Geofísica Internacional (2015) 54-3: 199-220

Original paper

Assessment of groundwater flow in volcanic faulted areas. A study case in Queretaro, Mexico

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Received: January 15, 2013; accepted: September 24, 2014; published on line: June 30, 2015

DOI: 10.1016/j.gi.2015.04.016

Resumen

En este trabajo se integra la estratigrafía local y fallas como restricciones para un modelo numérico de flujo del agua subterránea en la parte norte del acuífero fallado del Valle de Querétaro. La información geológica de base fue establecida a partir de la reinterpretación de registros litológicos de pozos, datación isotópica 40Ar*/39Ar de rocas y cartografía de campo. En particular, la datación isotópica permitió obtener el tiempo de emplazamiento de un dique magmático a lo largo de la falla de El Nabo. El aumento de la tasa de flujo y la temperatura en el pozo El Nabo sugieren que la falla y el dique transportan un flujo regional. Un modelo numérico fue implementado para evaluar las contribuciones de fallas y estructuras volcánicas en el flujo general de agua subterránea. El modelo realizado con el software Visual-Modflow y código Modflow 2000 fue parcialmente restringido por los resultados de una prueba de bombeo en pozo "El Nabo", el pozo más profundo (Lat. 20 ° 42 '14 "N, Long. 100 ° 28'45" O, aproximadamente de 1000 m de profundidad) ubicado en la zona de Querétaro. La interpretación de los resultados del modelo y las observaciones de campo sugieren que las fallas reciben un flujo regional, compartimentalizan el sistema, y son responsables de un importante aumento del gasto, de 6 a 47 l/s, cuando se la perforación del pozo El Nabo bajo de 850 m profundidad. El estudio que aquí se presenta permite la evaluación de fallas normales y intrusivos que determinan el flujo del agua subterránea y podría ser relevante para el conocimiento de la dinámica de flujo valles volcánicos cercanos. El modelo numérico implementado basado en información geológica, permitió una mejor comprensión de los sistemas acuíferos complejos, lo que no se puede evaluar por métodos analíticos. Por otra parte puede ser una aplicación útil para una mejor interpretación de pruebas de bombeo y para añadir datos complementarios de otras pruebas y/o de análisis de hidrogeoquímica.

Palabras clave: Flujo de aguas subterráneas, sistema acuífero fallado, modelación numérica, estructuras volcánicas, diques, México.

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Abstract

This work integrates local stratigraphy and faults to constraint a numerical model of groundwater flow in the North area of the Valley of Queretaro aquifer. Basic geological information was established from the reinterpretation of well logs, $^{40}Ar^*/^{39}Ar$ dating of rocks, and field mapping. In particular, dating allowed to obtain the timing of emplacement of a magmatic dyke inferred to be emplaced along the El Nabo fault. The increase of flow rate and temperature in the El Nabo well suggest that the fault and dike transport a regional flow. A numerical model was implemented to evaluate the contributions of faulting and volcanic structures in the overall groundwater flow. The model, accomplished with the *Visual-Modflow* software and Modflow 2000 code, was partially constrained by the results of a pumping test in the El Nabo well, the deepest well (Lat. 20°42'14"N, Long. 100°28'45"W, ca. 1000 m depth) located in the Queretaro area. The interpretation of the model results and field observations suggest that faults collect the regional flow, compartmentalize the reservoir, and are responsible of the dramatic increase of flow rate from 6 to 47 l/s when drilling the El Nabo well below a depth of 850 m. The study presented here allowed the assessment of normal faults and intrusives determining groundwater flow and might be relevant to the knowledge of flow dynamics in nearby volcanic valleys. The analysis of the pumping test suggest the presence of two different groundwater flow systems: (1) a flow related with the limestone and shale unit and (2) a regional linear flow through faults. The implemented numerical model, based on geological information, allowed a better understanding of complex aquifer systems that cannot be evaluated by analytical methods. Moreover it can be a useful application for a better interpretation of pumping tests and to add complementary data of other pumping tests and/or hydrogeochemical analysis..

Key words: Groundwater flow, faulted aquifers, numerical modeling, volcanic structures, dykes, Mexicos.

Introduction

Understanding groundwater flow systems is crucial for the management of groundwater resources in Mexico because many areas in arid zones depend on groundwater as the main source for urban, agricultural, and industrial development. In the Valley of Queretaro Aquifer (VQA), many wells are drilled near or along major faults and the high variability of piezometric levels in relatively short distances evidence changes on hydraulic properties (Carreón-Freyre *et al*., 2005; Figure 1). Furthermore, the spatial distribution of extraction wells and drawdown zones in the VQA during the last 30 years suggests that faults compartmentalize the aquifer system (Carreón-Freyre *et al*., 2005). In the VQA, groundwater is extracted from depths greater than two hundred meters; at this depth, geological heterogeneity should be considered for evaluating groundwater flow patterns to allow an accurate estimation of groundwater resources. Thus, the VQA could be considered a faulted aquifer, where faults and fracture zones strongly influence the overall flow dynamics of the system (Caine *et al*., 1996; Allen and Michel, 1999) and the assessment of the hydrogeologic behavior of major structures can be as important as obtaining the hydraulic properties of the stratigraphic sequences. This work examines the role of major structures (e.g., faults and volcanic or plutonic bodies) as hydrogeological independent units, rather than only as hydraulic boundaries, and presents a numerical modeling of the groundwater flow conditions in the faulted VQA. Integration of representative geological data in the model included: (a) vertical variations by assigning a hydraulic conductivity (K) to each geological unit; (b) faults; (c) lateral truncation of the hydro-stratigraphic units and; (d) the presence of intrusive rocks (Walton, 1970; Ingebritsen *et al*., 2006; Zoback, 2007), in particular dikes (Kulkarni *et al*., 2000).

The study area is located in the northwestern part of the VQA system (Figure 1). The Valley of Queretaro is located in the central part of the Miocene to Recent Trans Mexican Volcanic Belt (TMVB; Ferrari, 2000; Alaniz-Alvarez *et al*., 2002) and is delimited by groups of N-S and NE-SW trending faults active at least since the Miocene (Alaniz-Alvarez *et al*., 2001). We aim at having a better understanding on the role of major structures in groundwater flow patterns in the VQA by integrating them in a numerical model.

Faulted aquifer systems

Previous works have documented the variations in hydraulics properties induced by the complex architecture of regional faults (MaClay and Small, 1983; López and Smith, 1995; López and Smith, 1996; Caine *et al*.,