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THE SALINE INTRUSION IN THE COSTA DE HERMOSILLO AQUIFER IN SONORA, MÉXICO; A CHALLENGE TO RESTORE

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Abstract

The Costa de Hermosillo aquifer is located in the northwestern Pacific sector of Sonora, México, southwest of the City of Hermosillo. The area constitutes a sedimentary basin originated by normal faulting oriented NW-SE and NE-SW, probably developed during the basin-and-range tectonic events and during the opening of the Gulf of California. The geology of the study area includes four units: 1) Quaternary alluvium, 2) Miocene marine sediments, 3) Miocene gravels and sands, 4) crystalline basement (granite and volcanic rocks). The Quaternary sediments host the main aquifer, in which an excessive pumping rate, has exceeded the natural recharge for the last 50 years. In consequence, a saline intrusion has been penetrating into the continent, at a rate of about 650 m per year, in average. Three saline intrusion fronts have been identified, located between 28 and 32 km inland. This over-extraction originated the loss of hydraulic pressure in the aquifer, causing subsequent lowering of the piezometric water level. Our studies show the existence of a single aquifer, not two as previously postulated since 1968. Therefore, the extraction policy was based on a mistaken hydrogeological model, causing the water level decrease. The overpumping caused the formation of different aquifer zones, changing the original hydrogeological conditions. At present, every aquifer functions with individual hydrodynamic characteristics. This point is extremely important in order to establish a new policy for groundwater management. However, to revert and restore, at least partly, its natural condition and the generated environmental impact, many decades of time and strong investments by the administration will be required, and of course, a high social and economical cost.

Key words: Marine intrusion, Costa de Hermosillo, Hydrogeology, Groundwater management, Coastal aquifer.

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Introduction

The Coast of Hermosillo aquifer is located southwest of the City of Hermosillo, between coordinates 28°14′ and 28°57′ latitude North, and 111°15′ and 111°45′ longitude West. The study area, extending over a strip of 35 km wide and 55 km long, constitutes the southwestern part of the aquifer, and is located in a parallel disposition to the coast of Sonora (Figure 1). The region of the coast of Hermosillo is under a dry climate with an average annual temperature varying from 22 to 24°C, with warm weather in a rainy summer. Rain occurs from June to September, being July and August the months with the highest amount of precipitation, varying from 75 to 200 mm/year.

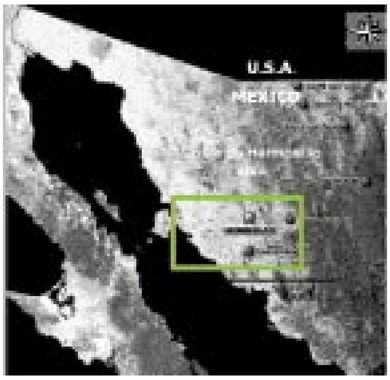

Figure 1. Location of the study area.

The pumping in this aquifer began in 1945 with 17 wells. Five years later, in 1949, the equipotential lines were already modified because of the pumping in more than 400 wells that were using groundwater for irrigation of wheat (Figure 2). Twenty years later, in 1965, the pumping rate increased up to 1,200 Mm^3/year with almost 1,000 wells and 120,000 ha of cultivated lands (Figure 3) (Matlock *et al*., 1966; SARH, 1978, 1982; Oroz, 2001). In those years, local farmers had extraction policies such as: "if a well yields less than 100 L/s, the discharge is considered as a bad result".

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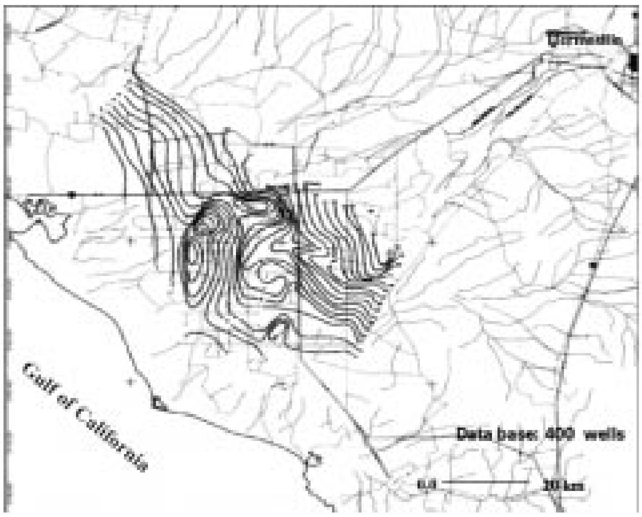

Figure 2. Groundwater surface level in 1949, Costa de Hermosillo aquifer.

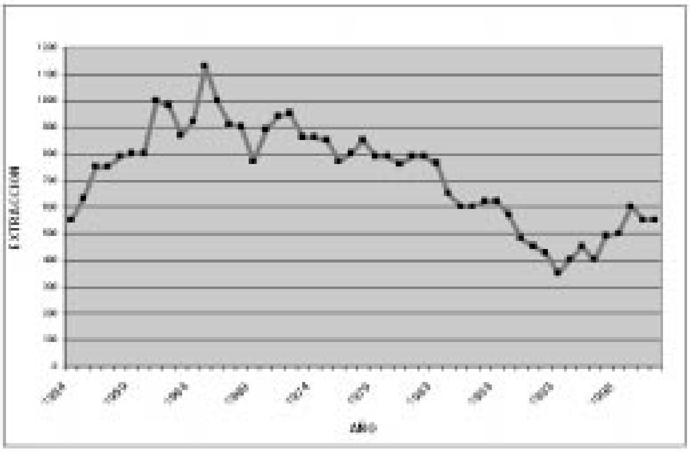

Figure 3. Evolution of pumping volumes in wells of the Costa de Hermosillo aquifer from 1954 to 2003.

Hydrogeology

Characterization of the aquifer system

The study area is part of a sedimentary basin originated by the development of grabens (normal faults oriented NW-SE and NE-SW) probably developed during the basin-and-range tectonics (De Cserna, 1988) and during the opening of the Gulf of California. This generation of faults formed a basin with an irregular basement, since in some areas it appears at a very shallow depth, (about 150 m), while in other cases, it has been identified at a depth of 500 m, and even 800 m below the ground level (Figure 4). This structural configuration influences the distribution, storage and movement of groundwater flow. In the bottom of these basins, above the crystalline basement, there are volcanic and volcano-sedimentary rocks as well as Miocene sedimentary deposits, restricted to the basin limits. These deposits can constitute storage of groundwater of interglacial origin, isolated inside these basins. Additional information about the hydrostratigraphy, intrusion front, hydrogeochemistry, isotope hydrology, etc., can be found in previous studies (Rangel and Cortés, 2000; Rangel *et al.*, 2000a, 2000b; 2002, 2003a, 2003b).

Even though the geological and geophysical information available is not sufficient to understand the subsurface stratigraphy with precision, a study of the available data (well-logging in sedimentary formations), allowed us to identify three hydro-stratigraphic units above a crystalline basement: 1) Upper unit, composed of Quaternary alluvium, 2) Middle unit, composed of Miocene sediments, and 3) Lower unit, made of semi-consolidated Miocene (Gómez, 1971) gravels and sands (Figure 4).

Historic evolution of piezometric changes

The analysis of the piezometric changes of the aquifer showed that the hydraulic response to high pumping rates in wells, and taking into account the recharge capacity, resulted in an imbalanced aquifer. The

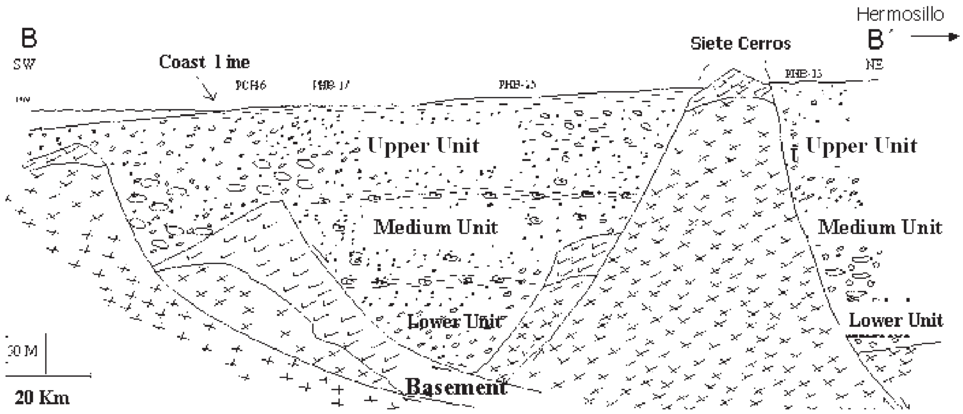

Figure 4. Sedimentary basin resulting from the fallen blocks generated through normal faults oriented NW-SE and NE-SW (Section B-B'; Kino Bay-Hermosillo).

equipotential lines have been highly modified since 1949, as a result of the over-pumping conditions (Figure 2). The drop off in the water table evolved from an initial condition of -2 m.a.s.l. in 1945 to -66.5 m.a.s.l. in 2003. The result of the intensive pumping was the formation of a wide drawdown cone, with a diameter of almost 60 km by the year 2003 (Figure 5). In 1968, a study (Arreguín *et al*., 1968) estimated that the recharge rate in 350 Mm^3/year and established a hydrogeological model that has guided during the last 32 years the groundwater extraction policy. As a result, a rigorous prohibition was set up, and local farmers were enforced to gradually reduce the pumping rate, to a global volume of 450 Mm^3/year. However, recent studies have estimated that the extraction in the aquifer system is about 550 Mm^3/year; and the recharge was evaluated in 150 Mm^3/year (Monreal *et al*., 2002), showing an obvious unbalanced between the availability and the demand.

Aquifer Dynamics

The "Costa de Hermosillo" aquifer is an unconfined aquifer. With the aid of 65 pumping tests it was determined that the southwestern part of the aquifer is the zone with the lowest permeability and with a radial flow pumping influence of 115 m. The zone of highest permeability was located to the northeast with a radial flow pumping influence of 435 meters. The transmissivity is highest at the centre of the aquifer and at the northeast zone, and diminishes towards the northwest and the coastal zone.

Semi-confining beds are evident between the granular unconfined aquifer This fact lead the community and previous authors to believe on the existence of two different aquifers; the so-called upper and lower aquifers (Arreguín *et al*., 1968; Flores-Marquez *et al*., 1998; Steinech *et al*., 1997). Nonetheless, data and evidences obtained in this study demonstrate the existence of only one aquifer, situated between 60 and 200 meters below sea level. Below this aquifer there is a hydrogeological unit, with ancient water (fossil?) stored in the upper Miocene marine detrital sediments, and other unit in the Tertiary volcanic rocks, which does not constitute an aquifer (Rangel, 2000b, 2002).

Marine-water Intrusion to the Aquifer

The evolution of the potentiometric surface has resulted in marked changes of the original piezometric surface. The contour lines of the original potentiometric surface in 1946 were parallel to the coastline but, after the intense pumping in the 60's, surpassing by a factor of three the volume of natural recharge to the aquifer (1200 Mm^3/year), cones of depression were developed (Figure 5).

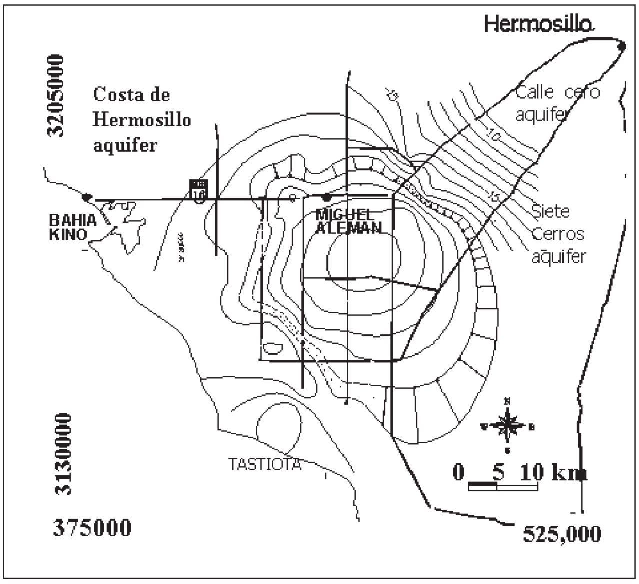

Figure 5. Monitoring wells and groundwater surface level in 2003.

The saline water intrusion was calculated in this study to be around 98 Mm^3/year, while the extraction continues at a rate of 550 Mm^3/year, with a fresh water recharge of about 150 Mm^3/year, showing a heavy unbalance.

Considering that the intruded section of the aquifer by marine water is an area of about 17 km by 65 km, the affected area extends over 1,113 km^2, from Kino Bay to Tastiota (Figure 6). Also, based on the electrical conductivity tests conducted in wells, a 29 m thick zone of saline water fringe was evidenced (3,227 Mm^3 of saline water) which is the result of 37 years of marine-water intrusion.

Hydrogeologic proposal

This paper presents the new hydrogeologic conditions of the aquifer as a result of the overexploitation, indicating that the abstraction of groundwater from the aquifer is greater than a given limit; if exploitation overcomes this limit, some consequences are observable (Tulipano, 2003). The proposed model herein

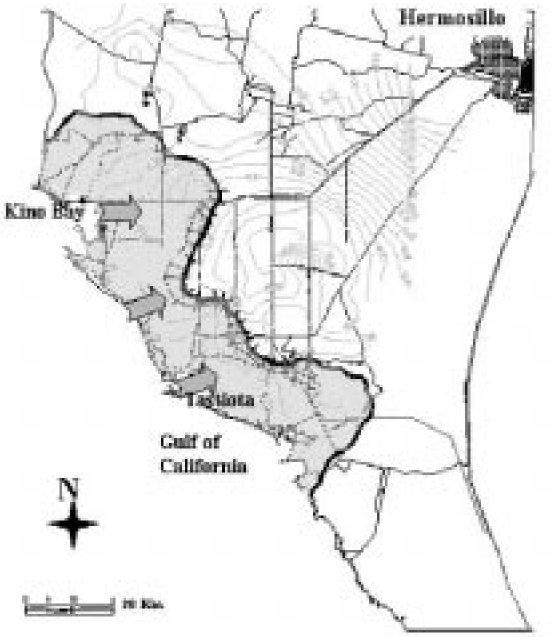

Figure 6. Groundwater surface level in the Costa de Hermosillo aquifer in 1999, gray arrows show the three seawater flow paths.

modifies the previous definition of the Costa de Hermosillo aquifer, into a system, with a subdivision in seven aquifers, named: (1) Costa de Hermosillo, (2) Siete Cerros, (3) Hermosillo-Calle Cero, (4) Hermosillo urban zone, (5) Bacoachi, (6) La Poza, and (7) Pedregoso. This subdivision agrees with the updated information on its hydrodynamic regime, recharge evaluation and a new conceptual model of the groundwater flow (Figure 7). The existence of the first three aquifers of this group reflects the importance of the tectonic framework. Because of the original hydrodynamic condition, the system worked as a group of communicated basins, but with the decreasing levels below the limits of the ranges, the piezometric heads became independent and single aquifers developed in each basin. Therefore, the administrative and legal regulations should be modified in response to these new conditions, because this aquifer is considered as overexploited, it is intruded by salt water and it is still subject to intensive pumping. Because of their importance to the understanding of the functioning of the aquifer system, following is a short description of the first three aquifers.

Costa de Hermosillo aquifer

This aquifer covers an area of around 3,000 km^2, near the coast of the Gulf of California. The aquifer varies in thickness from a minimum depth of 200 m and up to 340 m. It consists of sediments characteristic of fluvial and alluvial environments, deposited in ancient hillsides, fluvial sediments deposited through palaeochannels, and occasional deposits of lagoonal origin, appearing as mud packages of considerable thickness (50-100 m). It is estimated that in this aquifer about 35,200 Mm^3 of water were extracted in the last 50 years. Currently its saturated thickness is about 60 to 100 m, which represents an extraction

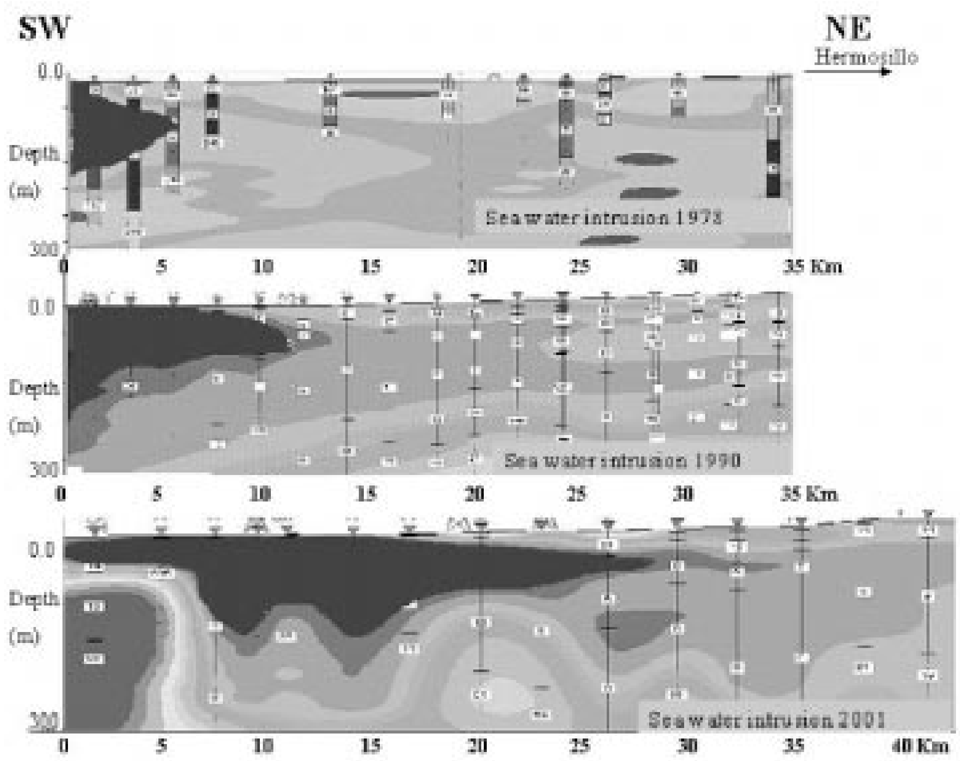

Figure 7. Evolution of the plume of the sea water intrusion (1978-2001).

representing between 60-70% of its storage volume (Figure 5). The water quality, as indicated by the E.C., varies from 500 to 40,000 µS/cm. C-14 ages of groundwater vary from 2,750 to 4,500 years B.P. (Rangel and Cortés, 2000; Rangel *et al*., 2000a; 2000b; 2003a, 2003b).

Siete Cerros aquifer

The Siete Cerros aquifer is formed by a strip of palaeochannels of the La Poza and Sonora rivers. With a mean width of about 10 km, its area is about 1500 km^2. This aquifer unit is located in the central part of the aquifer system. Its saturated thickness is about 120 m, with an estimated pumping rate of about 63Mm^3/year, its recharge is estimated to be around 28 Mm^3. The water quality, as indicated by the E.C., is lower than 500 µS/cm. The equipotential lines of this aquifer are still parallel, but some local drawdown cones have developed. The relative C-14 groundwater ages are from 280 to 640 years.

Hermosillo-Cero aquifer

This aquifer constitutes the entrance to the system; it is restricted to sediments of the Sonora River palaeochannel. It covers an area of around 1000 km^2. Its water table is still shallow, between 10 and 50 m in depth. This aquifer is being recharged by waste-water of Hermosillo city. The pumping rate is lower than 10 Mm^3/year, and it does not register an important drawdown. The relative C-14 ages are from 50 to 500 years.

Hydrogeochemistry

The groundwater quality of the Costa de Hermosillo aquifer has been affected because of the entrance of saline water in an intrusion front that began to penetrate at a velocity rate of 0.65m/year since 1975 (Rangel *et al.*, 2002, 2003). This saline body actually forms a fringe of about 80 km long, parallel to the shoreline, and varies in width from 28 km in the south to 32 km in the north (Figure 7). In the transition zone, the water salinity changed from 500 to 1500 mg/L in 1975 to E.C. values ranging from 2,500 to 40,000 mS/cm at present, and with Na-Cl and Ca-Cl water types.

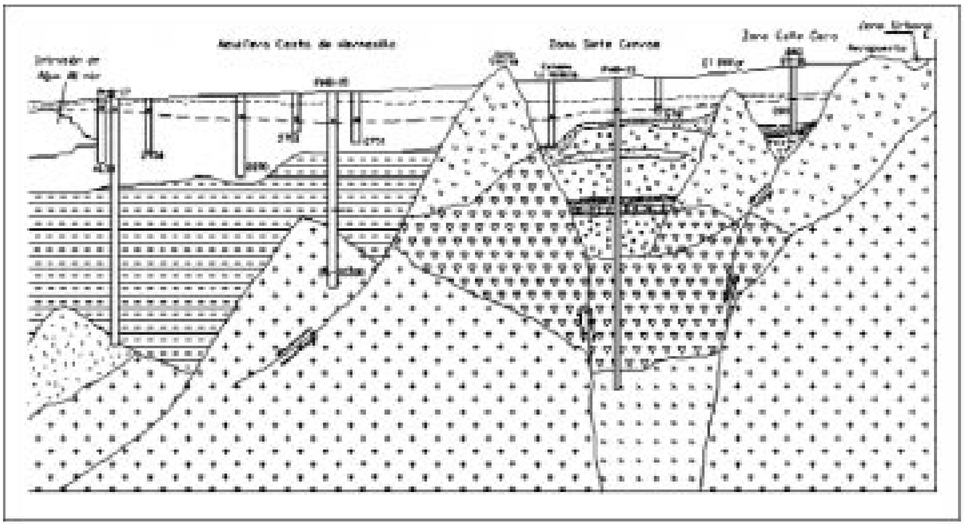

Figure 8. The regional subdivision shows a new hydrogeological model with three aquifers: Costa de Hermosillo, Siete Cerros and Calle Cero.

Conclusions

The aquifer zoning is defined herein as eight units occupying different structural basins. Seven of them are potential zones for horizontal recharge to the Costa de Hermosillo aquifer, and one is the discharge area. All aquifer units form the Coast of Hermosillo System and are, at present, actually hydrodynamically independent.

In the Hermosillo-Calle Cero aquifer there is modern recharge that depends on the distance to the actual river channels, mainly the Sonora river. The recovery of the shallow aquifers is fast; its recharge origin is local and has groundwater ages of tenths of years. The aquifers from this regime are the Sonora and Mesa del Seri-La Victoria. The Zanjón and San Miguel aquifers have a semi-regional flow, with an average residence time of 500 years. As the pumping in these aquifers intercepted the recharge flow to the system, it accelerated the lowering of the levels of the aquifer zones downward the slope.

The Costa Hermosillo and Siete Cerros aquifers do not seem to have seasonal variations related to modern recharge. Water ages vary from 500 to a little more than 4000 years. The system is recharged by the North-South flow from the Bacoachi River Basin, South-North from La Poza, both to the Costa de Hermosillo aquifer, and an East-Southeast flow from the Sonora River palaeochannel to the Siete Cerros aquifer.

The difference in water ages (500-4000 yrs) are evidence of the existence of regional and semi-regional flows and therefore. It is evident that the aquifer recovery could be achieved only through decades or hundreds of years, and also by administrating them as independent aquifers.

References

ARREGUIN, G., FIGUEROA, J. and PEÑA, S. (ARIEL CONSTRUCCIONES, S.A. de C.V.) (1968), Estudio hidrogeológico completo de los acuíferos de la Costa de Hermosillo, Sonora, Mex., México, D.F., Secretaria de Recursos Hidráulicos. (Internal), 1-220.

CSERNA DE, Z., 1989, An outline of the geology of Mexico, in Bally, A.W. and Palmer, A.R., eds., The geology of North Geology of North America, an overview: Boulder Colorado, The Geological Society of America, The geology of North America, V.A., 233-264.

FLORES-MÁRQUEZ, E.L., J.O. CAMPOS-ENRÍQUEZ, R.E. CHÁVEZ-SEGURA and J.A. CASTRO-GARCÍA, (1998), Saltwater intrusion of the Costa de Hermosillo aquifer, Sonora, México: a numerical simulation, Geofísica Internacional, 37 (3): 133-151.

GÓMEZ, P., M., (1971). Sobre la presencia de estratos marinos del Mioceno en el Estado de Sonora, México. Revista del Instituto Mexicano del Petróleo, III(4): 77-78.

MATLOCK, G., FOGEL, M. and BUSH, D., (1966), Utilization of water resources in a coastal ground water basin. J. Soil and Water Conserv. 21(5).

MONREAL S, R., MORALES M. M., RANGEL M., M. and CASTILLO G. J., (2002), Evaluación de la recarga al acuífero Costa de Hermosillo, Son., Informe inédito para la Comisión Nacional del Agua (CNA) Hermosillo, Sonora.

OROZ, L., (2001), Modelo Conceptual Hidrogeológico e Hidrogeoquímico de la Costa de Hermosillo, Tesis, Dpto. de Geología, Universidad de Sonora.

RANGEL, M.M., and A. CORTÉS, (2000), Contributions on the isotopic characterization of the Coast of Hermosillo aquifer and its relation with the marine intrusion, Sonora, Mexico. The Geological Society of America 2000 Annual Meeting, Reno Nevada. Abstract No. 50903. URL: http://rock.geosociety.org/absindex/annual/2000/50903.htm.

RANGEL, M. M., *et al.*, (2000a), Isotopic characteristics of the groundwater in the divide between the Matape and Sonora Basins. 4a. Reunión Internacional de Geología del Noroeste y zonas adyacentes, Memorias, Hermosillo, Sonora Mexico.

RANGEL, M. M., *et al.*, (2000b). Nuevas Aportaciones Para El Entendimiento Del Modelo Hidrogeológico de la Costa de Hermosillo, Utilizando Isótopos Ambientales (O-18; D) y Fechamiento de Agua (C-14). II Reunión Nal. UGM, Puerto Vallarta , Jalisco, México.

RANGEL, M. M., *et al.*, (2002), Determinación de la vulnerabilidad a la intrusión marina de acuíferos costeros en el pacifico norte mexicano; un caso, el acuífero costa de Hermosillo, Sonora. México. 23 al 25 de Abril del 2002, Ciudad de La Habana, CUBA. *Página web del CYTED XVII* http://tierra.rediris.es/hidrored/ponencias/Rangel.html..

RANGEL, M. M., *et al.*, (2003a), Caracterización geoquímica e isotópica del agua subterránea y determinación de la migración de la intrusión marina en el acuífero de la Costa de Hermosillo, Son., México. Publicaciones del Instituto Geológico y Minero de España, Serie Hidrogeología y aguas subterráneas 8(I): 325-335.

RANGEL, M. M., *et al.*, (2003b), Estimation of the vulnerability to saline intrusion of the Coast of Hermosillo aquifer, Sonora, Mexico. Proceedings of the First International Workshop on Aquifer Vulnerability and Risk; Salamanca, Mex. May, 2003.

SECRETARÍA DE AGRICULTURA Y RECURSOS HIDRÁULICOS (SARH), (1978), (1982), Reportes de perforación de Pozos de Observación y Centinelas en la Costa de Hermosillo, Son. (Internal).

STEINICH, B., I. SIMÓN, J.A. CHAVARRÍA, and L.E. MARIN, (1997), Geophysical investigations of the vadose zone in the valley of Hermosillo aquifer, Sonora México. Geofísica Internacional, 36: 191-200.

TULIPANO, L. (2003), Over-exploitation consequences and management criteria in coastal karstic aquifers. Publicaciones del Instituto Geológico y Minero de España, Madrid , España, Serie: Hidrogeología y Aguas Subterráneas 8(II): 113-126.