# Estimation of the vulnerability to saline intrusion of the coast of Hermosillo aquifer, Sonora, Mexico

Miguel Rangel-Medina[1], Rogelio Monreal S.[1], Mariano Morales M.[1] and José Castillo Gurrola[2]
[1] Dpto. de Geología, Universidad de Sonora, Hermosillo, Son., México
[2] Dpto. Agronomía, Universidad de Sonora, Hermosillo, Son., México

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## RESUMEN

La contaminación del agua subterránea tiene una amplia variedad de propagación ya sea fuentes puntuales o dispersas y su vulnerabilidad o el riesgo se han evaluado con métodos como DRASTIC, AVI, GOD, EPIK, SINTACS y otros, que poseen un común denominador, los contaminantes son adicionados sobre o cerca de la superficie del terreno. A diferencia de este mecanismo, la intrusión salina, o contaminación del agua dulce por agua de mar en acuíferos costeros, involucra características hidrogeológicas distintas de degradación. Ello obliga a usar metodologías más extensas, tardadas y a veces con alto grado de complejidad, pues el conocimiento de escenarios hidrogeológicos necesita de numerosas herramientas para la obtención de parámetros. En la costa noroeste del Pacífico mexicano, los principales acuíferos están gravemente afectados por sobrebombeo agrícola. El acuífero de la Costa de Hermosillo en Sonora ha sido intrusionado hasta 32 km tierra adentro; ello degradó la calidad del agua alcanzando conductividades eléctricas de hasta 40 000 μS/cm. Para conocer las zonas vulnerables por donde penetra diferencial y preferencialmente el agua de mar desde hace 37 años se actualizó el modelo hidrogeológico e identificaron la migración y posición del frente de intrusión utilizando la geometría del basamento, la hidroestratigrafía y propiedades del acuífero, obteniéndose a partir de ellas una clasificación de vulnerabilidad para tres zonas de riesgo: 1) Zona de vulnerabilidad Alta por subsidencia tectónica, 2) Zona de vulnerabilidad Media por permeabilidad del medio, 3) vulnerabilidad Baja definida por altos gravimétricos.

**PALABRAS CLAVE:** Costa de Hermosillo, intrusión salina, vulnerabilidad, acuíferos costeros, hidrogeología, hidroquímica.

## ABSTRACT

Vulnerability of aquifers is evaluated with methods such as DRASTIC, AVI, GOD, EPIK, SINSTACS, where pollutants are added near the surface. Intrusion by seawater involves hydrogeologic characteristics completely different from those used in vertical vulnerability assessment. In northwestern Mexico, coastal aquifers are heavily affected by high pumping rates. The coastal aquifer of Hermosillo has been intruded up to 32 km inland, and in some areas the water quality was degraded reaching EC of up to 40 000 μS/cm. In this study, the most vulnerable zones through which the seawater penetrates over the last 37 years are identified with the migration and position of the intrusion front. Vulnerability is studied in three risk zones: 1) Zone of high vulnerability due to tectonic subsidence, 2) Zone of medium vulnerability due to permeability of the aquifer, and 3) Zone of low vulnerability due to high gravimetric anomalies.

**KEY WORDS:** Costa de Hermosillo, saline intrusion, vulnerability, coastal aquifers, hydrogeology, hydrochemistry.

## INTRODUCTION

The "Costa de Hermosillo" aquifer is located southwest of the City of Hermosillo, between 28°14' to 28°57' latitude north and 111°15' to 111°45' longitude west. The study area is 35 km wide and 55 km long, including the southwestern part of the aquifer parallel to the coast of Sonora (Figure 1).

The coast of Hermosillo has dry climate with an average annual temperature from 22° to 24°C. Rain occurs from June to September. July and August are the months with highest precipitation, from 75 to 200 mm/year.

The exploitation of the aquifer began in 1945 with 17 wells, and by 1965 it reached a maximum volume of around 1200 million cubic meters per year ($Mm^3$/year) (Matlock *et al.,* 1966; SARH, 1978, 1982; CNA, 1997, 2000). Loss of hydraulic pressure in the aquifer caused subsequent lowering of the piezometric head forming a wide cone of depression and upsetting the dynamic balance between the body of freshwater and saline water in the aquifer. The water flow direction near the coast was originally from northeast to southwest, but in 1949, only 4 years after the beginning of pumping, saline-water encroachment into the aquifer from southwest to northeast was observed (Figures 2 and 3).

The current hydrogeological model and the position of the saline intrusion were obtained using the geochemistry of saline and fresh ground waters. The process of migration was defined using geophysical methods 850 SEV's and 408 TEM's (Morales *et al.,* 2000). Hydraulic parameters were

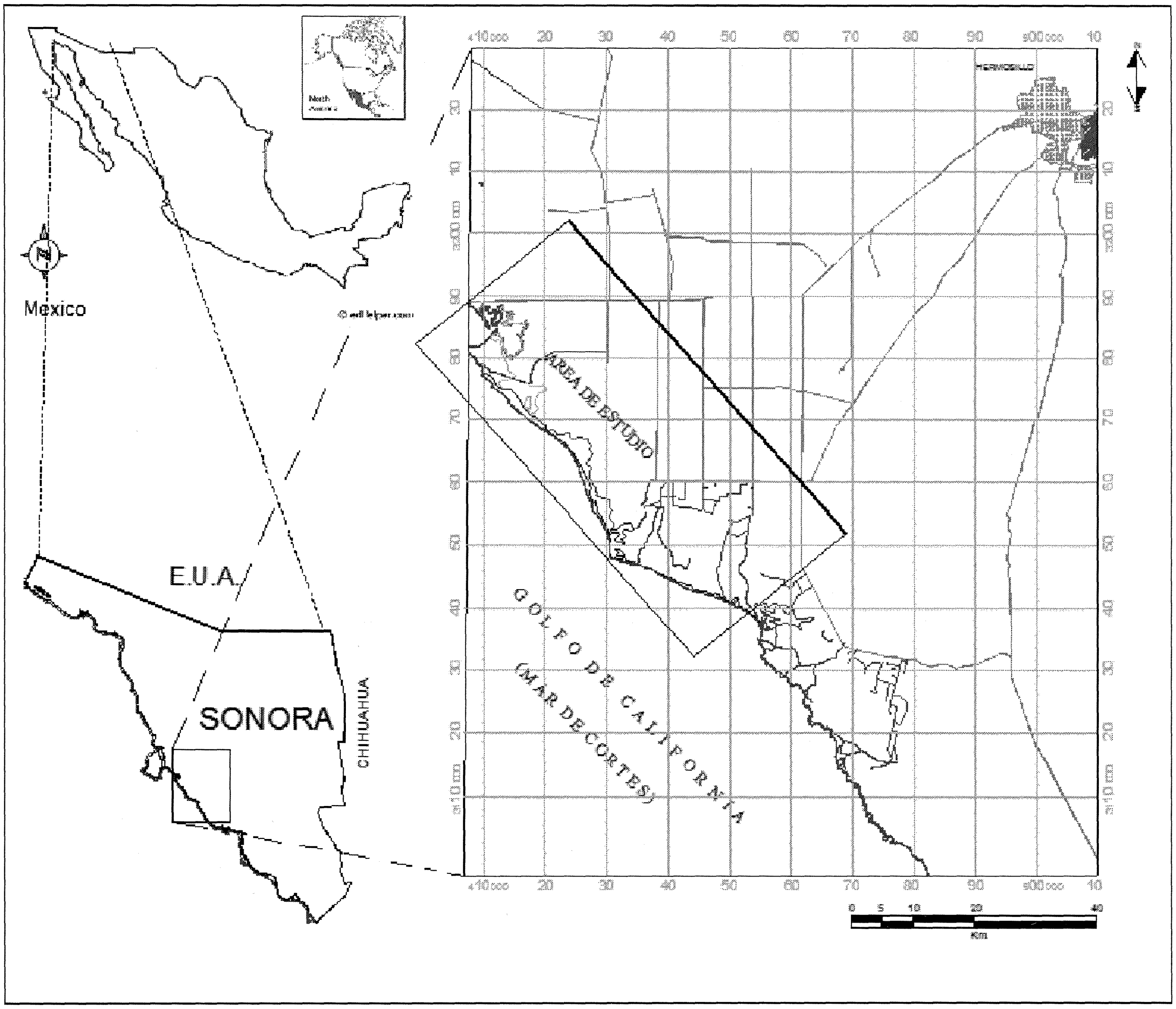


Fig. 1. Location of the study area in the Costa de Hermosillo Aquifer, Sonora Mexico.

obtained from more than 75 well pumping tests within the aquifer area. Gravity data from ESSA (1971) were used to explain the three dimensional characteristics of the most vulnerable zones through which the seawater preferentially penetrates the aquifer.

## GEOLOGY

Between the City of Hermosillo and the coast line is a large alluvial plain with faults characteristic of Basin and Range Tectonics (de Cserna, 1989), and of the opening of the Gulf of California (Angelier *et al.,* 1981; Colletta and Angelier, 1983). Sedimentary basins are limited by normal faults oriented NW-SE and NE-SW (Figure 4). Some of these faults have been probably re-activated at the end of the Tertiary, as evidenced by the juxtapositions of the sediments below 100 meters in depth. Faulted blocks are irregular and produce an irregular basement, with depth varying from 150 to 800 meters below surface (Figures 5 y 6).

Outcrops range from Paleozoic to Quaternary and from sedimentary to igneous extrusive rocks. In the sedimentary fill, three hydrostratigraphic units above the crystalline basement are identified: 1) An upper unit composed of quaternary alluvium, 2) a middle unit composed of Miocene sediments, and 3) a lower unit of semi-consolidated Miocene (?) gravels and sands (Figure 5).

The thickness of the aquifer is around 200 m and contains Upper Tertiary/Lower Quaternary (?) continental alluvial sediments above a pro-gradational sequence of upper Miocene deltaic and fossiliferous marine deposits (Gómez, 1971), on an igneous rock basement (Monreal *et al.,* 2000).

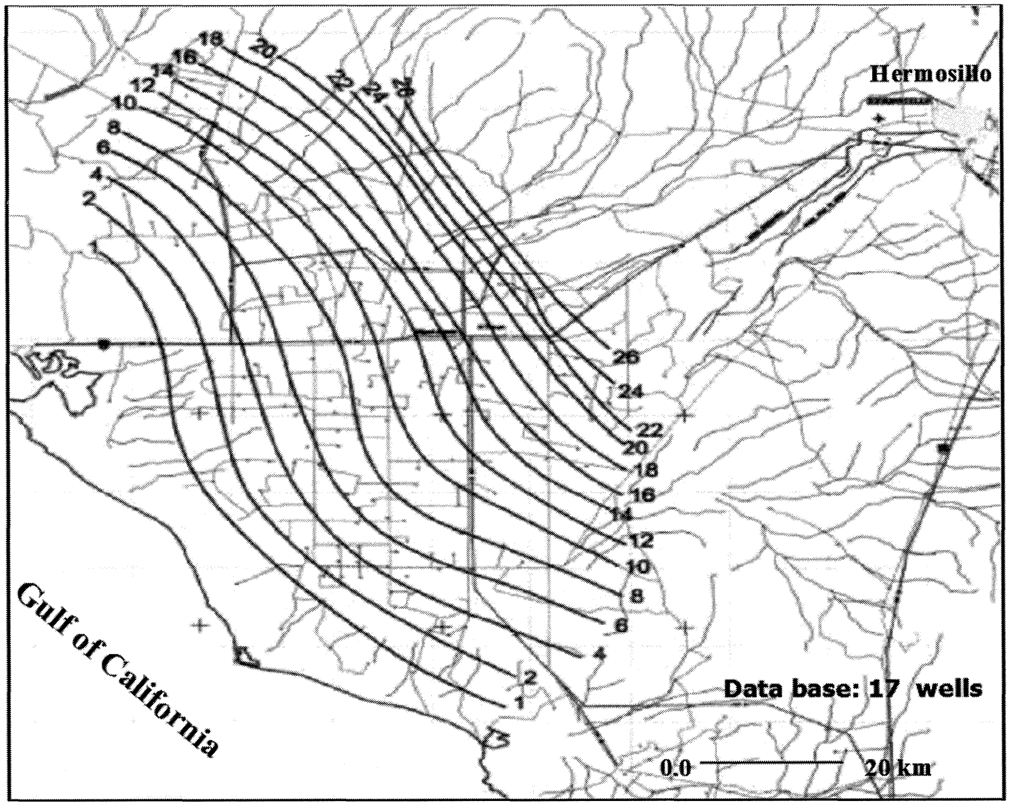


Fig. 2. Groundwater surface level 1945.

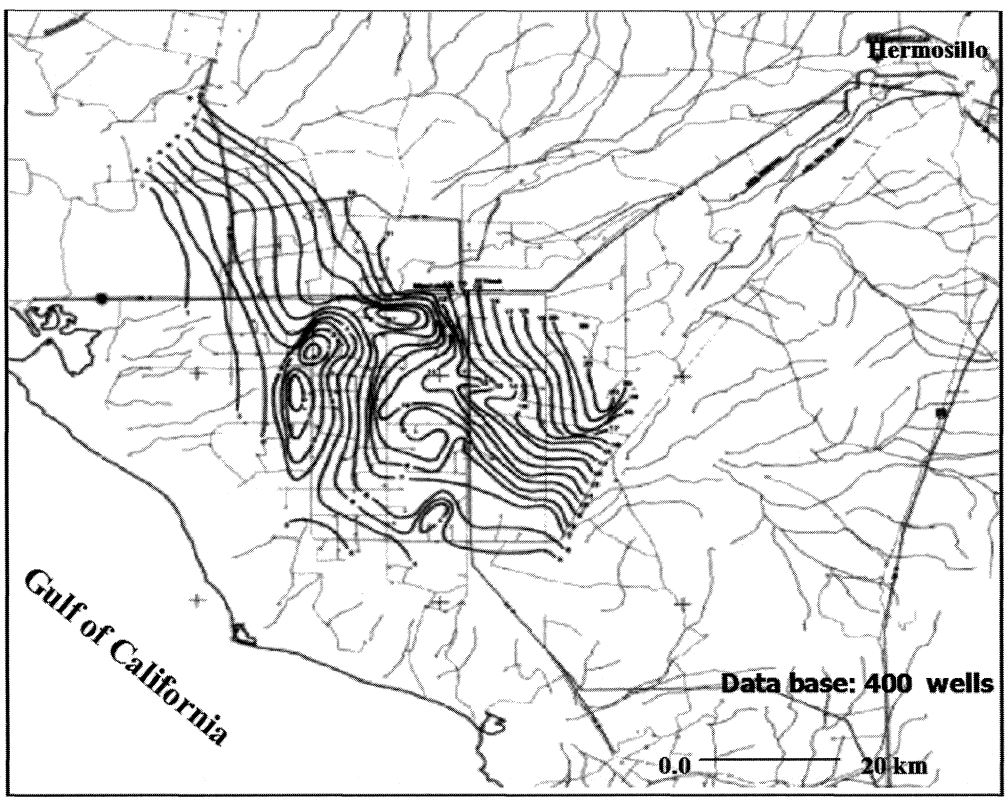


Fig. 3. Groundwater surface level 1949.

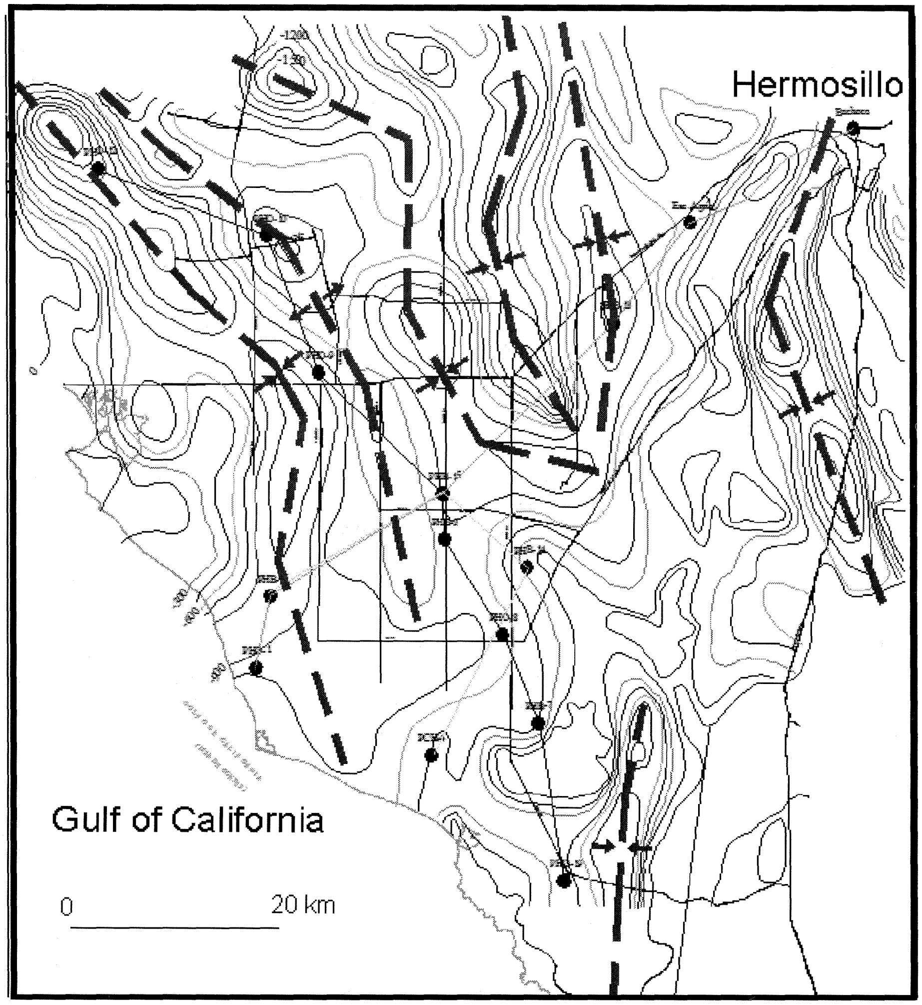


Fig. 4. Gravimetric up and downs in the Basin and Range Sonorense system.

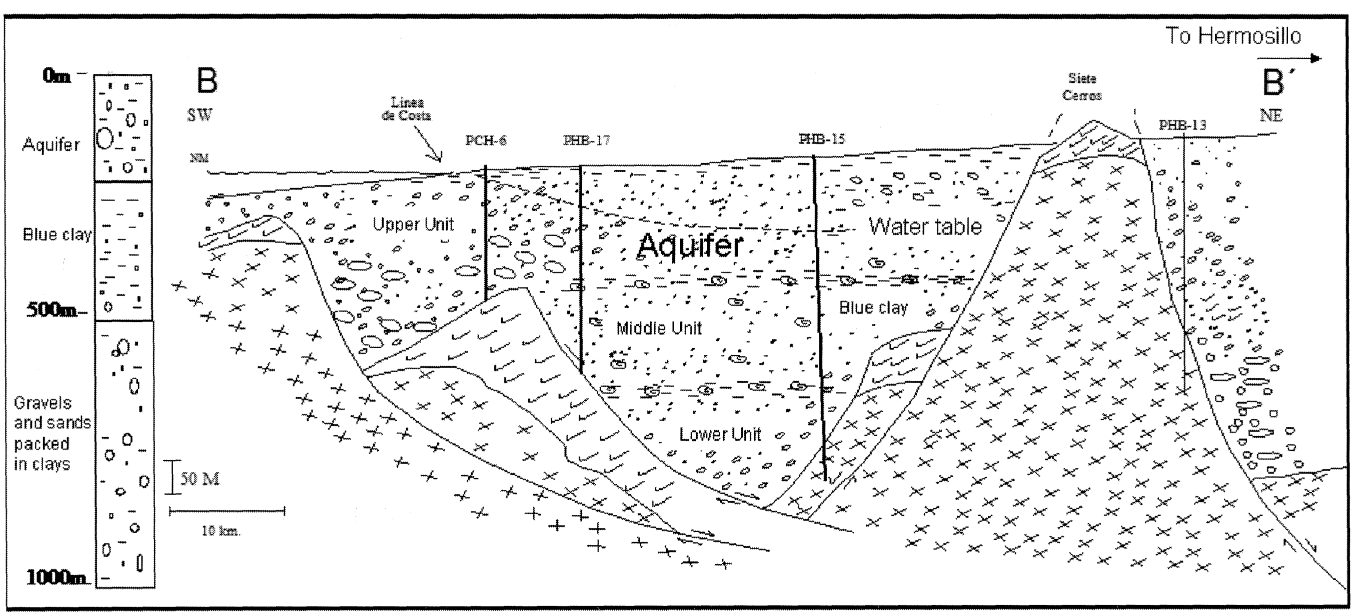


Fig. 5.- Schematic geologic section B-B' oriented SW-NE from the coast (left) towards the City of Hermosillo (right), showing location of some wells included in this study.

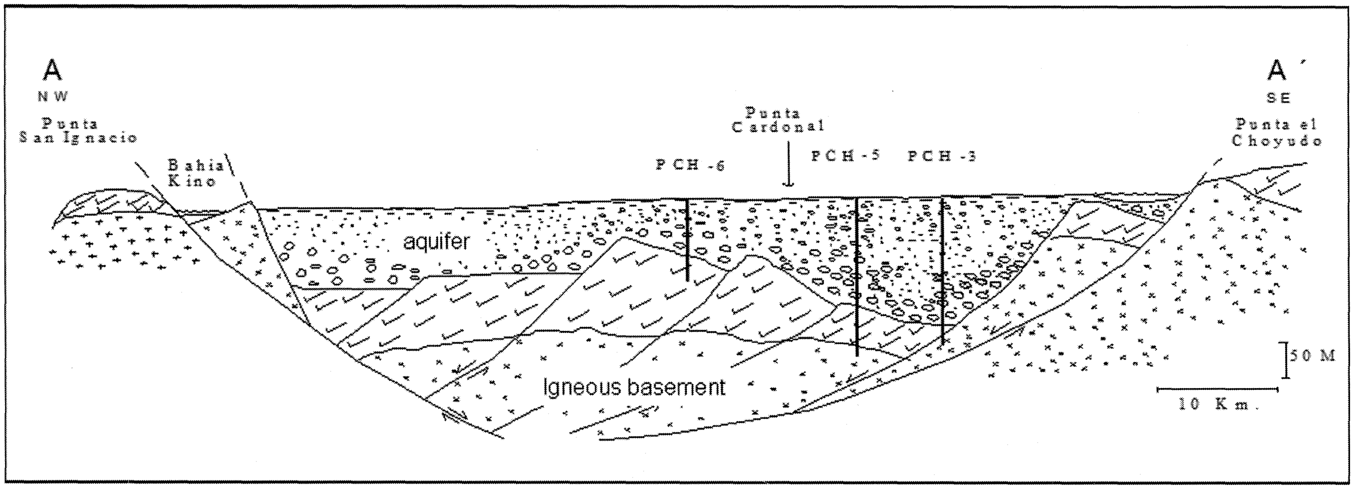


Fig. 6. Schematic geologic section A-A' oriented NW-SE, from Bahía Kino (left) to Punta Choyudo (right), showing location of some wells included in this study.

## HYDROGEOLOGY

The aquifer is multilayered and unconfined (Figure 7). There are semi-confining beds between the granular unconfining aquifer. Earlier authors consider the existence of an upper and a lower aquifer (Arreguín *et al.,* 1968; Payne *et al.,* 1978; Marín *et al.,* 1996; Steinich *et al.,* 1997; Flores Márquez *et al.,* 1998). However, evidence from this study and others (Rangel and Cortés, 2000; Rangel, 2000a) finds only one aquifer, between 60 to 200 meters below sea level. C-14 dating of water samples from this aquifer yields ranging from 2751 to 4630 ±30-50 years b.p.

Below this granular aquifer there is a lithostratigraphic unit of Miocene detrital blue shale and other Tertiary volcanic rocks that contain paleowater of 25 820 to 30 000 ±190 years b.p. of age. This unit does not constitute an aquifer, as shown by the stable isotope composition of the water (Rangel y Cortés, 2000; Rangel, 2000b).

The transmissivity distribution was obtained from two sources of data: 1) 75 well pumping tests from previous authors and 2) 15 new well pumping tests performed during this project. The highest values are found at the center and northeast of the aquifer, reaching 7 to $10*10^{-2}$ $m^2/s$. In the middle of the zone are the deepest ground water levels, diminishing towards the northwest near to the coast of Bahía Kino where transmissivities vary from $5*10^{-3}$ to $6.9*10^{-2}$ $m^2/s$. In the southwest of the area the transmisivity values vary from $2.5*10^{-3}$ to $3.5*10^{-2}$ $m^2/s$. In general the values tend to diminish toward the shoreline due to higher clay content (Castillo *et al.,* 2000; Oroz, 2001).

## HYDROGEOCHEMISTRY

Six water families were recognized. The most prominent are 1) calcic bi-carbonated the fresh water of the aquifer (EC = 250μS/cm) and 2) the sodic-calcic chloride water of the interface zone where saline and fresh waters mix (2000 – 10 000μS/cm).

Bromide, chloride, stronium, lithium and borax were used as tracers. The electrical conductivity (EC) was measured in 30 profiles along the coast across abandoned deep wells. The EC distribution (salinity) was obtained at 40, 70 and 100 m depth. We have identified the main zones of saline intrusion, and the pattern of migration of the saline front (Figure 8) (Rangel *et al.*, 2001; Rangel *et al.,* 2003).

As seawater intrusion advances, wells close to the coast become saline and have to be abandoned (Bear, 1999). This study shows the vertical distribution of the saline intrusion and a front of saline water 32 km inland, 80 meter thick and with salinity values ranging from 2900 to 40 800 mS/cm (Figure 9).

A survey of 408 electromagnetic soundings (TEM's) was used to correlate the chemical quality and fluid resistivity of 850 SEV to identify the final spatial and three-dimensional distribution of the routes of saline intrusion. These results were in agreement with the cone of water level depression developed by the intense water extraction. These routes coincide with the deepest grabens forming the topography of the basement and the horsts being the barriers to the seawater (Figures 10 and 11).

## DISCUSSION

Vulnerability routes in the Costa de Hermosillo aquifer were obtained by different tools. Data from 1000 m depth bore holes from previous work and hydraulic and piezometric analysis provided an explanation about the aquifer ca-

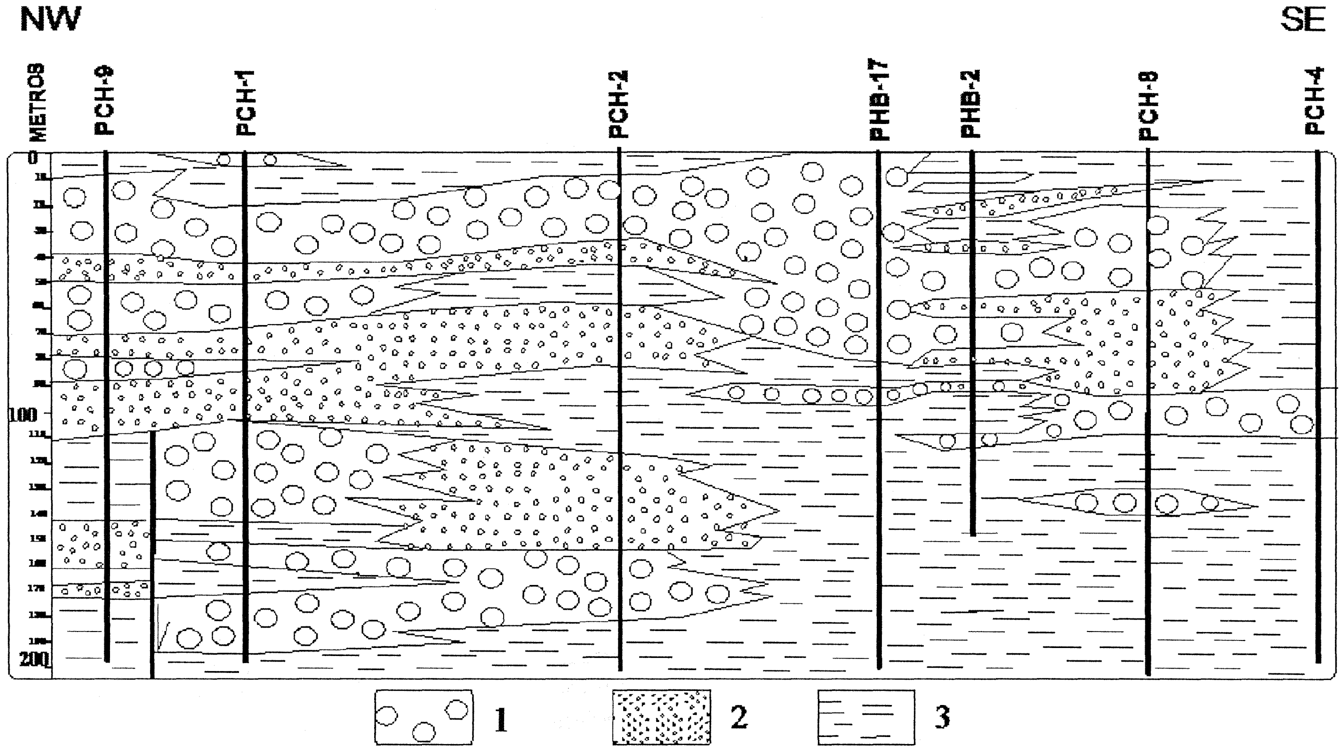


Fig. 7. Stratigraphic correlation of the upper unit, between wells (PCH-9, PCH-1, PCH-2, PHB-17, PCH-6 and PCH-4), showing the hydrostratigraphic units: 1 = high permeability, 2 = medium permeability, 3 = low permeability. Section oriented NW-SE parallel to the coast line and located 15 km from the coast.

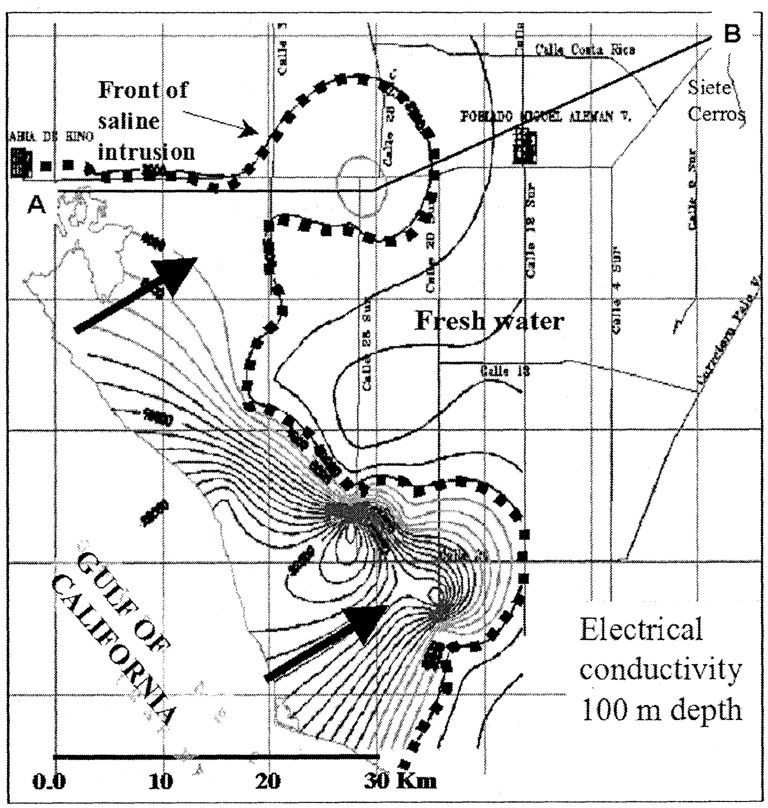


Fig. 8. Electrical conductivity distribution at 100 m depth. The dashed line is 2000 μS/cm and the arrows show preferential routes of saline intrusion.

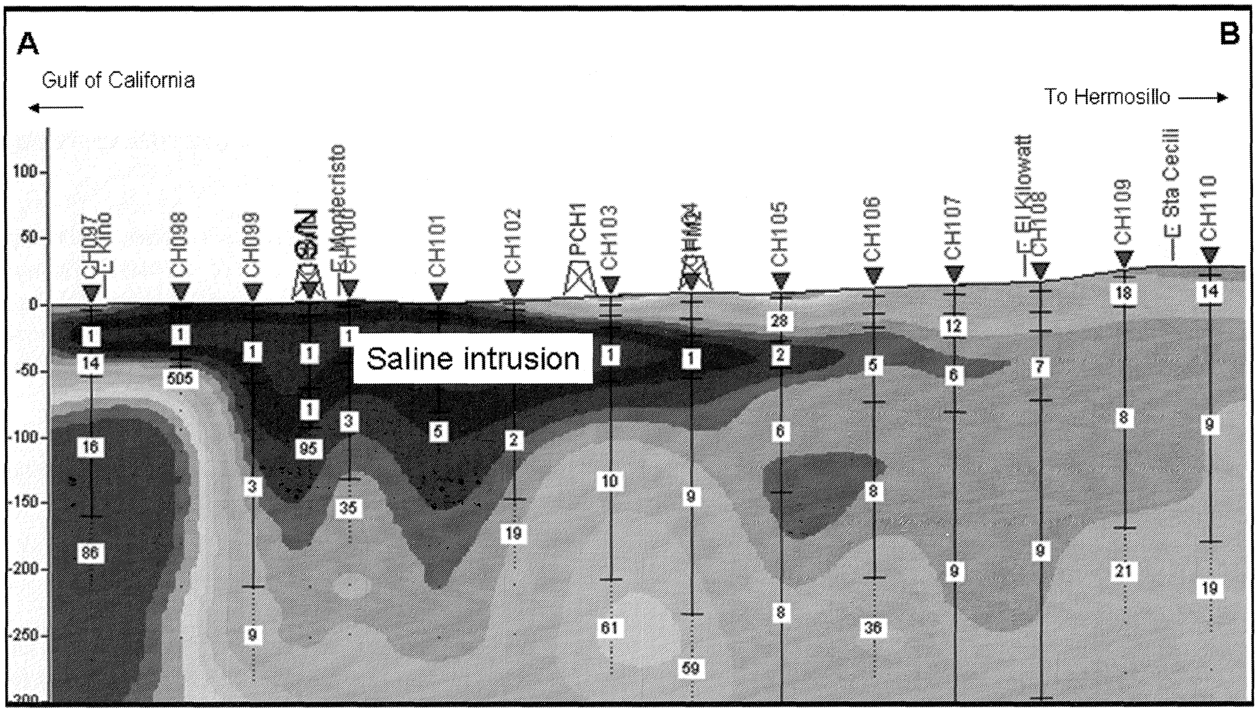


Fig. 9. Current position of the saline intrusion, showing the pollution plume (January, 2002).

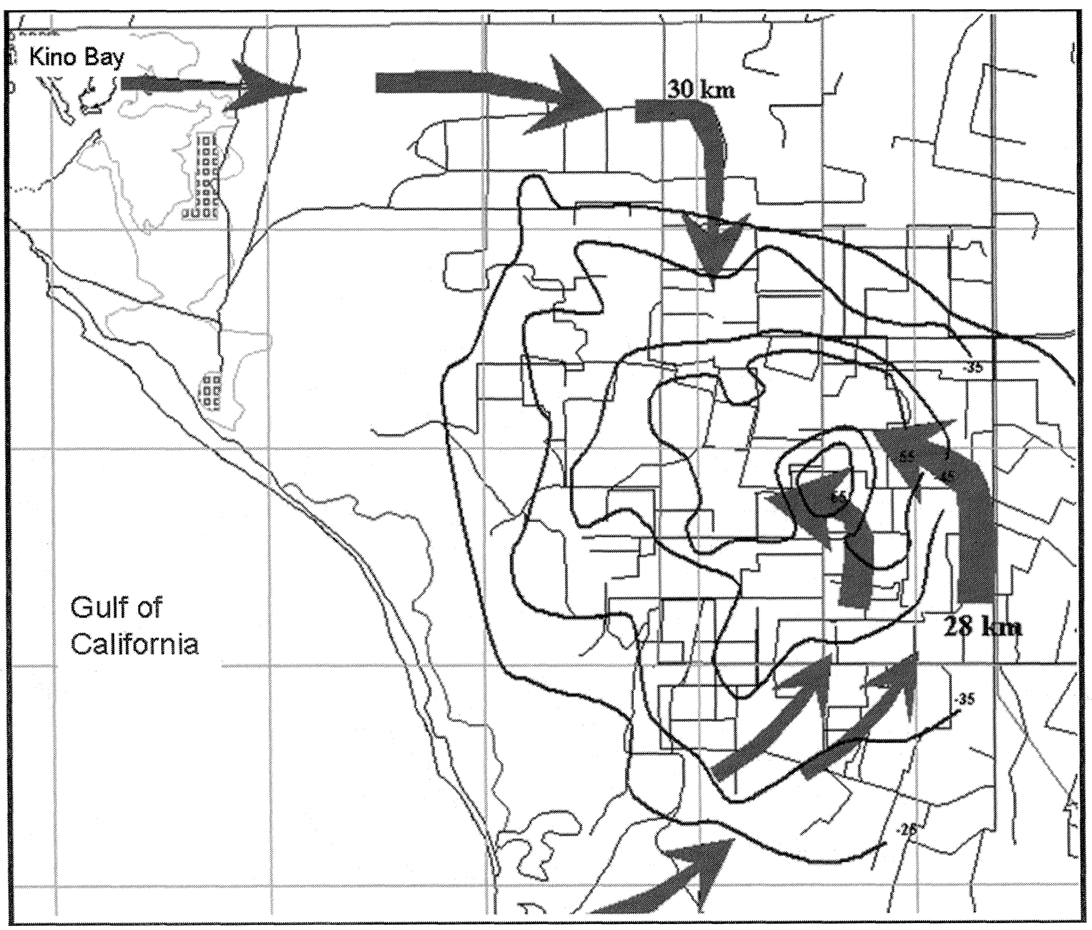


Fig. 10. Depression cone and saline intrusion routes.

pacity. The hydrogeologic model was changed on the basis of the lithostratigraphy. Only one aquifer was found instead of two, as assumed by previous authors; this hydrogeologic model was corroborated with the use of TEM and SEV sections, and more suitable zones in the aquifer (the paleo Sonora river) were defined.

The basement geometry was reconstructed from reinterpretation of the gravimetric data. This three-dimensional model was the basis for the interpretation that the sediments were deposited in tectonic basins aligned NNW-SSE, generated during the Basin and Range tectonics and Gulf of California opening events.

Electrical conductance profiles and ion ratios of water were correlated with aquifer salinity and lithologic distribution, and with higher transmissivity values. Saline penetration routes are found in the wells with higher salinities. Two zones were defined: 1) the transition zone which can be classified as a high vulnerability area (higher T and K values), where the saline intrusion front reaches up to 32 km inland, and 2) the sweet water zone, where the aquifer is not yet affected yet by the saline intrusion and the total dissolved solids (TDS) vary from 228 to 844 mg/lt (Figures 8, 9). Electrical conductivity profiles of abandoned wells along the intrusion zone show a fringe of saline water, at least 80 meters thick, with electrical conductivity values (CEV) ranging from 2900 y 40 800 μS/cm.

The routes coincide with gravity lows, which explains the greater facility of penetration of the marine flow. A line parallel to the coast shows topographic lows and highs in the Kino Bay (NW) and Cardonal (SE) areas. The unprotected area (high vulnerability) in Cardonal represents the continuation towards the south of the ancient Sonora River.

Geochemical anomalies coincides with the area of the depletion cone (Figures 10, 11 and 12).

## CONCLUSIONS

Over-pumping in the aquifer (550 Mm³/year) has exceeded the natural rate of recharge (150 Mm³/year) for the

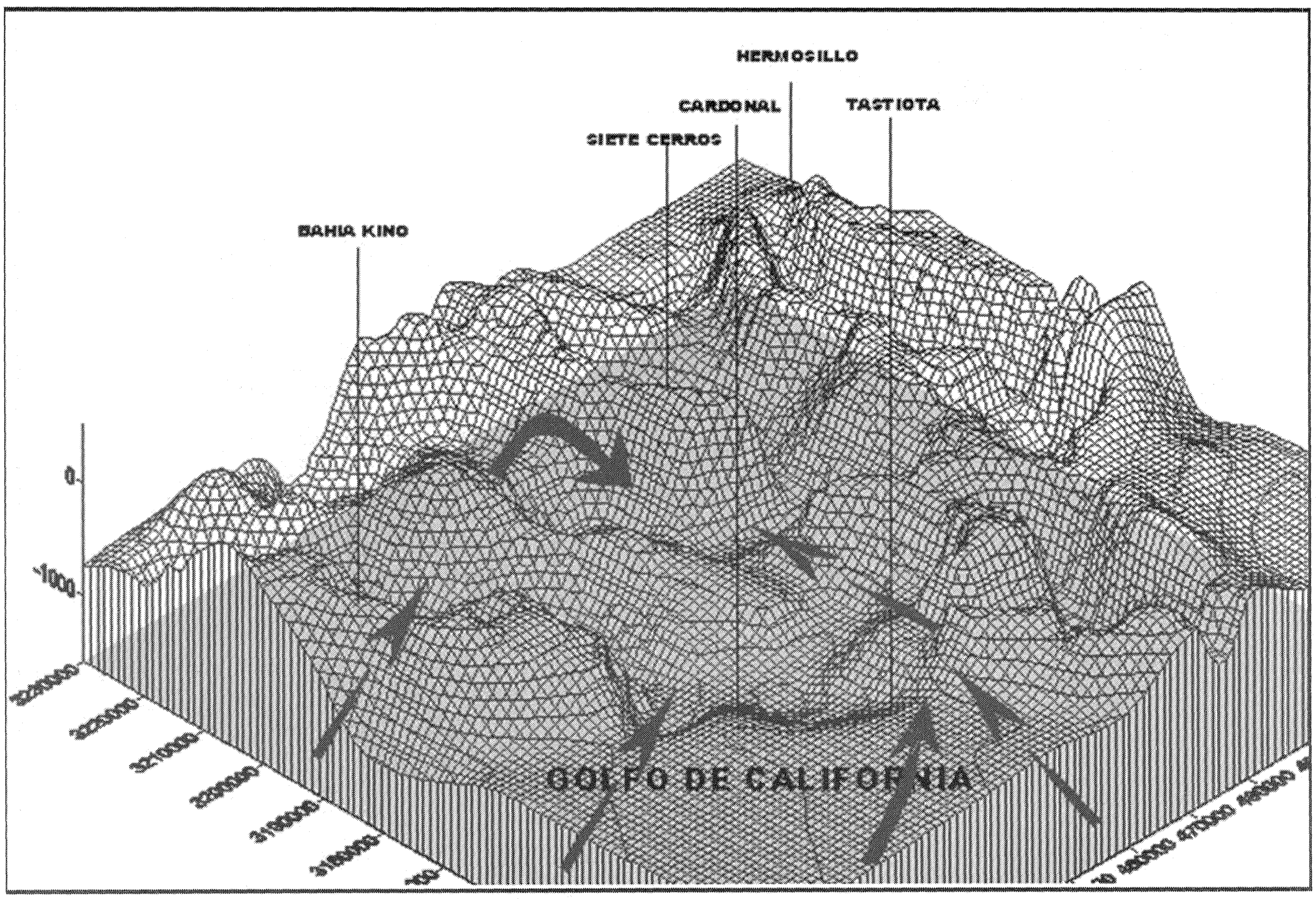


Fig. 11. Tridimensional view of the crystalline basement showing vulnerability routes.

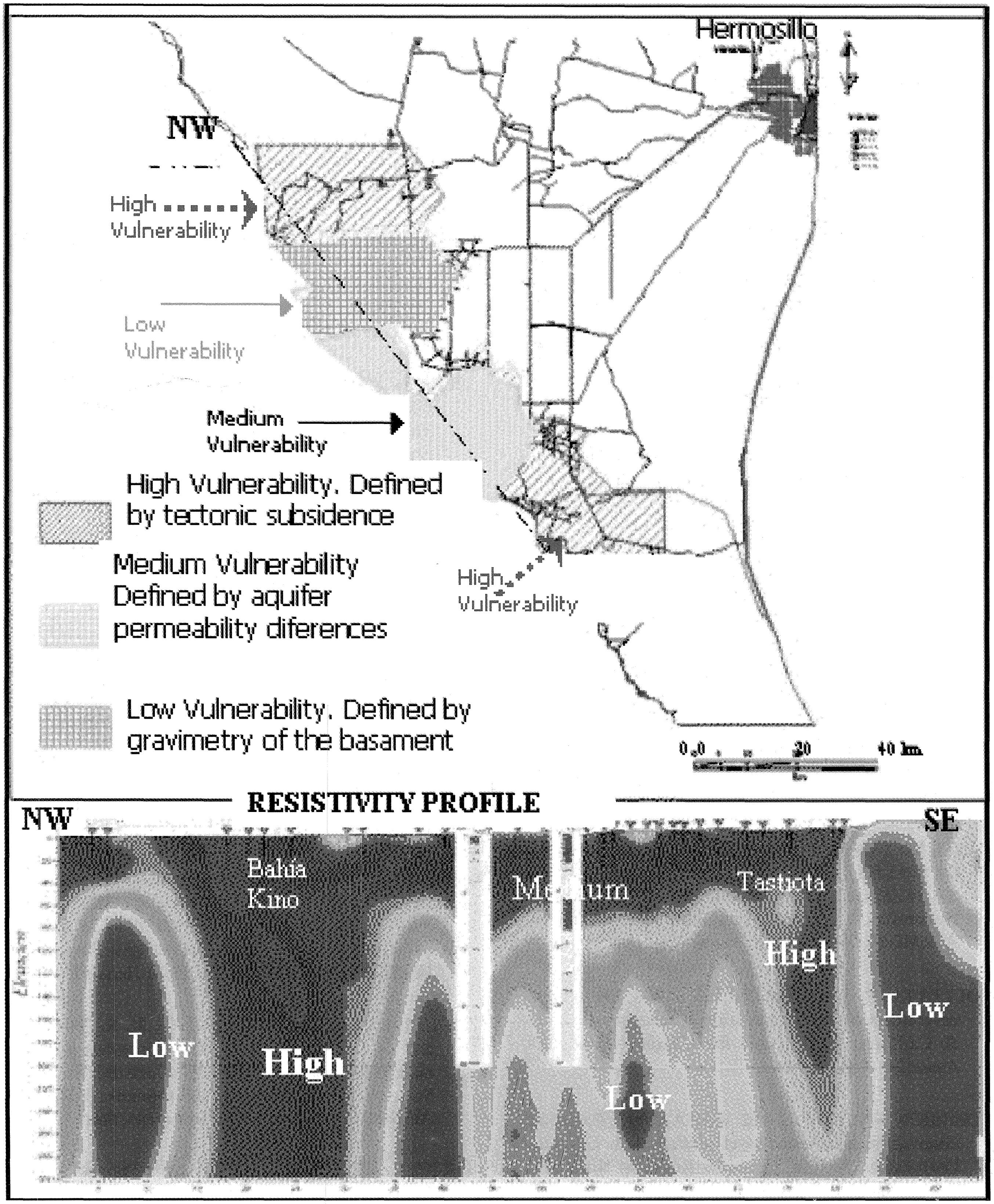


Fig. 12. Intrinsec vulnerability. 1) High vulnerability in Kino and Cardonal zones due to tectonic subsidence, 2) Medium vulnerability influenced by the transmissivity of the aquifer, and 3) Low vulnerability according to high gravimetric anomalies. (See the hydrochemical families)

last 50 years (Rangel *et al.,* 2003). Salt water intrusion has been penetrating into the continent by an average distance of 650 m per year. The front of this intrusion is currently 32 and 28 km inside the continent in the areas of Kino Bay and Cardonal Bay, respectively. It will continue to advance as a response of groundwater extraction.

Three preferential risk areas for saline intrusion are found. Two of these areas are related to the geometry of the basement and the third is related to the hydraulic properties of the aquifer. We classified the vulnerability of the aquifer as: 1) High vulnerability in Kino and Cardonal due to tectonic subsidence, 2) Medium vulnerability due to the transmissivity of the aquifer, and 3) Low vulnerability in areas of high gravimetric anomalies (Figure 12).

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Miguel Rangel-Medina[1], Rogelio Monreal S.[1], Mariano Morales M.[1] and José Castillo Gurrola[2]

[1] *Dpto. de Geología, Universidad de Sonora, Hermosillo, Son., Mexico*
*Email: mrangelm@geologia.uson.mx*
[2] *Dpto. Agronomía, Universidad de Sonora, Hermosillo, Son., Mexico*