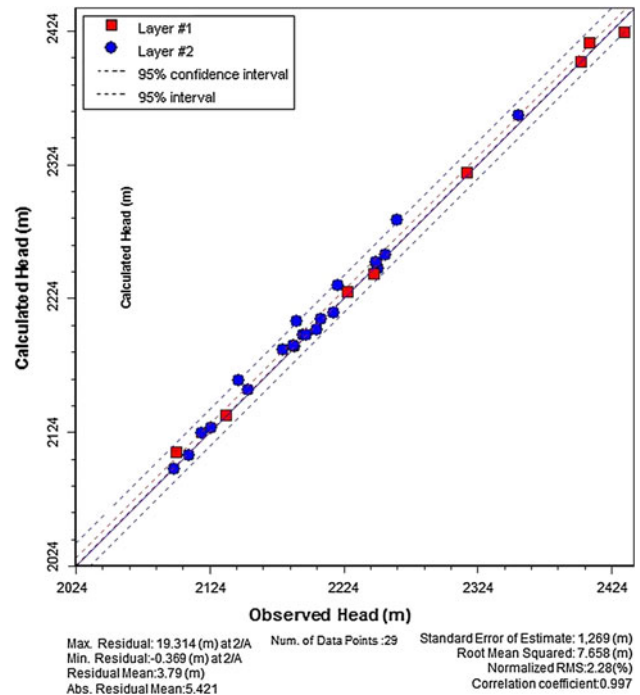


Fig. 5 Model calibration curve shows the fit of the calculated and observed hydraulic heads at 29 piezometers for 1997

the BAS (Basic) extensions, where the basic characteristics of the model are defined as the number of columns, rows, simulation layer types, etc.; Block-Centered Flow (BCF), which defines the hydraulic characteristics of the cells, and; WELL, which specifies cells that contain wells and pumping rates.

The next step groups the wells contained in each MODFLOW cell in the aquifer zone requiring optimization. This process is needed since both the MODFLOW and the MODRSP models solve the flow equation for each cell regardless of the number of wells contained in each one. For the PVA, the cells to be optimized were defined within the urban–industrial polygon zone. Forty cells were identified, representing 96 % of the extraction volume of the aquifer. The restricted area polygon is the zone in the aquifer in which optimization was performed.

Table 3 Components of the groundwater balance (units in Mm³/year) (Source of data: CONAGUA-IMTA 2007)

Aquifer	Inflow				Outflow					Change of storage ΔS
	Ih	Iv	Ir	Total	Evpt	Spr	Db	Dn base	Total	
Alto Atoyac, Tlaxcala State	83.1	108.09	8.71	199.9	64.0	10.4	130.7		205.1	-5.2
Valle de Puebla, Puebla State	179.4	135.2	25.0	339.6	42.0	34.0	282.5	14.8	373.3	-33.7
Total	237.5	243.29	33.71	539.5	106.0	44.4	413.2	14.8	578.4	-38.9

Ih horizontal inflows, Iv vertical infiltration, Ir return flows, Sh horizontal outflows, Evpt evapotranspiration, Spr springs, Dnbase base flow, Db extraction by deep wells, ΔS change in storage

The MODRSP program was then run in DOS environment. The run was performed sequentially, feeding the program with each of the model's input files. The program is executed automatically, depending on the number of wells included. For example, for the case of 40 cells with 63 wells, the program is solved 40 times, showing the influence the cells have on each of the wells and thereby obtaining the response function for each well in the system.

The MODRSP output files identify those files corresponding to the response functions (RF extension) in ASCII format; these files are generated for each of the stresses (pumping) selected in the optimization problem. For the VPA, the well option was selected (corresponding to each cell with a different number of wells), with response functions corresponding to each of the cells, indicated in the zone to be optimized.

Once the response functions are obtained, the pumping maximization (extraction) problem is proposed and the optimization constraints are established. For example, maximum supply in the zone or structural pumping limits the groundwater level or the amount of water with poor quality. Other restrictions can be established by reviewing the well extraction volume determined for each cell, which could be a significant constraint in optimization problems.

Simulation of scenarios

Scenario 1 In this scenario, the inertial trend of the extraction in the aquifer zone was analyzed, taking into account the wells in the state of Puebla and Tlaxcala. Figure 6 shows the results of the simulations from 2010 to 2025, with 2010 as the initial year for the simulation (Fig. 6a).

In Fig. 6b, the drawdown in VPA can be seen in localized zones: (1) in San Martín Texmelucan where a large number of wells are located, (2) in the urban area of the city of Puebla and (3) in the surrounding area of San Andrés Cholula and Necatitlán. In the zone located in the state of Tlaxcala, a drawdown is seen in the urban area of the city of Tlaxcala and the municipality of Apizaco.

Scenario 2 In this scenario, the inertial extraction trend was considered and the extraction by wells located in the city of Puebla was nullified. The results can be seen in Fig. 6c. The drawdown trend is very similar to Scenario 1. In the zone representing the state of Tlaxcala, a drawdown is observed in Apizaco and in the cities of Tlaxcala, Papalotla and San Isidro.

Scenario 3 In this scenario, in addition to nullifying extraction in the city of Puebla, the extraction in the rest of the VPA is reduced by 30 %, keeping the inertial extraction in the state of Tlaxcala. The maximum drawdown during the period is observed in the municipalities of Puebla State (San Martín Texmelucan, Nativitas, Tlaltenango, San

Salvador el Verde, Puebla, San Pedro and San Andrés Cholula). In the state of Tlaxcala (Fig. 6d), drawdown is observed in Apizaco and the cities of Tlaxcala, Papalotla and San Isidro.

Scenario 4 This scenario is based on the gradual reduction of water extraction in the urban-industrial polygon zone of the state of Puebla which has as its main constraint the safe yield of the aquifer (339 Mm³/year) and is considered to be one of the zones with the greatest amount of contamination and pumping. The drawdown is distributed in the municipalities of San Martín Texmelucan, Nativitas, Puebla, San Pedro and San Andrés Cholula. In the state of Tlaxcala, drawdown is observed in the zones of Apizaco and the city of Tlaxcala (Fig. 6e).

To compare the results of the scenarios, the drawdown in the three observation wells (Fig. 7) was mapped and the groundwater level evolution was evaluated for each scenario. In scenario 1, the accumulated drawdown for the period 2010–2025 for the observation wells is 10.99 m for well 1, 13.15 m for well 2 and 10.42 for well 3. The accumulated drawdown in scenario 2 is 8.45 m, 12.58 and 9.36 m for observation wells 1, 2 and 3, respectively. For scenario 3, the accumulated drawdown is 0.35, 3.87 and 7.08 m in observation wells 1, 2 and 3, respectively (Table 4; Fig. 7).

Contrasting the scenarios described above with Scenario 4, the drawdown is distributed in the same zones and is greater in the region of the urban areas in the states of Puebla and Tlaxcala. This scenario shows a recovery in the observation wells, although a drawdown continues to be observed. For example, from 2010 to 2025, there is a reduction and, therefore, a recovery in the groundwater level in well 1 of 1.90 m, in well 2, of 0.47 m and in well 3 of 2.07 m (Table 4; Fig. 7).

Based on the above quantitative information, scenario 4 was selected for optimization, since the feasibility of the application of a management policy with gradual reductions in extraction volumes.

In order to determine the response functions, it was necessary to group the wells in the cells based on the results obtained with MODFLOW for scenario 4 (gradual decrease in extraction in the restricted area polygon for the industrial-urban zone). As mentioned in the methodology section, the optimization was performed in the restricted area polygon because that area has the greatest volume of water extraction. This approach of reducing the number of wells in the input file (results of the run of scenario 4) allowed the simplification of the set of equations (matrix) to be solved by MODRSP. Based on the total number of cells included in the flow model, 63 wells were selected, which were represented in 40 cells located within the restricted area polygon. These represent 96 % of the total extraction from the aquifer when discretizing based on extraction from each one.

Fig. 6 Water table elevation (maslm) and drawdown (m) isopleths for the years 2010 and 2025. **a** Potentiometric groundwater level at initial year 2010. **b** Drawdown isopleths of scenario 1. **c** Drawdown isopleths of scenario 2. **d** Drawdown isopleths of scenario 3. **e** Drawdown isopleths of scenario 4

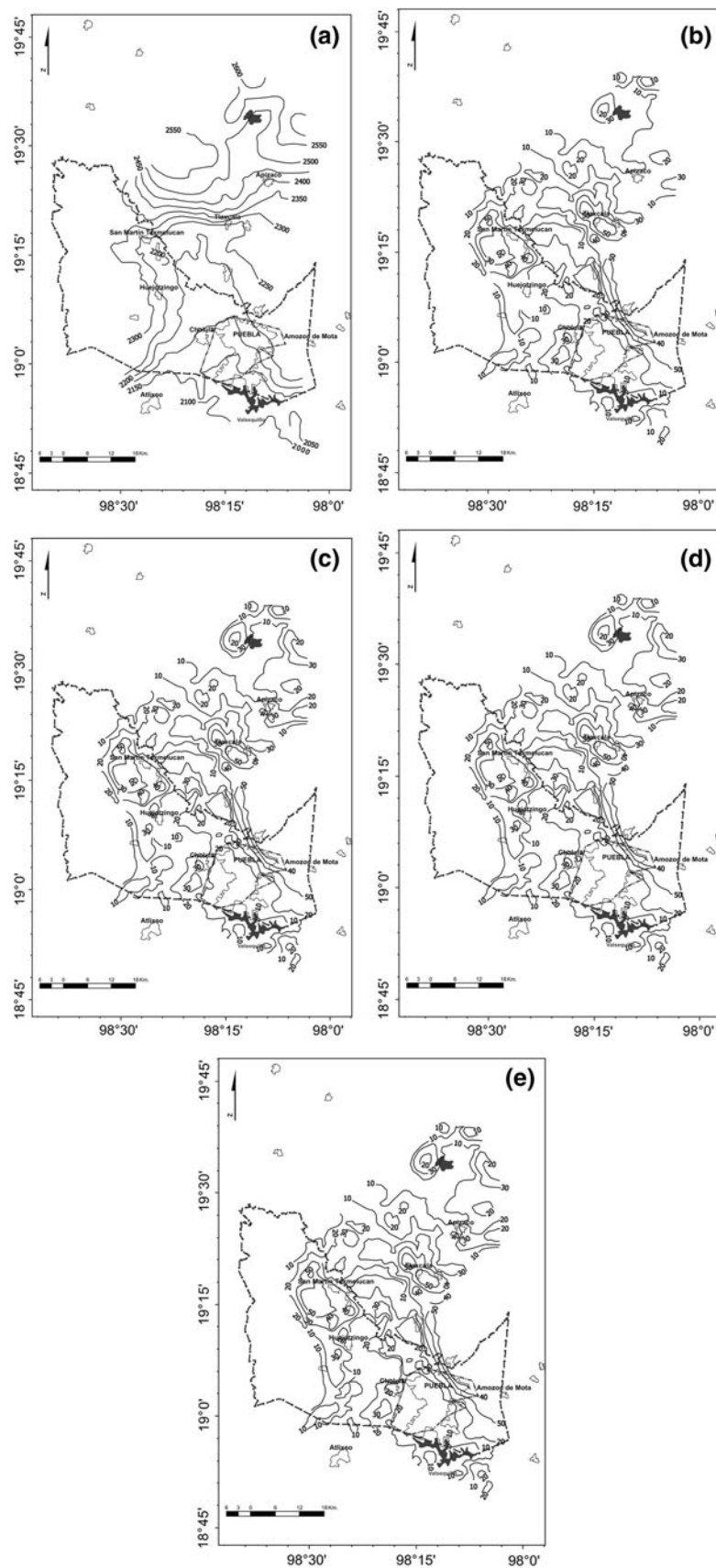
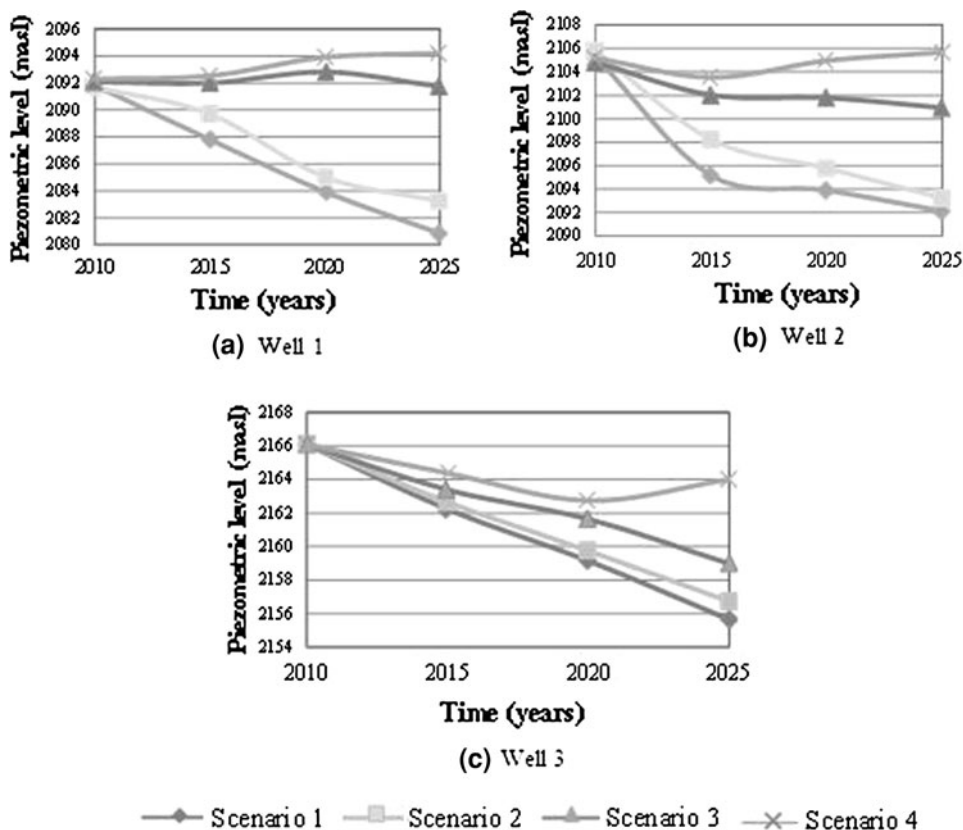


Fig. 7 Temporal evolution of the groundwater levels of wells 1, 2 and 3 based on the defined scenarios



The MODRSP program was then run, the results of which are presented in Table 5. Once the response functions were obtained, the pumping (extraction) maximization problem for the wells was determined with the 9 points representative of the upper aquifer and a maximum extraction of 10 Mm³/year per cell. With the maximization problem determined (objective and constraint functions) and based on Eq. (7):

$$\text{Max } Z = \sum_{i=1}^{40} Q(i).$$

As constraints, the drawdown cannot be greater than 60 m at the 9 points indicated; the extraction in each cell cannot be greater than 10 Mm³/year (Q_1 to $Q_{40} \leq 10$) and Q_T must be less than 339 Mm³/year. Given Eqs. 8, 9 and 10, then

$$\sum_{i=1}^{40} \beta(i,j)Q(i) \leq 60, \quad j = 1, 2, 3, \dots, 9$$

$$Q(i) \leq 10$$

$$\sum_{i=1}^{40} Q(i) < Q_T = 339.$$

Based on optimization with the LINDO program, an extraction value of 204.92 Mm³/year was obtained, less than the 339 Mm³/year that represents the safe yield for the Valley of Puebla, a value established as an extraction constraint for the management model. Therefore, the optimization of extraction volumes resulted in a reduction in extraction of 134.08 Mm³/year—or 30 %—in the polygon of the city of Puebla, a zone that represents 96 % of the total extraction of the aquifer. The reduction in extraction could be achieved by substituting an alternative water source for the 35 wells identified in Fig. 8 and Table 6, represented with dark gray circles.

Table 4 Accumulated drawdown (m) presented in the observation wells for each scenario

Well	Accumulated drawdown (m)			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
1	10.99	8.46	0.36	-1.91
2	13.15	12.59	3.88	-0.47
3	10.43	9.37	7.08	2.07

Conclusions

Continuing the current extraction policy, which follows an inertial scenario, would result in reductions of 10–13 m over a period of 15 years (2010–2025) in the Valley of Puebla aquifer and, thereby, would cause a more intensive

Table 5 Response functions obtained with the nine points representative of the upper aquifer at urban-industrial polygon zone of the state of Puebla (optimization area)

<i>i</i>	<i>Q</i> (<i>i</i>)	Coefficients obtained with MODRSP $\beta (i, j)_{m=9}$								
		$\beta (i, j)_1$	$\beta (i, j)_2$	$\beta (i, j)_3$	$\beta (i, j)_4$	$\beta (i, j)_5$	$\beta (i, j)_6$	$\beta (i, j)_7$	$\beta (i, j)_8$	$\beta (i, j)_9$
1	<i>Q</i> ₁	1.599	0.131	0.152	0.27	0.287	0.208	0.465	0.218	0.018
2	<i>Q</i> ₂	0.081	0.09	0.011	0.006	0.073	0.097	0.263	0.315	0.115
3	<i>Q</i> ₃	0.222	0.311	0.004	0.354	0.351	0.031	0.046	0.088	0.123
4	<i>Q</i> ₄	0.27	1.106	0.054	0.567	0.272	0.219	0.258	0.354	0.444
5	<i>Q</i> ₅	0.287	0.113	0.351	0.072	0.172	0.206	0.232	0.172	0.512
6	<i>Q</i> ₆	0.008	0.097	0.131	0.219	0.206	0.094	0.222	0.21	0.21
7	<i>Q</i> ₇	0.365	0.333	0.346	0.258	0.032	0.022	0.276	0.242	1.242
8	<i>Q</i> ₈	0.199	0.299	0	0.39	0.115	0.275	0.567	0.076	0.076
9	<i>Q</i> ₉	0.231	0.345	0.215	0.678	0.034	0.081	0.283	0.231	0.331
10	<i>Q</i> ₁₀	0.234	0.156	1.156	0.321	0.322	0.267	0.005	0.312	0.312
11	<i>Q</i> ₁₁	0.3451	0.1081	0.3121	0.1151	0.2111	0.0321	1.1451	0.3211	0.2701
12	<i>Q</i> ₁₂	0.0972	0.3332	0.5462	0.3452	1.2872	0.4562	0.2342	0.8562	0.5682
13	<i>Q</i> ₁₃	0.0883	0.9083	0.5663	1.4823	0.5913	0.6753	0.2003	0.5583	0.7083
14	<i>Q</i> ₁₄	0.3474	0.2344	0.5594	0.2114	0.3484	0.7564	0.1184	0.9034	0.3124
15	<i>Q</i> ₁₅	0.8785	0.3695	0.2975	0.3045	0.2315	0.4055	0.3075	0.1125	0.0425
16	<i>Q</i> ₁₆	0.9086	0.5066	0.6676	0.8896	0.0706	0.2206	1.5526	0.3226	0.7726
17	<i>Q</i> ₁₇	0.5677	0.6677	0.9077	0.4357	0.0737	0.1577	0.3457	0.4367	0.2007
18	<i>Q</i> ₁₈	0.9078	0.5438	0.5668	0.2348	0.3328	0.3788	0.4768	0.7678	0.7678
19	<i>Q</i> ₁₉	0.3979	0.3359	0.2159	0.5549	0.3889	0.3339	0.2009	0.4839	1.3839
20	<i>Q</i> ₂₀	0.102	0.887	0.056	0.334	0.881	0.589	0.115	0.207	0.207
21	<i>Q</i> ₂₁	0.0691	0.2871	0.6081	0.4651	0.2181	0.1981	0.1861	0.5691	0.6691
22	<i>Q</i> ₂₂	0.0712	0.1732	0.5972	0.4632	0.3152	0.2622	0.1572	0.0112	0.0712
23	<i>Q</i> ₂₃	0.0763	0.5513	0.5313	0.2463	0.4883	0.6163	0.2023	0.0763	0.0763
24	<i>Q</i> ₂₄	0.0804	0.4724	0.2194	0.3584	0.3544	0.2344	0.3574	0.0804	0.0804
25	<i>Q</i> ₂₅	0.0725	0.5725	0.2065	0.2325	0.1725	0.2605	0.7495	0.0725	0.0725
26	<i>Q</i> ₂₆	0.0706	0.2066	0.8946	0.8226	0.2106	0.1826	0.1206	0.0706	0.0706
27	<i>Q</i> ₂₇	0.0737	0.1327	0.8227	0.1007	0.2427	0.2247	0.1467	0.8937	0.0737
28	<i>Q</i> ₂₈	0.4578	0.1158	0.2758	0.5678	0.0768	0.3858	0.2778	0.3278	0.4578
29	<i>Q</i> ₂₉	0.2989	0.2349	0.8819	0.3839	0.7319	0.0159	0.2679	0.2189	0.2989
30	<i>Q</i> ₃₀	0.281	0.113	0.567	0.205	0.312	0.211	0.289	0.789	0.689
31	<i>Q</i> ₃₁	0.0081	0.2111	0.4321	0.0611	0.2701	0.5671	0.4561	0.1181	0.1181
32	<i>Q</i> ₃₂	0.3782	0.2872	0.4562	0.2342	0.5682	0.1452	0.2982	0.3782	0.3782
33	<i>Q</i> ₃₃	0.2343	0.5913	0.6753	0.2003	0.0083	0.9083	0.7763	0.2343	0.2343
34	<i>Q</i> ₃₄	0.6794	1.3484	0.3564	0.1184	0.0034	0.4654	0.5084	0.6794	0.6794
35	<i>Q</i> ₃₅	0.3485	0.2315	0.4055	0.3075	0.1125	0.1785	0.5995	0.3485	0.3485
36	<i>Q</i> ₃₆	0.6576	0.7226	0.4066	0.9966	0.1086	0.0706	0.8786	0.7796	0.7796
37	<i>Q</i> ₃₇	0.3077	0.1767	0.0677	0.7907	1.3337	0.0757	0.4567	0.5677	0.5677
38	<i>Q</i> ₃₈	0.2058	0.0678	0.0438	0.9438	0.0088	0.3328	0.0788	0.3248	0.2348
39	<i>Q</i> ₃₉	0.2159	0.0839	0.0359	0.9879	0.2349	0.5689	0.9079	0.1249	0.5549
40	<i>Q</i> ₄₀	0.456	0.005	0.987	0.087	0.369	0.881	0.456	0.284	0.384

exploitation of groundwater, increasing the problems of overexploitation of the aquifer (decline of levels, cones of depression, sulfurous water intrusion).

Using mathematical simulations for a management strategy for the VPA, a recovery of up to 5 m in the

groundwater levels was achieved during the simulation period of 15 years through a gradual reduction in extraction volume in the urban-industrial polygon zone (scenario 4); in this scenario the optimization of the management strategy indicates that a reduction in extraction of

Fig. 8 Location of the optimized wells and their pumping rates at the management cells of City of Puebla

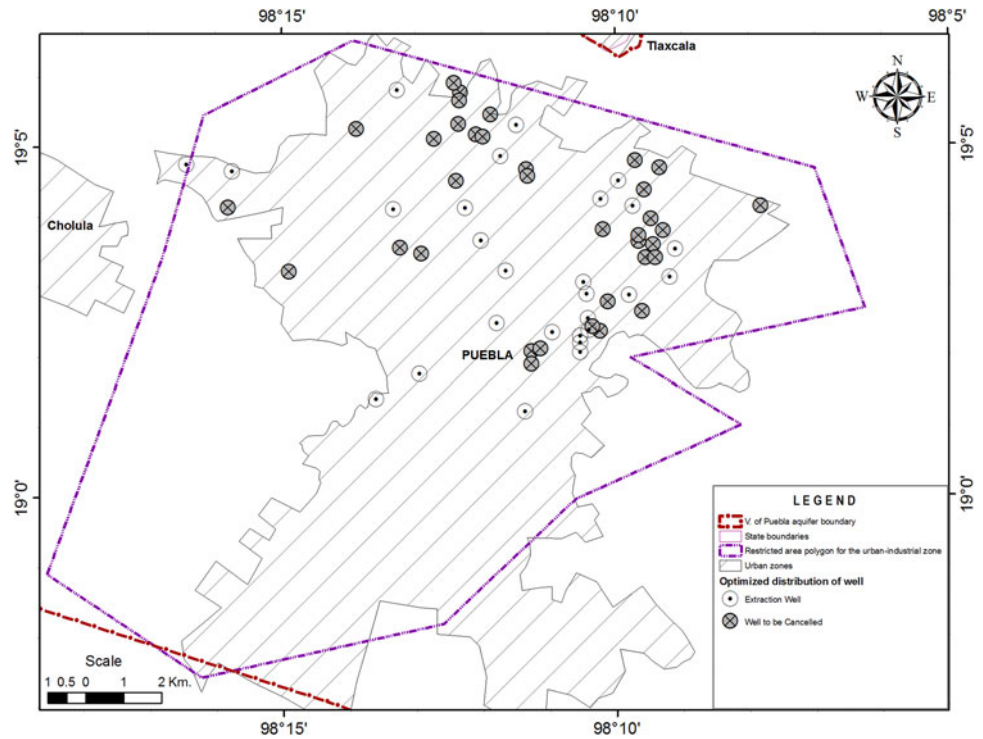


Table 6 Optimal schemes of groundwater exploitation ($Mm^3/year$) for the Valley of Puebla aquifer

Cells	Line	Column	Extraction (%)	Optimal groundwater pumping rate ($Mm^3/year$)
1	79	52	0.7583	$Q_3 = 10$
2	79	54		
	79	54	12.8302	$Q_9 = 0$
3	80	51	0.3792	$Q_{24} = 0$
4	80	53	3.2819	$Q_{29} = 0$
5	80	54	3.7152	$Q_{26} = 0$
6	80	55		
	80	55	1.6983	$Q_{40} = 0$
7	80	56	1.1736	$Q_{28} = 6.412$
8	80	59	0.7583	$Q_5 = 10$
9	81	47	0.4673	$Q_{15} = 10$
10	81	48	0.7269	$Q_6 = 10$
11	81	54	2.2569	$Q_{35} = 0$
12	81	55	1.0778	$Q_{22} = 6.502$
13	81	56		
	81	56	1.6331	$Q_{40} = 0$
14	81	58	1.5527	$Q_{12} = 0.218$
15	81	59	2.0606	$Q_{37} = 0$
16	82	52	0.1192	$Q_{32} = 10$
17	82	54	0.4514	$Q_{20} = 10$
18	82	58	0.2708	$Q_{27} = 10$

Table 6 continued

Cells	Line	Column	Extraction (%)	Optimal groundwater pumping rate ($Mm^3/year$)
19	82	59		$Q_{16} = 0$
	82	59	6.4504	
20	82	62	2.1666	$Q_{36} = 0$
21	83	53		
	83	53	2.4566	$Q_{34} = 0$
22	83	55	0.5417	$Q_{14} = 10$
23	83	58		
	83	58	4.5494	$Q_{21} = 0$
24	83	59		
	83	59		
	83	59		
	83	59	12.5774	$Q_{10} = 0$
25	83	60	0.1078	$Q_{38} = 10$
26	84	50	4.8749	$Q_{17} = 0$
27	84	55	0.156	$Q_{30} = 10$
28	84	57	0.7184	
	84	57		$Q_7 = 10$
29	84	59	0.3111	$Q_{25} = 10$
30	84	60	1.3989	$Q_{11} = 2.988$
31	85	55	1.2331	$Q_{19} = 6.306$
32	85	57		
	85	57		
	85	57	1.412	$Q_4 = 2.679$

Table 6 continued

Cells	Line	Column	Extraction (%)	Optimal groundwater pumping rate (Mm ³ /year)
33	85	58		
	85	58	2.893	$Q_{33} = 0$
34	85	59	4.5943	
	85	59		$Q_{18} = 0$
35	86	53	0.6717	$Q_8 = 10$
36	86	56		
	86	56	11.009	$Q_{13} = 0$
37	86	57		
	86	57	0.3851	$Q_{23} = 10$
38	87	52	0.1356	$Q_{31} = 10$
39	87	56	1.0577	$Q_1 = 9.824$
40	87	57	0.8342	$Q_2 = 10$

134.08 Mm³/year in the polygon would prevent overexploitation of the groundwater in the upper aquifer, as well as the intrusion of poor quality water. This proposed reduction represents 30 % of the safe yield of 339 Mm³/year. The application of this management policy will be possible by substituting alternative water sources for the 35 wells contained in the optimized cells (wells that should not continue to be pumped).

This gradual extraction policy can enable the reuse of treated wastewater for activities that comply with environmental norms—such as watering gardens or industries that do not require first grade water quality—or the use of surface water which, in this zone, would require pretreatment due to existing contamination of the Aleseca and Atoyac rivers.

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