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Jairo E. Hernández
Boise State University

Prasanna H. Gowda
USDA-ARS-Conservation and Production Research Laboratory

Terry A. Howell
USDA-ARS-Conservation and Production Research Laboratory

Jean L. Steiner
USDA-ARS-Grazinglands Research Laboratory

Francisco Mojarro
Universidad Autónoma de Zacatecas

See next page for additional authors

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Modeling Groundwater Levels on the Calera Aquifer Region in Central Mexico Using ModFlow

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

1. Department of Civil Engineering, Boise State University, Boise, ID 83725-2060, USA

2. USDA-ARS-Conservation and Production Research Laboratory, Bushland, TX 79012-0010, USA

3. USDA-ARS-Grazinglands Research Laboratory, St. El Reno, OK 73036, USA

4. Universidad Autónoma de Zacatecas, Zacatecas, C.P. 98000, México

5. Universidad Autónoma de Zacatecas, Calzada de la Universidad 108 Col Progreso, Zacatecas, C.P. 98058, México

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Abstract: A conceptual model for the Calera Aquifer has been created to represent the aquifer system beneath the Calera Aquifer Region (CAR) in the State of Zacatecas, Mexico. The CAR area was uniformly partitioned into a 500 × 500 m grid generating a high resolution model that represented the natural boundaries of the aquifer. A computer model was calibrated and validated to verify output from the model corresponding to situations that matched the historical aquifer performance. Predicted groundwater levels were compared with measured data collected from nine observation wells between 1954 and 2004 to evaluate model performance. The main objective of this study was to develop and evaluate a groundwater modeling system using ModFlow-2000 for the CAR. Performance statistics indicated that the model performed well in simulating historic groundwater levels in the central part of the CAR where irrigated agriculture was concentrated. Results evaluation yielded average coefficients of determination of 0.81 and 0.67 and root mean square error values lower than 25.1 m and 25.9 m for the calibration and validation processes, respectively. These results are indicative of a good agreement between predicted and observed groundwater levels. However, further improvements in the conceptual model may be needed to improve predictions in other parts of the CAR for evaluating alternative groundwater management strategies.

Key words: Water management, irrigation, groundwater modeling, ModFlow, Calera aquifer.

1. Introduction

Water availability and groundwater management policies, combined with water saving technology adopted in the future, will shape the rural landscape in the coming decades. This is particularly true in the case of the 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 made in the State of Zacatecas. The Calera Aquifer is the only water resource in the CAR [1] and provides drinking water for the State Capital, the city of Zacatecas. Irrigated agriculture is the most important economic activity in the CAR followed by mining and industry. Agricultural irrigation accounts for 80% of the total water extracted from the Calera 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

Corresponding author: Jairo E. Hernández, Ph.D., research fields: remote sensing for surface-groundwater interactions, reservoir system optimization, water resource management, artificial intelligence, computer modeling for water resources. Email: jairohernandez@boisestate.edu.

industrial water demand, has contributed to unacceptable rate of water table decline (0.4 to 1.15 m per year) in the Calera's groundwater levels [2].

The Precious Metal Mexican Mining Company announced that they are expanding silver exploitation to produce 42 to 43 million ounces in 2011, becoming the world largest silver producer, and most of this production will come from Fresnillo mines located within the CAR (http://www.fresnilloplc.com/ operations/). Current and future management of the aquifer will determine whether it remains as a sustainable source of water for drinking water, industry and irrigated agriculture. Further, changes in the climate may also alter its sustainability.

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. Zacatecas urban areas had problems in obtaining drinking water [3], which were solved systematically by drilling new and deeper wells with no long-term vision for managing the Calera Aquifer. However, Rivera [3] also noted that there is consensus about the fact that overexploitation of groundwater is producing undesirable short- and long-term consequences. Furthermore, there is only a limited integrated effort to protect Zacatecas' most valuable resource, the Calera Aquifer. 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 from USDA-ARS Laboratories in Bushland and Lubbock, Texas, Kansas State University, Texas A&M University, West Texas A&M University, and Texas Tech University. Therefore, there is an opportunity for researchers from the United States of America and Mexico to collaborate on similar research goals. The main goal of this U.S.-Mexico joint study is to develop technological tools and to provide better decision support to the many organizations and individuals who must develop and implement policies to manage groundwater resources in both regions and countries and to foster stronger international relationships. The specific objective of this study was to develop and calibrate an integrated regional groundwater model using observed groundwater levels between 1954 and 2004.

2. Materials and Methods

2.1 Study Area

This study is geographically limited to the CAR that includes General Enrique Estrada and Morelos Municipalities, and partial areas from Calera, Fresnillo, Pánuco, Vetagrande, and Zacatecas Municipalities (Fig. 1). The study area occupies 2,056 km^2 equivalents to 2.8% of Zacatecas State. The CAR is a closed basin and all waterways are non-perennial streams [4]. Therefore, there are no major reservoirs or rivers in the study area except Santa Ana Lake.

2.1.1 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 [4]. Precipitation varies from 400 mm yr^{-1} in the Northeast edge to 450 mm yr^{-1} in the Southwest end of the study area [5]. Annual average temperature for the same period is 16 ^{o}C, and May and June are the warmest months of the year whereas January is the coldest month of the year. Mean annual class A-pan evaporation is 1,990 mm, which is more than four-fold average precipitation in the CAR and

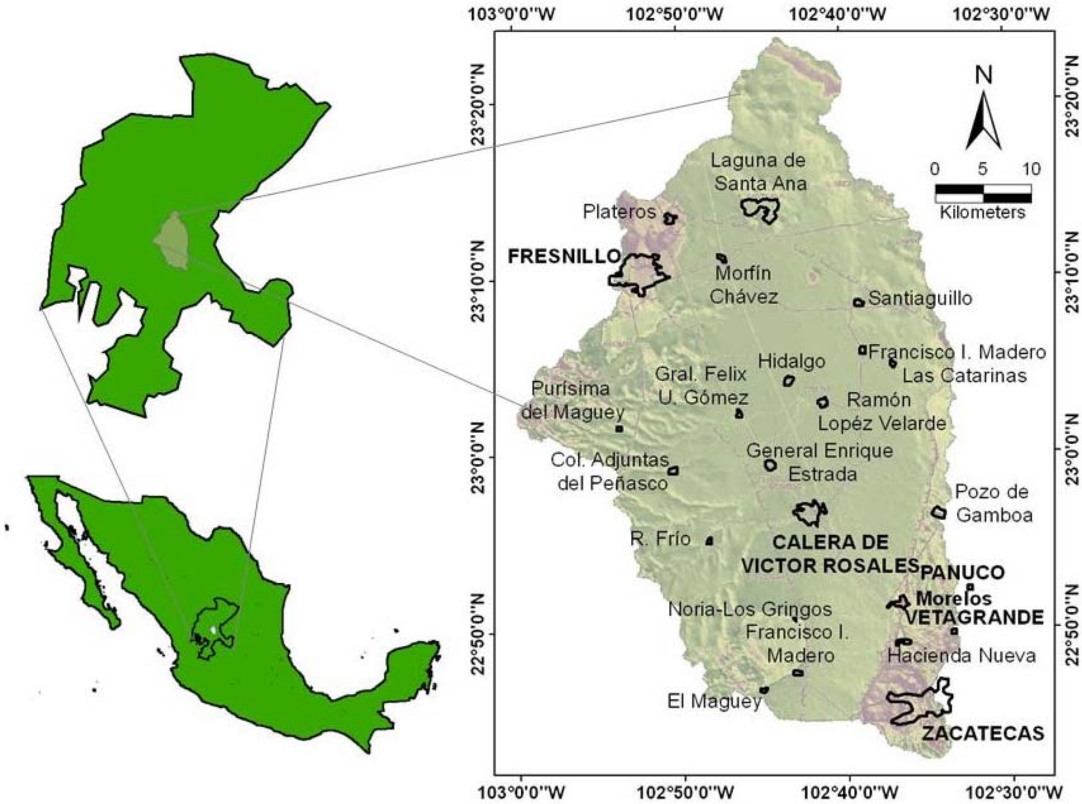

Fig. 1 Calera Aquifer Region and main locations.

leaves little water for groundwater recharge. Surface water availability is limited because water evaporates quickly due to the dry climate.

2.1.2 Geology

Calera Aquifer is considered as an unconfined aquifer [6]. It was formed by alluvial and lacustrine deposits of clay, silt, sand, gravel, and gravel-sand conglomerates cemented with calcareous clay [7]. 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 for this model were obtained from a Master's thesis [8] 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 [8].

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 [8]. 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 [9]. 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.

2.1.3 Agriculture

Land use in the study region includes cropland, managed under irrigated and dry land conditions, and rangeland. The main crops in this 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 [10], 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 2, 2009 showed 47% rangeland and 52% cropland leaving 1% for other uses (Fig. 2).

2.1.4 Groundwater

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 impounding [11]. According to the same reference, in the 1950s, the aquifer exploitation for agricultural purposes became more intensive and there was no registered information for early exploitation wells. 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.

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 [12] 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} [10].

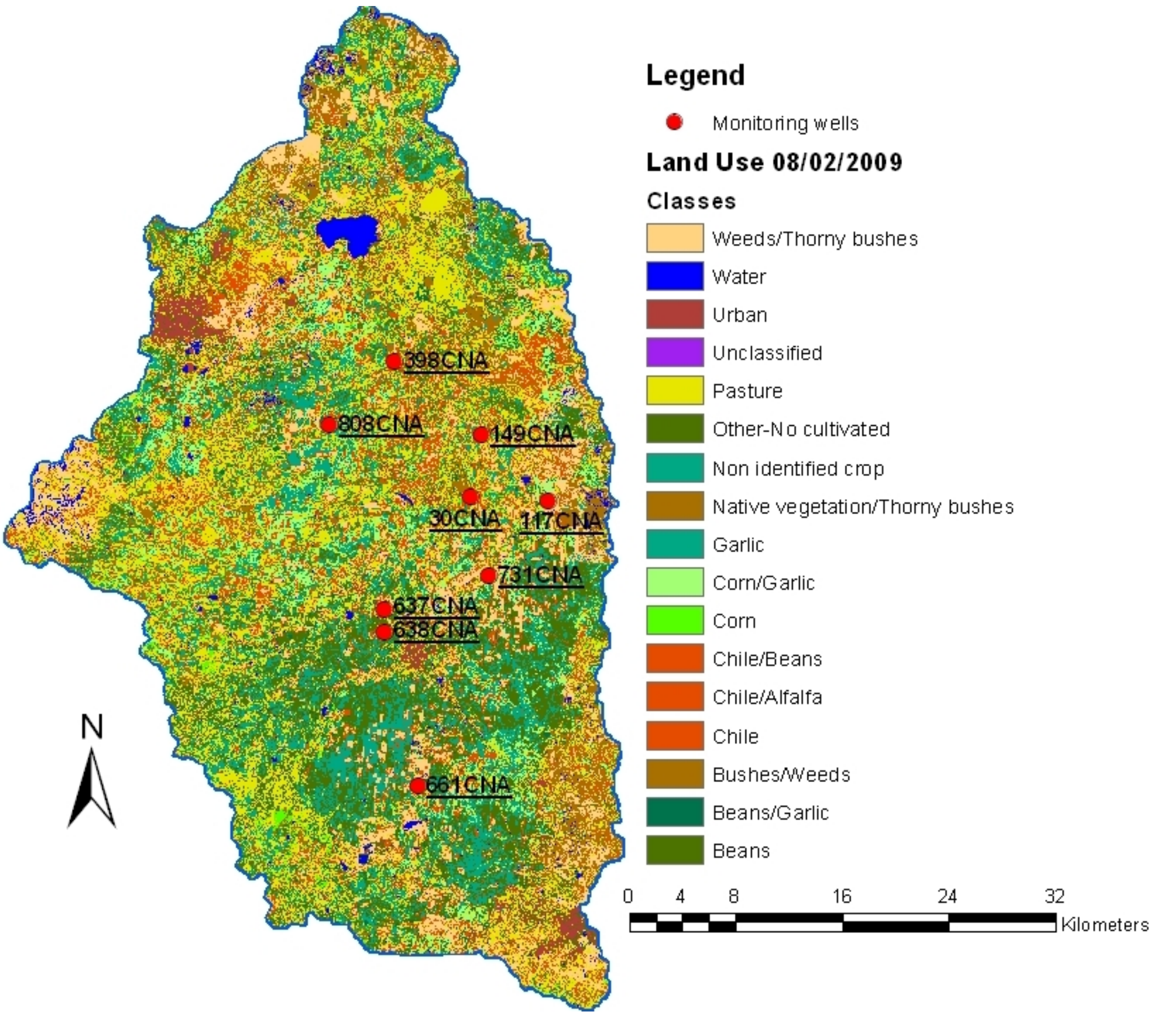

Fig. 2 Land use map and location for monitoring stations.

Water table change for the period of 1980 to 1994 [2] showed depletions of about 5 m in areas close to aquifer's natural boundaries, near Santa Ana, Santiaguillo, Morfín Chávez, and Las Catarinas towns (Fig. 1) in the North, and close to General 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}.

Additionally, groundwater levels registered in 1997 indicated that depth to groundwater level was about 20 m in the north and 40 to 50 m in the central area [10]. Monitoring wells for registered groundwater levels used for this study are concentrated in the valley area (Fig. 2). It is worth mentioning that there are no monitoring wells in the Northern portion of the CAR.

Groundwater exploitation census performed in 1992 [13] 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.

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.

2.2 Conceptual Model

A conceptual model has been created to represent the aquifer system beneath the CAR. The area was partitioned into a 500 × 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 [14].

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. A total of 1,921 exploitation wells were included in the model (Fig. 3), and data were obtained from the Public Office for Water Rights Registry (REPDA from Spanish acronym) database [9, 10]. 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

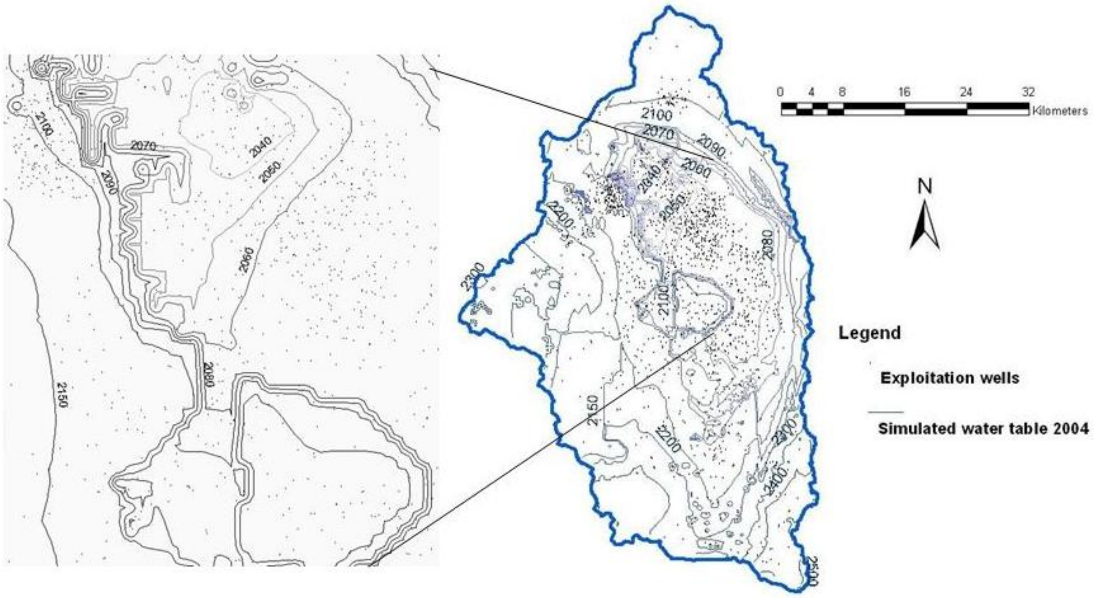

Fig. 3 Exploitation wells and simulated water table for the year 2004 (m above MSL).

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 to avoid mathematical instability represented by cycles of wet-dry-wet cells.

2.3 Model Calibration and Validation

Calibration of the model was done to verify that output from the model was corresponding to situations that matched the historical aquifer performance for an *a posteriori* validation process. Multiple computer simulations were performed to match historical groundwater levels by means of parameter modification and conceptual model adjustment. Model validation was performed by one simulation with no modification to the conceptual model or to the parameters. The validation process was evaluated by comparing the predicted groundwater levels against observed data.

Data from nine monitoring stations were used to calibrate the model for the period (1954-1990). Historically, registered groundwater levels were available for only the central portion of the Calera Aquifer. Therefore, results should be considered representative for the central area and results for the remainder of the study region should be used with caution. Calibration of the model was performed by comparing results to observed groundwater levels for 1954, 1980, 1985, and 1990. Hydraulic conductivity was used as major calibration parameter to adjust large discrepancies between historical and predicted groundwater levels. The adjustment applied was up to two orders of magnitude in some cases.

The validation process was performed by comparing results yielded from the model with recorded groundwater levels for years 1997 and 2004. Registered historical data from monitoring locations in the study area were used for this purpose. A statistical analysis was done to evaluate model performance by quantifying differences between simulated and historical groundwater levels for both calibration and validation processes. Statistics used for this purpose were the coefficient of determination (r^2), Root Mean Square Error (RMSE), and Normalized Root Mean Square Error (NRMSE). Uncertainty was evaluated computing confidence intervals at a 0.05 significance level. Finally, the water balance was checked for differences between the volume of water that is leaving and entering into the system.

3. Results and Discussion

Historical and simulated groundwater levels were compared for calibrating and validating the ModFlow-based conceptual model. The model largely overestimated groundwater levels for the northern-most part of the CAR. This may be due to the narrow geomorphology and the 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. Consequently, there are no contour lines shown in Fig. 3 for this zone.

For the calibration period (1954-1990), simulated groundwater levels accounted for 81% of the variation in the observed groundwater levels. The RMSE and NRMSE values for that period were 25.1 m and 25%, respectively (Table 1). For all calibration years (1954, 1980, 1985, and 1990), the model consistently under predicted the groundwater levels for station 661CNA (Fig. 4A). Groundwater levels at stations 637CNA and 638CNA were under predicted for years 1985 and 1990, respectively (see Fig. 2 for locations). These stations were located along the south-central part of the CAR. The model over predicted groundwater levels are for locations 149CNA for the year 1980, 30CNA for years 1985 and 1990, and 117CNA for the year 1990. All these stations were located in the east-central part of the study area.

The first year for model calibration was the year 1954 and results, obtained by comparing observed and simulated groundwater levels, produced acceptable correlation with a coefficient of determination of 0.80 (Table 1). The RMSE and NRMSE were 27.6 m and 30%, respectively. 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 2,079 to 2,118 m above the MSL, indicating good performance by the model in predicting groundwater levels.

Table 1 Statistics for the calibration and validation periods.

Year	Total observations	r^2	RMSE (m)	NRMSE (%)
CALIBRATION PERIOD				
1954	9	0.80	27.6	30
1980	9	0.87	29.1	23
1985	8	0.74	24.5	27
1990	9	0.81	19.2	21
Average	9	0.81	25.1	25
VALIDATION PERIOD				
1997	8	0.75	25.3	25
2004	4	0.59	26.4	87
Average	6	0.67	25.9	56

The model produced best calibration results for the year 1990 with RMSE and NRMSE of 19.2 m and 21%, respectively, and a coefficient of determination of 0.81. 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 2,175 m above the MSL. This clearly indicated that the model captured the observed variability in groundwater levels in 1990.

For the validation period (1991-2004), simulated groundwater levels accounted for 67% of the variation in the observed groundwater levels. The RMSE and NRMSE values for that period were 25.8 m and 56%, respectively (Table 1). The model under predicted the groundwater levels for locations 637CNA, 638CNA, and 661CNA for the year of 1997. These stations were spread over the southern portion of the CAR.

The model over predicted groundwater levels at 117CNA and 30CNA for year 1997 during the validation period. These stations were situated close one to the other in the central part of the CAR. Data from only four stations were available for the validation year of 2004. The model over predicted groundwater levels for all these four locations (Fig. 4B). Even though the NRMSE for year 2004 was high (87%), the maximum residual was 34 m. This result is not far from 25 m that is the average RMSE for the calibration process. We speculated that the 2004 model performance might have resulted from an incomplete database for exploitation wells or water demand.

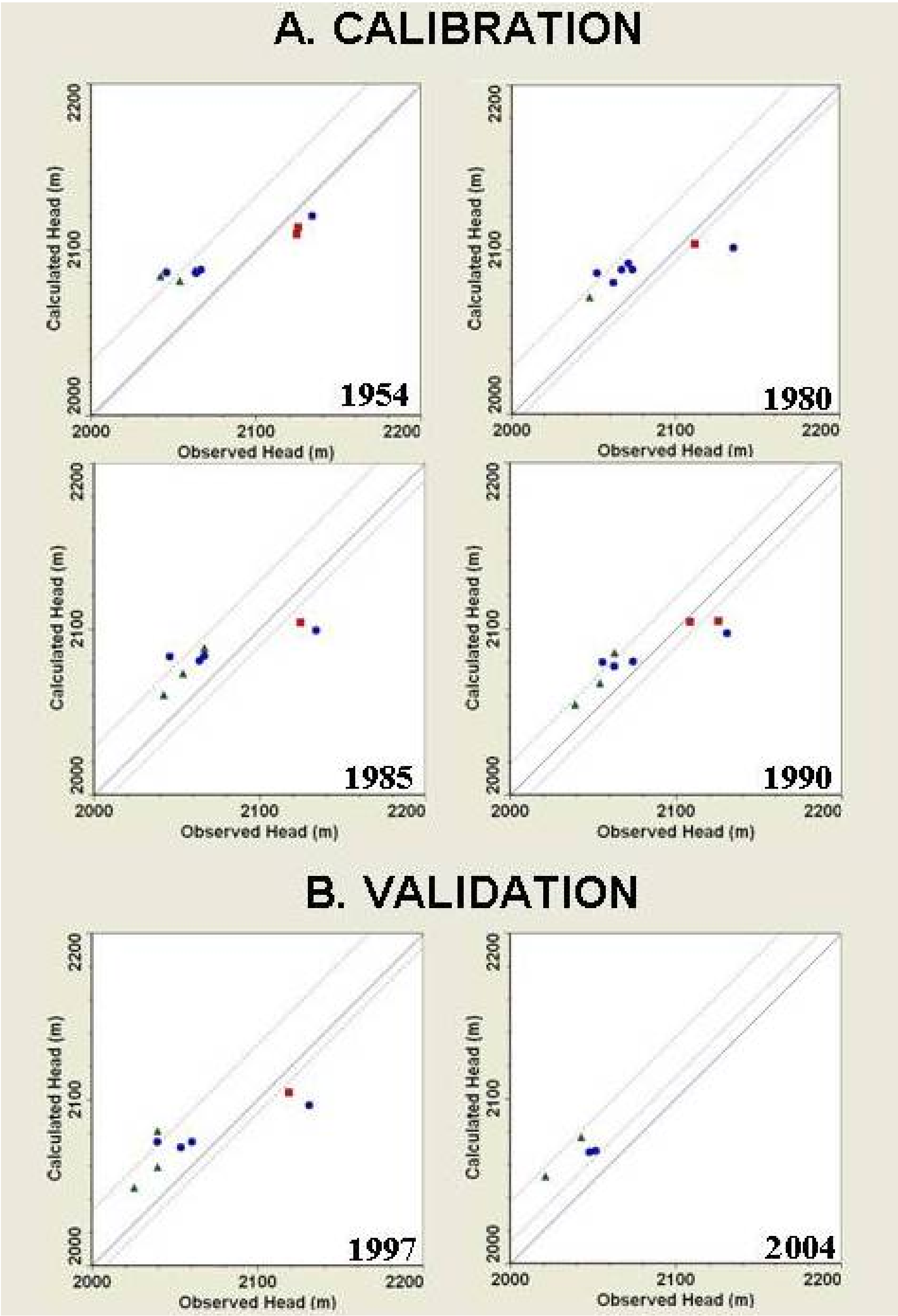

Fig. 4 Calculated and observed groundwater levels for model (A) Calibration and (B) Validation. Dotted lines represent 95% confidence interval and solid line indicates a 1:1 line.

Previous description represents weaker points for the calibration and validation processes. It is noteworthy to mention that the rest of the points are located inside the 95% confidence interval. A balance for water volume was also checked for the entire model. The difference between the total volume of water entering and leaving the system was 1%, showing very good agreement between inflow and outflow. Statistical results indicated that the performance of the model was satisfactory (Table 1). Overall, the model was over predicting groundwater levels for the central part of the study area, whereas the Southern part experienced under prediction of groundwater levels.

4. Conclusion

A groundwater model for the Calera Aquifer Region (CAR) in the Central Mexico was developed, calibrated, and validated using observed groundwater levels for the period of 1954-2004. Calibration of the conceptual model was performed by adjusting the input parameters such as hydraulic conductivity and recharge rates. Multiple computer simulations were performed to calibrate and validate the ModFlow-based conceptual model. 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 average coefficients of determination of 0.81 and 0.67 and RMSE values lower than and equal to 25.1 m and 25.9 m for the calibration and validation processes, respectively. These results are indicative of a good agreement between predicted and observed groundwater levels. Comprehensive investigation of the northern part of the CAR 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.

Acknowledgments

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