Groundwater Modeling of the Calera Aquifer Region in Central Mexico

Jairo E. Hernández[1], Prasanna H. Gowda[2], Terry A. Howell[3], Jean L. Steiner[4], Francisco Mojarro[5], Ernesto P. Núñez[6], and José R. Avila[7]

[1]Research Agricultural Engineer, USDA-ARS-Conservation and Production Research Laboratory, Bushland, TX USA 79012-0010; PH: (806) 356-5718; FAX: (806) 356-5750; email: jairo.hernandez@ars.usda.gov

[2]Research Agricultural Engineer, USDA-ARS-Conservation and Production Research Laboratory, Bushland, TX USA 79012-0010; PH: (806) 356-5730; FAX: (806) 356-5750; email: prasanna.gowda@ars.usda.gov

[3]Acting Laboratory Director, USDA-ARS-Conservation and Production Research Laboratory, Bushland, TX USA 79012-0010; PH: (806) 356-5746; FAX: (806) 356-5750; email: terry.howell@ars.usda.gov

[4]Laboratory Director, USDA-ARS-Grazinglands Research Laboratory, El Reno, OK USA 73036; PH: (405) 262-5291; FAX: (405) 262-0450; email: jean.steiner@ars.usda.gov

[5]Professor, Universidad Autónoma de Zacatecas, Jardín Juárez 147 Centro Histórico, C.P. 98000 Zacatecas, México, PH: (492)92-22001 email: mojarro_fr@yahoo.com.mx

[6]Professor, Universidad Autónoma de Zacatecas, Calzada de la Universidad 108 Col Progreso, C.P. 98058 Zacatecas, México, PH: (492)92-26470, email: epnunez@yahoo.com.mx

[7]Graduate student, Universidad Autónoma de Zacatecas, Jardín Juárez 147 Centro Histórico, C.P. 98000 Zacatecas, México, PH: (492)92-22001, email: avilacarrasco@yahoo.com.mx

ABSTRACT

Calera Aquifer is the main source of water for irrigated agriculture, industrial and drinking water purposes in the Calera Aquifer Region (CAR) in the State of Zacatecas, Mexico. Irrigated agriculture accounts for 80% of total groundwater extracted from the Calera Aquifer. Limited rainfall and low agricultural water use efficiency in combination with fast growing industrial and urban water demand are contributing to groundwater depletion at an unsustainable rate. The main objective of this study was to develop and evaluate a groundwater modeling system using MODFLOW-2000 for the CAR. Predicted groundwater levels were compared with measured data collected from observation wells between 1954 and 2004. Performance statistics indicated that the model performed well in simulating historic groundwater levels in the central part of the CAR where irrigated agriculture is concentrated. However, further improvements in the conceptual model may be needed to improve predictions in other parts of the CAR.

INTRODUCTION

Water availability, cost, and policy combined with technology development adopted in the near future will shape the rural landscape in the coming decades. This is particularly true in the case of Calera Aquifer Region (CAR) located in the central portion of the State of Zacatecas, Mexico. With 300,000 inhabitants (27% of Zacatecas State population), the CAR accounts for 13% of the total employment and 73% of the gross domestic products produced in the State of Zacatecas. Unfortunately, limited data and planning tools are available for local governmental/nonprofit agencies in the CAR to evaluate alternatives and develop strategies for sustainable progress of the region. Furthermore, there is only a limited integrated effort to protect Zacatecas' most valuable resource, the Calera Aquifer.

The Calera Aquifer is the only water resource in the CAR (CONAGUA 2007) and provides drinking water for the State Capital, the City of Zacatecas. The CAR is a closed basin with an area of approximately 2,087 km^2 (CONAGUA, 2009). The most economically important activity in the CAR is irrigated agriculture, followed by mining and industry. Agricultural irrigation accounts for 80% of the total water extracted from the aquifer. Growing urban areas account for another 16% of groundwater use. Limited rainfall and low water use efficiency, due to lack of technologies or inefficient water management practices, in combination with a rapidly expanding urban population and a growing industrial water demand, has contributed to unacceptable rate of water table decline (0.4 to 1.15 m per year) in the groundwater levels (CONAGUA, 2002) with an aquifer storage depletion.

Rivera (2000) reported that there are problems in obtaining drinking water in the Zacatecas urban area, which are solved systematically by drilling new and deeper wells. This study also noted that there is no long-term vision for managing the Calera Aquifer. However, there is consensus about the fact that overexploitation of groundwater is producing undesirable short- and long-term consequences. The concern is that diminishing groundwater supplies in the CAR would severely reduce regional crop and industrial production, which in turn reduces the economic activity in the region and decreases water availability for urban use.

The Ogallala Aquifer Region (OAR) in the Central United States covering the Texas High Plains and parts of seven other states is also experiencing groundwater declines at an unsustainable rate. In 2003, the U.S. Congress authorized the OAR Program to develop strategies at farm, district, and regional scales to improve the sustainability of the OAR, particularly for the Texas High Plains and Kansas. The OAR is a multi-institution research effort consisting of more than 100 researchers. Therefore, there is an opportunity for researchers from the U.S. and Mexico to collaborate on similar research goals to develop technological tools and to provide better decision support to the many organizations and individuals who must develop and implement policy to reduce groundwater depletion in both regions and countries and to foster stronger international relationships. Thus, the main goal of this US-Mexico joint study is to develop improved information to support decision- making regarding groundwater management in the Calera Aquifer Region of Zacatecas, Mexico. The specific objective of this study was to develop and calibrate an integrated regional groundwater model using observed groundwater levels between 1954 and 2004.

MATERIALS AND METHODS

Study Area

This study is geographically limited to the Calera Aquifer Region that includes General Enrique Estrada and Morelos Municipalities and partial areas from Calera, Fresnillo, Pánuco, Veta Grande and Zacatecas Municipalities (See Figure 1). The study area occupies 2,087 km^2 equivalent to 2.8% of Zacatecas State. The CAR is a closed basin and all waterways are non-perennial streams (Nuñez et al., 2004). Therefore, there are no major reservoirs or rivers in the study area except Santa Ana Lake.

Climate. The climate in the CAR is semi-arid with an annual average rainfall of 411 mm for the period of 1958 to 2000, which was computed from Calera and Fresnillo weather stations (see Figure 1; Nuñez et al., 2004). Annual average temperature for the same period is 16^oC and May and June are the warmest months of the year whereas January is the coldest month of the year. Precipitation varies from 400 mm yr^{-1} in the northeast edge to 450 mm yr^{-1} in the southwest end of the study area (SAGARPA-SEDAGRO-UAZ, 2010). Mean annual pan evaporation is 1,990 mm, which corresponds to more than three-fold average precipitation and leaves little water for recharge in the groundwater system. Surface water availability is limited because water evaporates quickly due to the dry climate.

Geology. Calera Aquifer is considered as an unconfined aquifer (Navarro et al., 2005). It was formed by alluvial and lacustrine deposits of clay, silt, sand, gravel, and gravel-sand conglomerates cemented with calcareous clay (Villalpando et al., 2005). Lithology of the CAR rocks are polymictic conglomerates from the Quaternary period merged to igneous and metamorphic fractured rocks from the Triassic and Cretaceous periods by tectonic movements. Geologic profiles were obtained from Nuñez (2003) and they do not cover the zone for and from Santa Ana Lake to the north. Groundwater flow direction is mainly from south to north discharging toward Santa Ana Lake (see Figure 1).

Estimation of saturated thickness of the Calera Aquifer indicates that maximum saturated thickness ranges from 38 m in the north to 570 m in the central area of CAR (Nuñez, 2003). Hydraulic conductivity varies from 10^{-8} to 10^{-5} m s^{-1} and specific yield from 0.01 to 0.5 in the study area (CONAGUA, 1996). Aquifer base varies in elevation from approximately 1,620 m above mean sea level (MSL), on the south-central area of the CAR, to approximately 2,125 m above MSL, in the west central area.

Agriculture. Land use in the study region includes cropland, managed under irrigated and dry land conditions, and rangeland. The main crops in the region are red dry pepper, corn, garlic, onion, dry beans, oats, peaches, and forages such as alfalfa and grasses for hay production. According to 1992 water use census (CONAGUA, 2009), about 125 Mm^3 (or 125 GL) of groundwater is withdrawn per year and 100 Mm^3 (or 100 GL) is withdrawn for irrigation purposes, about 20 Mm^3

(or 20 GL) is withdrawn for municipal purposes, leaving 5 Mm^3 (or 5 GL) for other uses such as livestock, and mining. The dominant land uses obtained from an irrigated area map using Landsat 5 Thematic Mapper imagery developed for this study for August 13, 2010 showed 47% rangeland and 52% cropland leaving 1% for other uses (see Figure 2).

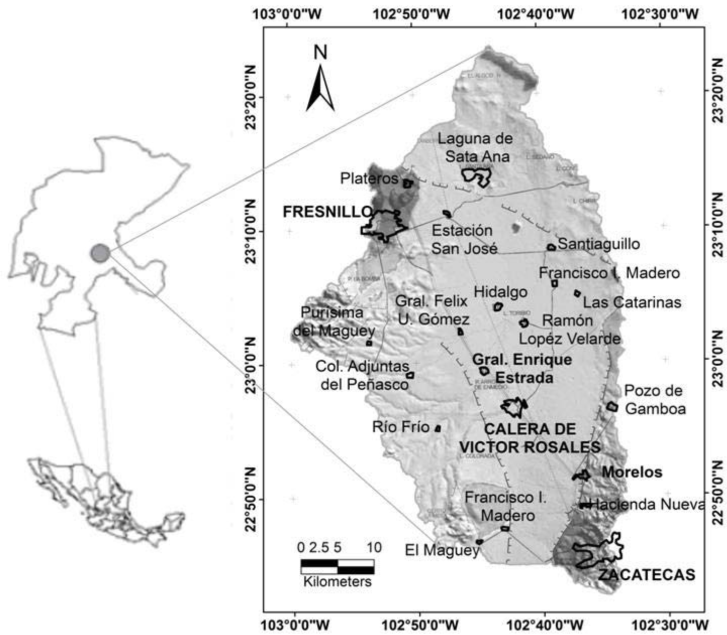

Figure 1. Calera Aquifer Region and main locations.

Water levels. Water table change for the period of 1980 to 1994 (CONAGUA, 2002) showed depletions of about 5 m in areas close to aquifer's natural boundaries, near Santa Ana, Santiaguillo, Morfín Chávez, and Las Catarinas towns (see Figure 1) in the north and close to Enrique Estrada, Noria-Los Gringos, and Pozo de Gamboa towns in the southern portion of the CAR. Major depletions of 15 m or more were recorded in the central-north area of the valley where large numbers of irrigation wells are located. Overall, the average depletion rate for the period of 1980 to 1994 was estimated between 0.4 and 1.15 m y^{-1}. Groundwater levels registered in 1997 indicate that depth to groundwater level was about 20 m in the north and 40 to 50 m in the central area. Recent studies concluded that aquifer recharge was about 100 Mm^3 y^{-1} and groundwater withdrawals were estimated at 180 Mm^3 y^{-1} (CONAGUA, 2009). Monitoring wells for registered groundwater levels used for this study are concentrated in the valley area and mostly to the central east side (see Figure 2). It is worth mentioning that there is absence of monitoring wells in the north area specifically.

Wells. In the 1930's, water tables discovered close to the surface were exploited using "norias" (a water scoop wheel) and a few wells were perforated due to realization of presence of water ponding (Magallanes, 1993). In the 1950's, the aquifer exploitation for agricultural purposes became more intensive. In 1954, the first observation well network was established and it was composed of 21 wells. The Secretary of Agriculture and Hydraulic Resources Office (SARH from Spanish acronym and currently CONAGUA) performed the first Calera Aquifer hydrogeological study in 1968 (SARH, 1968) including geomorphologic, geologic, and hydrogeological descriptions for geologic units, total withdrawal estimation, water table elevation, hydraulic parameters, and recharge estimations. The study from 1968 concluded that aquifer recharge was approximately 100 $Mm^3\ y^{-1}$, groundwater withdrawals were estimated to be 180 $Mm^3\ y^{-1}$, and these values were similar to 2009 estimates by CONAGUA (CONAGUA, 2009).

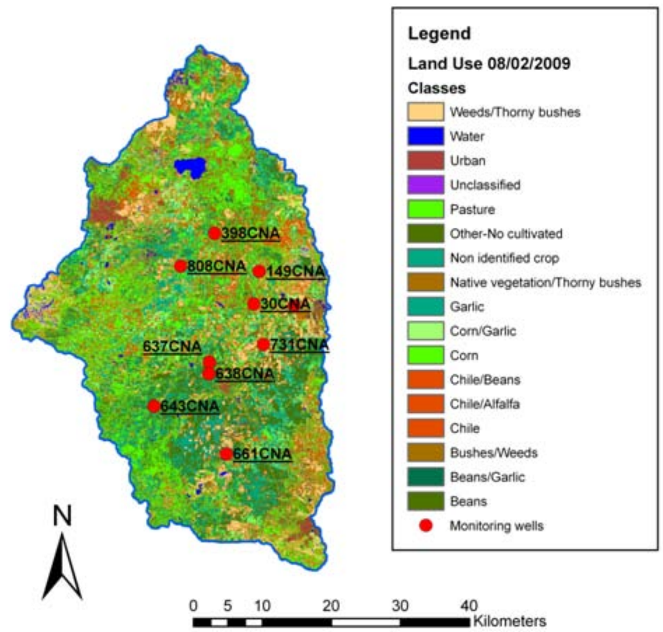

Figure 2. Land use map and location for monitoring stations.

Groundwater exploitation census performed on 1992 (CONAGUA, 1992) showed the existence of 1,190 active wells, which were identified as 868 pumping wells and 322 artesian wells; and 198 non-operating wells. Groundwater from 1,081 active wells was for agriculture use, 59 wells for urban water supply, 36 wells for domestic grazing, and 14 wells were for industrial use. Total withdrawal was quantified as 125 $Mm^3\ y^{-1}$ according to the census and in terms of volume 79.4% (99 $Mm^3\ y^{-1}$) of pumped water corresponded to agricultural use, 15.8% (20 $Mm^3\ y^{-1}$) was for urban water supply, 4.8% (6 $Mm^3\ y^{-1}$) was for industrial use, and less than 0.5% (0.04 $Mm^3\ y^{-1}$) for domestic grazing.

Historically, groundwater in the study area was not exploited extensively until the mid 20th century (Magallanes, 1993) and there is no registered information for early exploitation wells. Based on the assumption that aquifer exploitation was not perceptible before 1954, the aquifer was considered in natural equilibrium for modeling purposes. The period before 1954 will be referred from now on as the predevelopment period. After 1954, the anthropogenic groundwater exploitation changed through time. The exploitation period will be referred from now on as the period of 1954 to 2004 for the purpose of this study. Calibration of the groundwater model for the study area was performed for the period of 1954 to 1990.

Before the exploitation period, the excess groundwater from the Calera Aquifer discharged naturally by seepage to streams and springs. These discharges were diminished during drought periods and natural groundwater levels remained constant until the next rainy season, repeating the cycle. According to this premise, the Calera Aquifer can be considered naturally in equilibrium before 1954, obtaining recharge from precipitation and withdrawing water by means of evapotranspiration from plants, stream flows, and spring discharge and keeping groundwater levels stable. This described hydraulic performance can be assimilated to a steady-state water flow and the steady-state aquifer model used for this period represents it. The difference between aquifer behaviors for exploitation and predevelopment periods is the effect of pumping water from the aquifer for human use. This variability is assimilated into a hydraulic transient-flow. Therefore, the exploitation period is represented in the model by a transient model.

Conceptual Model. A conceptual model has been created to represent the aquifer system beneath the Calera Aquifer Region. The area was partitioned into a 500 x 500 m grid and natural boundaries of the aquifer were used for defining the spatial extent of the model. The groundwater divide was defined as a no-flow boundary condition. The MODFLOW model requires the definition of at least one active cell containing a head dependent boundary for finding a solution for steady-state flow. A general dependent flow boundary corresponds to a cell that flows from or to an external source proportionally to the head difference between the cell and the head assigned to the external source. For Santa Ana Lake, dry-season water level was used as a dependent flow boundary with a static head of 2,047 m above MSL (Gaytán et al., 2006).

Pumping for irrigation purposes is the primary mechanism used for aquifer discharge, whereas precipitation is the main mechanism for recharge, the latter representing a small proportion because of high evaporation from the soil and transpiration from plants. A total of 1,921 exploitation wells were included in the model and data were obtained from the Public Office for Water Rights Registry (REPDA from Spanish acronym) database (CONAGUA, 1996 & 2009). Groundwater exploitation rates ranged from 40 to 136 Mm^3 y^{-1} for years 1955 and 2007, respectively. Recharge rates were adopted as 5% of the annual average precipitation that corresponds to 20 mm y^{-1}. Recharge was applied over the first active layer in the model. The dry cell wetting options were set to keep a minimum saturated thickness of 5 m for the bottom layer.

Model Calibration. Data from ten monitoring stations were used to calibrate the model for the exploitation period (1954-2004). Historically, registered groundwater levels were available for only the central portion of the Calera Aquifer and was used in the model calibration. Therefore, results should be considered representative for the central area and results for the remainder of the study region should be used with caution. Multiple computer simulations were performed modifying parameters and adjusting the conceptual model. Calibration of the model was performed by comparing results to observed groundwater levels for 1954, 1980, 1985, and 1990.

Hydraulic conductivity was adjusted to reduce the differences between historical and simulated water levels.

A statistical analysis was performed to evaluate model performance by quantifying differences between simulated and historical groundwater levels for the exploitation period. Statistics used for this purpose were the coefficient of determination (r^2), Root Mean Square Error (RMSE), and Normalized Root Mean Square Error (NRMSE).

RESULTS AND DISCUSSION

Historical and simulated groundwater levels were compared as shown in Figure 3. The MODFLOW model grossly overestimated groundwater levels for the northern-most part of the CAR. This may be due to the narrow geomorphology and uncertainty associated with geologic parameters used in the development of the conceptual model. Therefore, it was decided to make this zone inactive for model performance and evaluation purposes. For this reason, there are no contour lines drawn in Figure 3 for this zone.

Predevelopment period results obtained by comparing observed and simulated groundwater levels produced low correlation, with a coefficient of determination of 0.63 and high RMSE and NRMSE of 43.6 m and 34%, respectively. We speculate that these results are indicative of the low quality historical data. Historical groundwater levels for year 1954 ranged from 2,047 to 2,174 m above the MSL and simulated groundwater levels for the same year ranged from 2,093 to 2,118 m above the MSL, showing smaller variations in groundwater levels. In other words, the model is not reproducing the groundwater level variability along the whole CAR for predevelopment period. However, one can expect smaller variations in the groundwater levels during 1954 when there were no exploitation wells, or few exploitation wells, for irrigation purposes.

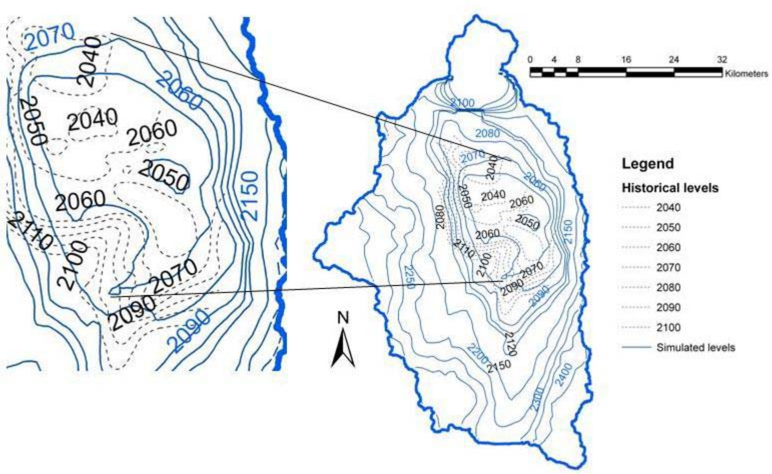

Figure 3. Historical and simulated groundwater levels (m above MSL).

Hydraulic conductivity was adjusted for calibration because during the process there were some cells that presented large discrepancies between historical and simulated water levels. The adjustment applied was up to two orders of magnitude in some cases. The model produced the best results for the year 1990, which is the last year of calibration, with a high coefficient of determination of 0.87 and the minimum RMSE and NRMSE of 28.0 m and 21%, respectively. Historical groundwater levels for year 1990 ranged from 2,039 to 2,172 m above the MSL and simulated groundwater levels for the same period ranged from 2,055 to 2,124 m above the MSL (see Figure 3). This clearly indicated that the model captured the observed variability in groundwater levels in 1990 better than that in 1954.

For the calibration period (1954-1990), simulated groundwater levels accounted for 80% of the variation in the observed groundwater levels. The RMSE and NRMSE values for that period were 34.3 m and 27%, respectively. In every year, the model consistently under predicted the groundwater levels for stations 643CNA, 661CNA, 637CNA, and 638CNA (see Figure 2 for locations). These stations are located in the southwest area of the CAR. Some observation stations located in the northeast part of the study area over predicted groundwater levels. For example, the well 149CNA over predicted observed groundwater levels for year 1980, 30CNA for year 1985, and 117CNA, 808CNA, and 30CNA for 1990. However, the model predicted the best for observation wells located in the central part of the study area where most of the exploitation wells are concentrated to support irrigated agriculture.

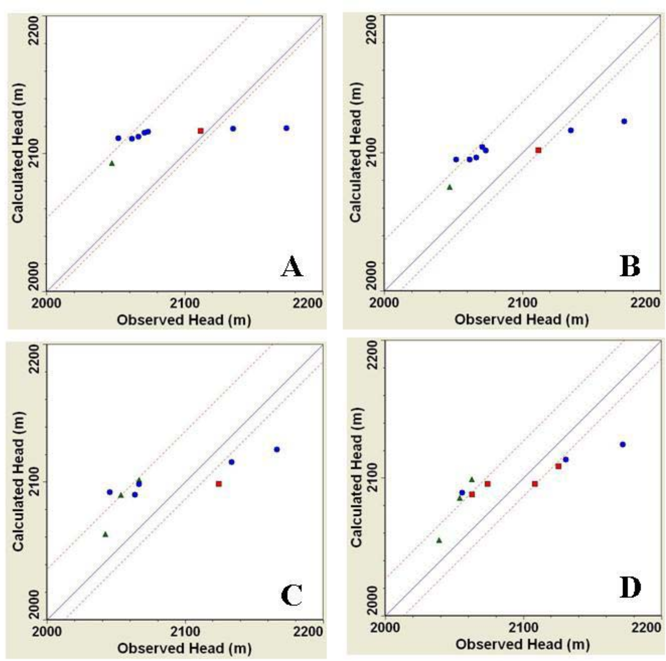

Figure 4. Calculated and observed groundwater levels for years (A) 1954 (B) 1980 (C) 1985 (D) 1990. Dotted lines represent 95% confidence interval.

Water balance was checked for the entire model. The difference between total volume of water entering and leaving the system, as a percentage, was 0.3% showing very good agreement between inflow and outflow. The general performance of the model is satisfactory according to results and statistical analyses that are presented in Table 1.

Table 1. Statistics for the Calibration Period.

Year	Total Observations	r^2	RMSE	NRMSE
1954	9	0.63	43.6 m	34%
1980	9	0.87	32.6 m	26%
1985	9	0.81	33.0 m	26%
1990	10	0.87	28.0 m	21%
Average	9	0.80	34.3 m	27%

SUMMARY

A groundwater model for the Calera Aquifer Region (CAR) in Central Mexico was developed and calibrated using observed groundwater level data. Calibration of the conceptual model was performed by adjusting the sensitive parameters such as hydraulic conductivity and recharge. Multiple computer simulations were performed to match simulated values to historical groundwater levels. Performance statistics indicated that simulated groundwater levels followed trends and magnitudes in the observed historical groundwater levels in the underlying Calera Aquifer. Overall, calibration results yielded coefficients of determination greater than 0.63 and NRMSE values lower than and equal to 34% indicating good agreement between the predicted and observed groundwater levels. Thorough investigation is needed to further improve the conceptual groundwater system of the Calera Aquifer Region. Improved model is expected to be used for evaluating alternative groundwater management policies for their impact on sustainability of the Calera Aquifer.

Acknowledgements

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