*Water Qual. Res. J. Can. 2008 · Volume 43, No. 2/3, 1–10*


# Distinguishing the Hydrochemistry of Two Hydrological Basins in Northern Mexico Using Factor Analysis

Lia C. Méndez-Rodriguez,[1*] Susan C. Gardner,[1] Luis Brito-Castillo,[2] Baudilio Acosta-Vargas,[1] Jobst Wurl,[3] and Sergio T. Alvarez-Castañeda[1]

[1] *Centro de Investigaciones Biológicas del Noroeste (CIBNOR) Mar Bermejo 195. Playa Palo de Santa Rita, La Paz, B.C.S. 23090, México.*
[2] *Centro de Investigaciones Biológicas del Noroeste, Unidad Guaymas, Guaymas, Sonora, México.*
[3] *Universidad Autónoma de Baja California Sur (UABCS), La Paz, B.C.S. México.*

**Hydrochemical parameters of groundwater from two hydrological basins in northwestern Mexico were measured. In one of them is located the city of Puerto Peñasco, and in the other one is the city of El Rosarito. A factor analysis was used to characterize the main influences that affected the water quality of each region. Based on the results of this method, the aquifer located in Rosarito is mainly affected by seawater intrusion and the presence of high levels of manganese, while the groundwater characteristics at Puerto Peñasco are influenced by reductive conditions, probably caused by bacterial contamination. Although most of the parameters analyzed in this study were within normal ranges for groundwater, knowledge of the factors affecting sources of water can help to develop restoration projects and preventive management practices to prevent an irreversible degradation of groundwater quality.**

*Key words:* **groundwater, factor analysis, northwestern Mexico, nutrients, trace metals**

## Introduction

Mexico is one of the largest users of groundwater in the world and faces growing challenges for the management of water resources (Scott and Shah 2004). Ninety percent of the country's irrigation zones and 70% of its industrial plants are located in the northern region, which receives less than 40% of the country's total rainfall (Sandoval 2003). Droughts in northern Mexico in recent years have exacerbated water deficits. Mexico's National Water Commission along with other federal and state water management institutions have made significant efforts to respond to the country's growing water demands (Hearne 2004; Sandoval 2004). But despite regulatory measures to reduce groundwater overdraft, in many regions, pumping continues to exceed aquifer recharge and leads to declining water tables and deterioration of groundwater quality (Scott and Shah 2004).

Groundwater quality is influenced by several factors, including evapotranspiration, salinization, and rock-water and soil-water interactions (Liu et al. 2003). Hydrochemical analyses have been used throughout Mexico in recent years to assess groundwater quality and contamination by wastewater (Barragan et al. 2001; Dominguez-Mariani et al. 2004; Muñoz et al. 2004). However, available water quality records from northern Mexico are scarce. Factor analysis is an integral statistical method that can help to define and evaluate the structural-functional organization of systems (Kaplunovsky 2005). Factor analysis techniques have been applied to aquifers to achieve a variety of objectives such as identifying chemical and physical groups for the delineation of optimal operational zones (Melloul 1995), comparing groundwater composition of different survey areas (Helena et al. 2000), identifying salinization attributed to sea water intrusion (Morell et al. 1996), tracing ground water circulation in volcanic terrains (Join et al. 1997), and assessing groundwater contamination by anthropogenic activities (Subbarao et al. 1996). The present study used factor analysis to compare the water quality from two hydrological basins in northwestern Mexico. In one of them is located the city of Puerto Peñasco, while in the other one is located the city of El Rosarito. The two areas have very different rainfall patterns even though they are at the same latitude and within a distance of a few hundreds of kilometers. Under that condition we wanted to establish the degree to which weather and anthropogenic activities could affect groundwater quality in these areas. Puerto Peñasco has an average annual rainfall of 109 mm, occurring mostly in the summer, and is considered one of the most arid regions of México. El Rosarito has an average of 175 mm, occurring mostly in winter with a Mediterranean weather pattern (CNA 1991); this means that the territory has a distinctive wintertime precipitation regime (Pavia and Graef 2002).

## Materials and Methods

### Study Area

Puerto Peñasco is located in northwestern Sonora, south of the Altar Desert. The groundwater was sampled from

* Corresponding author: lmendez04@cibnor.mx

17 wells (Fig.1). The area is characterized by hot, dry conditions throughout most of the year, with long episodes of low precipitation in which the water supply becomes very low. In the last 70 years, three critical low rainfall periods have occurred: the 1930s, 1950s, and 1990s (Brito-Castillo et al. 2003). Puerto Peñasco is located in the basin of the Altar and Bamori rivers, within the irrigation districts of Altar-Pitiquito-Caborca and part of the Colorado River. Since surface water is scarce, both districts rely on groundwater from the aquifer. Well water is used for agriculture, cattle ranching, food processing (fish processing), and domestic activities (Cervantes-Rosas and Arredondo-García 1999). Puerto Peñasco has been growing rapidly, and it currently occupies 977,445 hectares with a population of 31,200 (INEGI 2000b). Some wells in the area surpass 100 m in depth (Table 1), indicating that the static level of the aquifer is very deep (INEGI 1981b). Fishery and tourism are the main economic activities in Puerto Peñasco.

El Rosarito is on the west coast of the Baja California Peninsula. Groundwater was sampled from 9 wells (Fig. 1). The study area is located in a semi-arid region south of Tijuana, inside the Tijuana-Arroyo de Maneadero river basin (INEGI 1981a). The average annual precipitation increases from 175 mm near the coast to 350 mm in the Juarez Mountains to the east (CNA 1991). This area has a high population density of 63,400 within 3,400 hectares (INEGI 2000a). The main uses of water are residential and commercial (INEGI 2000a).

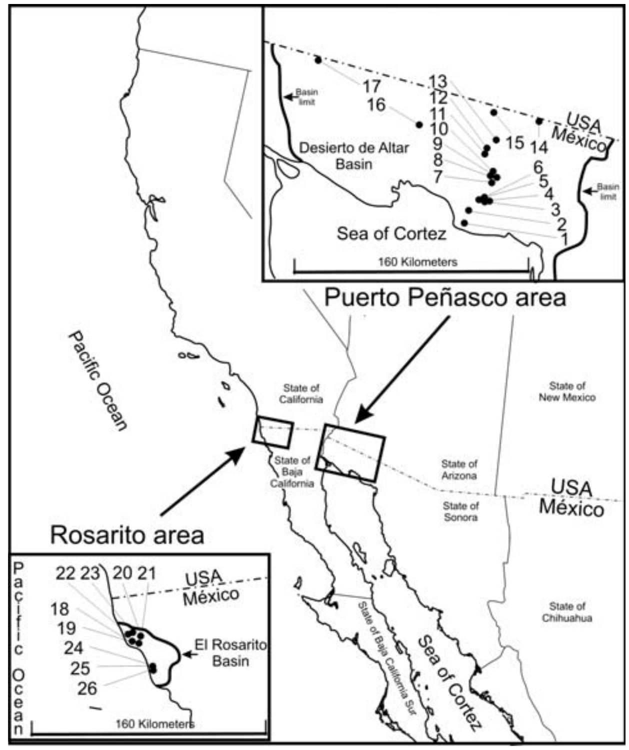


**Fig. 1.** Location of stations in the hydrological basins in Rosarito, Baja California, and Puerto Peñasco, Sonora.

**TABLE 1.** Summary of means, minimum, and maximum levels of the parameters and major constituents in the groundwater of Puerto Peñasco, Sonora and Rosarito, B.C., Mexico

| | | *Puerto Peñasco, Sonora* | | | *Rosarito, B.C.* | | |
|---|---|---|---|---|---|---|---|
| *Parameter* | *Units* | *Mean* | *Min.* | *Max.* | *Mean* | *Min.* | *Max.* |
| Depth | m | 79 | 3.21 | 150 | 11.8 | 1 | 46 |
| TDS | mg/L | 916 | 115 | 1612 | 2448 | 763 | 5157 |
| pH | — | 8.18 | 7.8 | 10.4 | 7.29 | 6.72 | 7.9 |
| E.C. | µS/cm | 1652 | 216 | 2873 | 4216 | 1375 | 8690 |
| Hardness | mg/L | 63 | 16 | 118 | 1517 | 277 | 3462 |
| Alkalinity | mg/L | 192 | 79 | 394 | 314 | 74.4 | 458 |
| Ca | mg/L | 8.89 | 2.2 | 23 | 293 | 52.1 | 849 |
| Mg | mg/L | 9.91 | 0.52 | 21.84 | 191 | 8 | 368 |
| Na | mg/L | 221 | 1.0 | 395 | 122 | 19 | 299 |
| Mn | mg/L | 0.013 | 0.002 | 0.032 | 0.509 | 0.014 | 1.95 |
| Cu | mg/L | 0.005 | 0.002 | 0.007 | 0.059 | 0.045 | 0.073 |
| Fe | mg/L | 0.068 | n.d. [b] | 0.894 | 0.009 | 0.004 | 0.018 |
| Cl | mg/L | 562 | 70 | 998 | 1516 | 513 | 3115 |
| $N\text{-}NH_4$ | mg/L | 0.011 | n.d. | 0.146 | 0.143 | n.d. | 0.871 |
| $N\text{-}NO_2$ | mg/L | 0.009 | n.d. | 0.05 | 0.099 | n.d. | 0.519 |
| $N\text{-}NO_3$ | mg/L | 0.97 | n.d. | 1.4 | 0.81 | n.d. | 1.43 |
| $P\text{-}PO_4$ | mg/L | 0.014 | n.d. | 0.168 | 0.013 | n.d. | 0.062 |

[a] E.C. = electrical conductivity.
[b] n.d. = not detected.

### Sample Collection and Analysis

Water samples from 26 wells were analyzed. In both areas the distribution of the sampled wells was representative of the extent of each hydrological basin. The locations of the wells were determined with a portable GPS (Magellan 315, Thales Navigation, Santa Clara, Calif.). Preservation of samples and analytical protocols were conducted according to standard methods for surface water analyses (APHA 1992). Samples from the wells were taken in bottles free of phosphates and heavy metals. A total of 16 variables were measured in each sample. In the field, conductivity and temperature were determined with a salinometer (YSI-85), and pH was determined with a pH meter (Orion 290A). In the laboratory, calcium (Ca), magnesium (Mg), sodium (Na), copper (Cu), iron (Fe), and manganese (Mn) were analyzed using an atomic absorption spectrophotometer (GBC model AVANTA). Analytical data were verified with standard, blank measurements, duplicate samples, and spikes after every block of ten samples. Ammonium ($N\text{-}NH_3$), nitrites ($N\text{-}NO_2$), nitrates ($N\text{-}NO_3$), and orthophosphates ($P\text{-}PO_4$) were analyzed with an auto-analyzer of ions with a continuous flow FIAS (Latchat model Quik Chem 8000). Chlorides ($Cl^-$) and sulfates ($SO_4^{-2}$) were analyzed using a spectrophotometer (Spectronic 21D) according to the methodologies recommended by APHA (1992).

### Statistical Analyses

Hydrochemical data were statistically analyzed by factor analysis using a varimax-rotated empirical orthogonal function. To reduce the number of variables and detect structure in the relationships between variables, factor analytic techniques were used to classify variables. Series of data of two or more variables that are in a scatter plot generate a regression line that represents the "best" summary of the linear relationship between the variables. Therefore, two or more variables were reduced in a linear combination called a factor. During the computational process, the Cartesian axes were rotated. The objective was to maximize the variance (variability) of the factor while the variance around the factor was minimized. This type of rotation is called variance maximizing. After the first line had been drawn through the data, we continued and defined another line that maximized the remaining variability. This process continued until the totality of the variance was covered. During this process, consecutive factors were extracted. Because each consecutive factor was defined to maximize the variability not considered by the preceding factor, consecutive factors were uncorrelated or orthogonal, with a minimum independence between each other (Hill and Lewicki 2007).

The series of data were also analyzed by calculating the correlation index with the objective of evaluating the relationship between the variables. Both statistical methods were done using STATISTICA computer software, version 5.0. Factor analysis and correlation index offer a more complete understanding of water quality and the status of groundwater systems than traditional quantitative methods. Both statistical methods determine the relationships between chemical variables and identify possible sources and factors that influence water systems (Liu et al. 2003; Simeonov et al. 2003).

## Results and Discussion

### Water Quality

The mean, minimum, and maximum levels of the hydrochemical analyses are shown in Table 1. Although 71 underground water sources have been recorded in the basin in which Puerto Peñasco is located (SIUE 1999), of those, only 17 were operating in 2003. The wells sampled in this study were only domestic wells.

The static levels of the Puerto Peñasco wells ranged from 3.21 to more than 150 metrers below ground surface (Table 1). Water level is mainly affected by the extraction through wells. The increase of ground water is very limited by the scarce rain precipitation in this region or other sources of refilling. In some coastal areas, water filtration occurs from the aquifer to the sea (SIUE 1999). The positive migration of water from the ground aquifer to the sea has reduced seawater intrusion into the aquifer (SIUE 1999). However, evidence of seawater intrusion was recorded in some of the areas around Puerto Peñasco. On the other hand, in El Rosarito, static levels ranged from 3.47 to 12.80 metres below ground surface. The monitored wells in this area are mainly affected by domestic extraction.

The total dissolved solids (TDS) in the groundwater of Puerto Peñasco area ranged from 115 to 1,612 mg/L with a mean of 916 mg/L, and is classified as oligohaline (Por 1972), in contrast to the values for El Rosario, which are much higher with a mean of 2,448 mg/L and a range from 763 to 5,157 mg/L that is almost three times the average concentration in Puerto Peñasco. The high levels of TDS in both aquifers suggest seawater intrusion, which is corroborated by a high average of chloride concentrations (562 and 1,516 mg/L respectively) greater than 250 mg/L, the maximum level recommended for human consumption (WHO 1996). The chloride levels in El Rosarito are almost three times higher than in Puerto Peñasco. The combination of high levels of TDS and chloride was the reason of the discontinued use as a water supply from the El Rosarito aquifer in 2001. Therefore, the future use of this aquifer seems to be very difficult because chloride is a conservative ion that is difficult to remove by most processes other than precipitation at very late stages of salinization (Richter and Kreitler 1993).

The pH level was found outside of the acceptable range (pH 6.5 to 9.5 [WHO 1996]) in only one sample from Puerto Peñasco (Well 12, pH 10.4). Well 12 also had Fe concentrations (0.894 mg/L) above the recommended level for drinking water (0.30 mg/L [WHO 1996]). The Mn and Cu concentrations in all wells of Puerto Peñasco were within safe levels established for drinking water (0.5 mg/L and 2.00 mg/L, respectively).

At El Rosarito, Mn concentrations were generally higher than the values considered normal for drinking water (WHO 1996). Concentrations higher than 0.1 mg/L impart an undesirable taste and stain plumbing fixtures and laundry (Griffin 1960). However, Cu, Fe, and pH were within the established margins of health safety (WHO 1996).

Na was higher than the maximum established level (200 mg/L) in 9 of the 17 wells sampled in Puerto Peñasco and 2 of the 9 wells from Rosarito (Table 1). Calcium concentrations ranged from 2.2 to 23 mg/L in Puerto Peñasco and from 52.1 to 849 mg/L in El Rosarito. Levels of Ca above 100 mg/L are common in natural water, and higher levels, up to 300 mg/L, have an acceptable taste for consumers (National Research Council 1977). The highest concentrations of Mg were 21.84 mg/L in Puerto Peñasco and 369 mg/L in El Rosarito. Mg levels in natural water are typically up to 10 mg/L (National Research Council 1977). High levels of calcium and manganese, such as those recorded in El Rosarito, are associated with aragonite (Ahn 2004) and dolomite aquifers (Dobrzynski 2007).

Groundwater hardness of the Puerto Peñasco aquifer is generally classified as soft (lower than 75 mg/L), although some wells have water that was slightly harder (75 to 150 mg/L [Sawyer and McCarty 1967]). In contrast, Rosarito well water was considered very hard, with measurements ranging from 277 to 3,462 mg/L. It is worthwhile noting that some studies have related hardness to cardiovascular disease (Leoni et al. 1985; Dzik 1989). On the other hand, both aquifers have adequate alkalinity, with a total alkalinity at Puerto Peñasco and Rosarito ranging from 74.4 mg/L to 458 mg/L, while most of the surface streams contain less than 200 mg/L, but in groundwaters, somewhat higher concentrations are not uncommon (Hem 1992). The recommended alkalinity of drinking water (i.e., the concentration of bicarbonate) should not be less than 60 mg/L (1 meq/L [Sedin 2001]).

The hardness in Puerto Peñasco is lower than the alkalinity, while in Rosarito, this condition is the opposite. If hardness exceeds alkalinity, the excess is considered as noncarbonated hardness (Hem 1992); therefore, in Rosarito, a big proportion of the anions are not carbonates.

Nitrates were the nutrient of the highest concentration in both aquifers, which is common in groundwater (Nolan and Stoner 2000). Nitrate concentrations in groundwater can increase significantly from agricultural fertilizers and septic tanks (Kampbell et al. 2003). The highest concentrations of nitrates and nitrites in groundwater at Puerto Peñasco (10.00 mg/L) and Rosarito (3.0 mg/L) were below the maximum levels recommended by WHO (1996). Ammonia concentration was found only in one sample (0.87 mg/L from Rosarito Well 12) over the maximum tolerable limit (0.2 mg/L [WHO 1996]). Ammonia does not generally have direct relevance for human health, but it is an important indicator of fecal contamination and disinfection efficiency, and its presence in high levels causes unfavorable taste and odor (WHO 1996). Phosphates are not included in the list of drinking water contaminants (Environmental Protection Agency 2002). However, higher concentrations could be indicative of agricultural activities, domestic pollution, or extensive degradation of subterranean organic matter (Meybeck 1982; Griffioen 2006). Natural dissolved inorganic phosphate in river water should average about 0.01 mg/L, which is a similar level to that found in both zones. Phosphate concentrations up to 14 mg/L are related to waste disposal (Hem 1992).

## Aquifer Characterization

Based on the chemical profiles shown in Tables 2 and 3, the two aquifers have different composition patterns. Five principal components with eigenvalues >1 in Puerto Peñasco and Rosarito explained 92 and 90%, respectively, of the total variance in the water quality data set (Table 2). For loading values of the variables greater than 0.75, 0.75 to 0.5, and 0.5 to 0.3, the designations "strong," "moderate," and "weak," respectively, are used (Liu et al. 2003).

In Puerto Peñasco, the first factor explained 48% of the total variance with strong negative factor loadings for pH, Fe, $NO_2$, and $PO_4$ (Table 3, A). These parameters are associated with reductive environments characterized by high levels of soluble iron and nitrites. The second factor explained 19% of the total variance with a strong positive factor loading for TDS, conductivity, and chlorides, and a strong negative factor loading for ammonium, indicating sewage or agricultural contamination (Kampbell et al. 2003; Panno et al. 2006). Bacteriological pollution was not found in municipal drinking water from the city of Nogales, Sonora, although, up to 160 million counts per 100 mL of total coliforms were recorded in samples from wells used to supply water to areas not covered by the municipal system (Sanchez 1995).

The third factor explained 12% of the variance with strong positive factor loadings for Cu, Mg, and hardness, indicating leaching from overlying soils probably caused by water extraction, which results in an increase of minerals in the water. The fourth factor explained 7% of the total variance with a strong negative loading for alkalinity and a weak loading for nitrates; both values indicated a biological denitrification process that results in decreasing levels of alkalinity and nitrates (Flores III et al. 2007). The fifth factor explained 6% of the variance with a strong negative loading for Ca and a moderate positive loading for Na, indicating influences of seawater intrusion into the aquifer.

In El Rosarito (Table 3, B), the first factor accounted for 43% of the total variance with strong positive loadings in TDS, conductivity, Cu, Ca, hardness, and chlorides, indicating major salinization of the aquifer from seawater intrusion, typically a result of water extraction (Simeonov et al. 2003), confirming our observation previously stated in this manuscript at the beginning of the discussion. The second factor accounted for 18% of the total variance with a strong positive loading for pH and a strong negative loading for nitrites, perhaps indicative of organic contamination problems. The third factor accounted for 13% of the total variance with a strong negative loading for alkalinity, nitrates, and phosphates, which can also be related to a biological denitrification process (Flores III et al. 2007), such as in Puerto Peñasco, and a precipitation of phosphates. The fourth factor accounted for 9% of the total variance with strong positive loadings for Mn and Fe, indicating reduced conditions. This conclusion was corroborated by the strong odour of $H_2S$ detected in some of the wells. The fifth factor explained 7% of the total variance with a moderate loading for ammonium.

## Relationships Between Water Components

In both areas, chloride is the anion present in the highest concentrations (Table 1). Chloride in Puerto Peñasco (Table 4) is associated with nitrites, nitrates, ammonium, and phosphates, probably indicating sewage influence (DeSimone and Howes 1998) and redox reactions. Phosphate concentrations associated with ammonium and $CO_2$ pressure in near-neutral pH pressure are related to low levels of oxygen and organic matter degradation (Griffioen 2006). Chloride in Rosarito is associated with hardness (Table 5), confirming that it is a noncarbonate hardness type.

In Rosarito (Table 5), Na significantly correlates with hardness ($r = 0.73$, $p < 0.001$), while in Puerto Peñasco (Table 4), it correlates with alkalinity ($r = 0.51$, $p < 0.04$),

**TABLE 2.** Eigenvalues, percentage of variance, cumulative eigenvalues, and cumulative percentage of variance for the varimax-rotated factor analysis of hydrochemical constituents of ground water at Puerto Peñasco, Sonora (A) and Rosarito, B.C. (B), México

| | *Eigenval.* | *% total Variance* | *Cumul. Eigenval.* | *Cumul. %* |
|---|---|---|---|---|
| *A. Puerto Peñasco* | | | | |
| 1 | 7.6874 | 48.0465 | 7.6874 | 48.0465 |
| 2 | 2.9916 | 18.6974 | 10.679 | 66.7438 |
| 3 | 1.9571 | 12.2316 | 12.6361 | 78.9755 |
| 4 | 1.0717 | 6.6981 | 13.7078 | 85.6735 |
| 5 | 1.0307 | 6.442 | 14.7385 | 92.1156 |
| 6 | 0.4225 | 2.6405 | 15.161 | 94.7561 |
| 7 | 0.336 | 2.0999 | 15.497 | 96.856 |
| 8 | 0.2172 | 1.3575 | 15.7142 | 98.2135 |
| 9 | 0.1331 | 0.8318 | 15.8472 | 99.0453 |
| 10 | 0.0762 | 0.4763 | 15.9235 | 99.5216 |
| *B. Rosarito* | | | | |
| 1 | 6.8818 | 43.0111 | 6.8818 | 43.0111 |
| 2 | 2.8092 | 17.5577 | 9.691 | 60.5688 |
| 3 | 2.0601 | 12.8757 | 11.7511 | 73.4445 |
| 4 | 1.4847 | 9.2796 | 13.2359 | 82.7241 |
| 5 | 1.1903 | 7.4395 | 14.4262 | 90.1637 |
| 6 | 0.6516 | 4.0728 | 15.0778 | 94.2365 |
| 7 | 0.3012 | 1.8825 | 15.379 | 96.119 |
| 8 | 0.24 | 1.5 | 15.619 | 97.619 |
| 9 | 0.0476 | 0.2976 | 15.6667 | 97.9167 |
| 10 | 0.0476 | 0.2976 | 15.7143 | 98.2143 |

**TABLE 3.** Loading factors obtained in the factorial analysis for Puerto Peñasco, Sonora (A) and Rosarito, B.C.(B)

| | *A* | | | | | | *B* | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Factor 1* | *Factor 2* | *Factor 3* | *Factor 4* | *Factor 5* | | *Factor 1* | *Factor 2* | *Factor 3* | *Factor 4* | *Factor 5* |
| TDS | 0.3505 | 0.8520 | 0.2318 | -0.1202 | 0.2528 | TDS | 0.9631 | 0.0096 | 0.1191 | 0.0869 | 0.0269 |
| pH | -0.9262 | -0.2936 | -0.1087 | 0.1147 | -0.0127 | pH | -0.4686 | 0.7530 | -0.1929 | -0.3425 | 0.1551 |
| COND[a] | 0.3653 | 0.8513 | 0.2315 | -0.1243 | 0.2403 | COND | 0.9582 | 0.0051 | 0.1321 | 0.0964 | 0.0331 |
| Mn | -0.5933 | -0.0969 | -0.1265 | 0.2233 | -0.6406 | Mn | -0.1768 | -0.0679 | 0.2033 | 0.8417 | 0.0616 |
| Cu | -0.1090 | 0.0715 | 0.8528 | -0.2857 | 0.1396 | Cu | 0.7922 | 0.0998 | -0.1874 | -0.2311 | 0.4672 |
| Fe | -0.9573 | -0.1258 | -0.1464 | 0.0956 | 0.0139 | Fe | 0.3650 | -0.1301 | -0.0967 | 0.8183 | 0.2765 |
| Ca | 0.1683 | -0.4701 | 0.2875 | -0.1526 | -0.7612 | Ca | 0.8148 | 0.0919 | 0.4457 | 0.1474 | -0.2160 |
| Mg | 0.3374 | 0.3386 | 0.7805 | 0.3187 | 0.1520 | Mg | 0.5764 | 0.5909 | 0.1473 | 0.1053 | -0.4733 |
| Na | 0.2598 | 0.3006 | 0.2235 | -0.3843 | 0.7315 | Na | 0.5397 | 0.0540 | 0.1711 | 0.5913 | -0.3579 |
| Hard.[a] | 0.3818 | -0.0002 | 0.8225 | 0.1732 | -0.3289 | Hard. | 0.7746 | 0.3105 | 0.3521 | 0.1406 | -0.3413 |
| Alk. | 0.2901 | 0.2261 | 0.0041 | -0.8217 | 0.0763 | Alk. | -0.1421 | -0.4335 | -0.8617 | 0.0454 | -0.1347 |
| $N\text{-}NO_2$ | -0.8948 | -0.0847 | -0.1134 | 0.1719 | -0.1722 | $N\text{-}NO_2$ | -0.2735 | -0.8947 | -0.1098 | 0.0276 | 0.0693 |
| $N\text{-}N0_3$ | 0.3758 | 0.5082 | -0.0708 | -0.6449 | 0.2530 | $N\text{-}N0_3$ | -0.2636 | 0.0028 | -0.8380 | -0.2326 | 0.0687 |
| $N\text{-}NH_4$ | 0.2301 | -0.8367 | 0.1550 | 0.3278 | -0.0485 | $N\text{-}NH_4$ | -0.0573 | 0.0383 | -0.3423 | -0.3340 | -0.7409 |
| $P\text{-}PO_4$ | -0.9479 | -0.1409 | -0.0848 | 0.1579 | -0.0952 | $P\text{-}PO_4$ | -0.0772 | 0.4684 | -0.7626 | -0.0540 | -0.2311 |
| $Cl^-$ | 0.3855 | 0.8567 | 0.2185 | -0.0999 | 0.2060 | $Cl^-$ | 0.9635 | 0.0064 | 0.1125 | 0.0817 | 0.0490 |
| Exp.Var.[a] | 4.8759 | 3.7635 | 2.3988 | 1.7491 | 1.9511 | Exp.Var. | 5.8468 | 2.2648 | 2.6964 | 2.1461 | 1.4721 |
| Prp.Totl.[a] | 0.3047 | 0.2352 | 0.1499 | 0.1093 | 0.1219 | Prp.Totl. | 0.3654 | 0.1416 | 0.1685 | 0.1341 | 0.0920 |

[a] COND = conductivity; Hard. = hardness; Exp. Var. = explained variance; Prp. Totl. = proportion of total variance.

indicating that in Rosarito, Na is not associated mainly with the carbonate fraction. Therefore, in Rosarito, phosphates positively correlate with nitrates ($r$ = 0.59, $p$ < 0.01, Table 5), while in Puerto Peñasco, phosphates negatively correlate with nitrates ($r$ = -0.53, $p$ < 0.03, Table 4) and positively correlate with nitrites ($r$ = 0.93, $p$ < 0.001, Table 4). Both compounds, natural constituents, are at low levels, but the sites with high concentrations could be related to sewage or to the agricultural use of fertilizers or pesticides. In Puerto Peñasco, phosphates show a strong correlation with Fe ($r$ = 0.98, $p$ < 0.001, Table 4). During anoxic conditions, iron is reduced and suspended into the water column. When an oxygenation reaction occurs, iron is precipitated, again binding to phosphates (Griffioen 2006). This correlation could also indicate the presence of minerals such as strengite ($FePO_4{\cdot}2H_2O$) and metastrengite (Speiser and Kistler 2002) in this area. The strong correlation between nitrates and chlorides ($r$ = 0.68, $p$ < 0.001, Table 4) at Puerto Peñasco is a confirmative influence of domestic sewage on the water quality of the wells of this area.

## Conclusions

Factorial analysis has been shown to be an adequate methodology for the detection of the possible causes that are affecting the quality of a hydrological basin. This statistical method gave several factors, however, the first two were enough to evaluate the main problems that affected the water quality of a hydrological basin, and they could be corroborated by using a correlation analysis which gives a clear relationship between the parameters evaluated.

Groundwater from areas near El Rosarito is mainly affected by seawater intrusion and the presence of high levels of manganese, while groundwater characteristics at Puerto Peñasco are influenced by reductive conditions that were probably caused by bacterial contamination, mainly by septic systems and domestic sewage. Puerto Peñasco is a very arid zone where the only source of fresh water is the aquifer. At Rosarito, the aquifer is no longer exploited officially but continues to be used locally. The evaluation of the degree in which environmental and

**TABLE 4.** Matrix correlation for hydrochemical data in Puerto Peñasco, Sonora [a]

| | *TDS* | *pH* | *E.C.* [b] | *Mn* | *Cu* | *Fe* | *Ca* | *Mg* | *Na* | *Hard.* [b] | *Alk.* [b] | *N-NO₂* | *N-NO₃* | *N-NH₄* | *P-PO₄* | *Cl⁻* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TDS | 1.00 | | | | | | | | | | | | | | | |
| | — | | | | | | | | | | | | | | | |
| pH | -0.60 | 1.00 | | | | | | | | | | | | | | |
| | 0.01 | — | | | | | | | | | | | | | | |
| E.C. | 1.00 | -0.62 | 1.00 | | | | | | | | | | | | | |
| | 0.00 | 0.01 | — | | | | | | | | | | | | | |
| Mn | -0.53 | 0.60 | -0.53 | 1.00 | | | | | | | | | | | | |
| | 0.03 | 0.01 | 0.03 | — | | | | | | | | | | | | |
| Cu | 0.28 | -0.08 | 0.28 | -0.15 | 1.00 | | | | | | | | | | | |
| | 0.29 | 0.76 | 0.28 | 0.56 | — | | | | | | | | | | | |
| Fe | -0.48 | 0.94 | -0.50 | 0.59 | -0.07 | 1.00 | | | | | | | | | | |
| | 0.05 | 0.00 | 0.04 | 0.01 | 0.78 | — | | | | | | | | | | |
| Ca | -0.44 | -0.04 | -0.43 | 0.30 | 0.08 | -0.15 | 1.00 | | | | | | | | | |
| | 0.08 | 0.87 | 0.09 | 0.25 | 0.75 | 0.58 | — | | | | | | | | | |
| Mg | 0.58 | -0.46 | 0.58 | -0.35 | 0.53 | -0.45 | -0.05 | 1.00 | | | | | | | | |
| | 0.01 | 0.07 | 0.01 | 0.17 | 0.03 | 0.07 | 0.84 | — | | | | | | | | |
| Na | 0.61 | -0.40 | 0.61 | -0.71 | 0.33 | -0.35 | -0.51 | 0.37 | 1.00 | | | | | | | |
| | 0.01 | 0.11 | 0.01 | 0.00 | 0.19 | 0.17 | 0.04 | 0.14 | — | | | | | | | |
| Hard. | 0.22 | -0.41 | 0.23 | -0.12 | 0.49 | -0.46 | 0.56 | 0.80 | 0.01 | 1.00 | | | | | | |
| | 0.39 | 0.11 | 0.38 | 0.66 | 0.05 | 0.06 | 0.02 | 0.00 | 0.98 | — | | | | | | |
| Alk. | 0.43 | -0.40 | 0.43 | -0.41 | 0.16 | -0.41 | -0.04 | -0.01 | 0.51 | -0.03 | 1.00 | | | | | |
| | 0.09 | 0.11 | 0.08 | 0.10 | 0.54 | 0.10 | 0.87 | 0.96 | 0.04 | 0.90 | — | | | | | |
| N-NO₂ | -0.46 | 0.90 | -0.47 | 0.65 | -0.15 | 0.89 | -0.03 | -0.36 | -0.48 | -0.32 | -0.37 | 1.00 | | | | |
| | 0.06 | 0.00 | 0.06 | 0.01 | 0.56 | 0.00 | 0.92 | 0.15 | 0.05 | 0.22 | 0.14 | — | | | | |
| N-NO₃ | 0.69 | -0.59 | 0.70 | -0.61 | 0.15 | -0.43 | -0.24 | 0.06 | 0.67 | -0.09 | 0.67 | -0.51 | 1.00 | | | |
| | 0.00 | 0.01 | 0.00 | 0.01 | 0.58 | 0.08 | 0.36 | 0.82 | 0.00 | 0.72 | 0.00 | 0.04 | — | | | |
| N-NH₄ | -0.61 | 0.06 | -0.62 | 0.02 | -0.09 | -0.10 | 0.46 | 0.02 | -0.34 | 0.29 | -0.33 | -0.02 | -0.56 | 1.00 | | |
| | 0.01 | 0.81 | 0.01 | 0.93 | 0.73 | 0.70 | 0.06 | 0.94 | 0.18 | 0.25 | 0.20 | 0.93 | 0.02 | — | | |
| P-PO₄ | -0.50 | 0.96 | -0.51 | 0.64 | -0.09 | 0.98 | -0.03 | -0.39 | -0.43 | -0.35 | -0.44 | 0.93 | -0.53 | -0.03 | 1.00 | |
| | 0.04 | 0.00 | 0.03 | 0.01 | 0.73 | 0.00 | 0.90 | 0.12 | 0.08 | 0.17 | 0.08 | 0.00 | 0.03 | 0.90 | — | |
| Cl⁻ | 0.99 | -0.64 | 0.99 | -0.50 | 0.25 | -0.51 | -0.42 | 0.59 | 0.58 | 0.24 | 0.42 | -0.48 | 0.68 | -0.60 | -0.53 | 1.00 |
| | 0.00 | 0.01 | 0.00 | 0.04 | 0.32 | 0.03 | 0.10 | 0.01 | 0.01 | 0.35 | 0.09 | 0.05 | 0.00 | 0.01 | 0.03 | — |

[a] Statistical significance ($p$) is indicated below each parameter.
[b] E.C. = electrical conductivity; Hard. = hardness; Alk. = alkalinity.

**TABLE 5.** Matrix correlation for the hydrochemical data of ground water at Rosarito, B.C.

| | *TDS* | *PH* | *E.C.*[b] | *Mn* | *Cu* | *Fe* | *Ca* | *Mg* | *Na* | *Hard.*[b] | *Alk.*[b] | *N-NO₂* | *N-NO₃* | *N-NH₄* | *P-PO₄* | *Cl⁻* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TDS | 1.00 | | | | | | | | | | | | | | | |
| | — | | | | | | | | | | | | | | | |
| pH | -0.51 | 1.00 | | | | | | | | | | | | | | |
| | 0.32 | — | | | | | | | | | | | | | | |
| E.C. | 0.99 | -0.51 | 1.00 | | | | | | | | | | | | | |
| | 0.00 | 0.03 | — | | | | | | | | | | | | | |
| Mn | -0.03 | -0.29 | -0.01 | 1.00 | | | | | | | | | | | | |
| | 0.89 | 0.24 | 0.95 | — | | | | | | | | | | | | |
| Cu | 0.75 | -012 | 0.75 | -0.36 | 1.00 | | | | | | | | | | | |
| | 0.00 | 0.64 | 0.00 | 0.15 | — | | | | | | | | | | | |
| Fe | 0.43 | -0.50 | 0.43 | 0.63 | 0.28 | 1.00 | | | | | | | | | | |
| | 0.08 | 0.03 | 0.07 | 0.01 | 0.25 | — | | | | | | | | | | |
| Ca | 0.89 | -0.51 | 0.88 | 0.07 | 0.45 | 0.29 | 1.00 | | | | | | | | | |
| | 0.00 | 0.00 | 0.00 | 0.78 | 0.06 | 0.24 | — | | | | | | | | | |
| Mg | 0.62 | 0.05 | 0.61 | -0.05 | 0.25 | 0.08 | 0.72 | 1.00 | | | | | | | | |
| | 0.01 | 0.85 | 0.01 | 0.83 | 0.32 | 0.75 | 0.01 | — | | | | | | | | |
| Na | 0.57 | -0.54 | 0.57 | 0.26 | 0.09 | 0.56 | 0.73 | 0.59 | 1.00 | | | | | | | |
| | 0.01 | 0.02 | 0.01 | 0.30 | 0.71 | 0.02 | 0.00 | 0.01 | — | | | | | | | |
| Hard. | 0.83 | -0.31 | 0.83 | 0.02 | 0.40 | 0.22 | 0.95 | 0.89 | 0.73 | 1.00 | | | | | | |
| | 0.00 | 0.21 | 0.00 | 0.93 | 0.10 | 0.37 | 0.00 | 0.00 | 0.00 | — | | | | | | |
| Alk. | -0.26 | -0.13 | -0.27 | -0.10 | -0.08 | 0.08 | -0.52 | -0.41 | -0.17 | -0.51 | 1.00 | | | | | |
| | 0.30 | 0.61 | 0.28 | 0.69 | 0.76 | 0.76 | 0.03 | 0.09 | 0.49 | 0.03 | — | | | | | |
| N-NO₂ | -0.29 | -0.52 | -0.28 | 0.07 | -0.29 | 0.06 | -0.41 | -0.72 | -0.21 | -0.57 | 0.53 | 1.00 | | | | |
| | 0.24 | 0.03 | 0.25 | 0.79 | 0.23 | 0.80 | 0.09 | 0.00 | 0.39 | 0.01 | 0.02 | — | | | | |
| N-NO₃ | -0.38 | 0.38 | -0.38 | -0.22 | 0.01 | -0.26 | -0.61 | -0.38 | -0.50 | -0.56 | 0.77 | .098 | 1.00 | | | |
| | 0.12 | 0.12 | 0.12 | 0.38 | 0.96 | 0.30 | 0.01 | 0.12 | 0.03 | 0.02 | 0.00 | 0.70 | — | | | |
| N-NH₄ | -0.14 | 0.14 | -0.15 | -0.27 | -0.19 | -0.41 | -0.11 | 0.25 | -0.16 | 0.04 | 0.37 | -0.12 | 0.36 | 1.00 | | |
| | 0.59 | 0.58 | 0.55 | 0.27 | 0.45 | 0.09 | 0.67 | 0.32 | 0.52 | 0.89 | 0.14 | 0.63 | 0.14 | — | | |
| P-PO₄ | -0.19 | 0.54 | -0.20 | -0.36 | 0.01 | -0.15 | -0.35 | 0.26 | -0.03 | -0.12 | 0.51 | -0.25 | 0.59 | 0.37 | 1.00 | |
| | 0.45 | 0.00 | 0.42 | 0.00 | 0.99 | 0.55 | 0.15 | 0.30 | 0.91 | 0.64 | 0.00 | 0.31 | 0.01 | 0.13 | — | |
| Cl⁻ | 0.99 | -0.50 | 0.99 | -0.04 | 0.77 | 0.43 | 0.87 | 0.60 | 0.56 | 0.82 | -0.25 | -0.29 | -0.37 | -0.15 | -0.19 | 1.00 |
| | 0.00 | 0.00 | 0.00 | 0.89 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.31 | 0.25 | 0.13 | 0.55 | 0.45 | — |

[a] Statistical significance (*p*) is indicated below each parameter.
[b] E.C. = electrical conductivity; Hard. = hardness; Alk. = alkalinity.

human impacts affect the quality of the water used for the population can help national and state water managers to develop more effective allocation practices to prevent irreversible degradation of the resource.

## Acknowledgments

We thank the financial support provided by The Secretariat of Environment and Natural Resources (SEMARNAT), project 739-0 and CIBNOR projects PC 2.2 and PC 3.6. The staff editor at CIBNOR improved the English text.

## References

**Ahn JW, Choi KS, Yoon SH, Hwan K.** 2004. Synthesis of aragonite by the carbonation process. J. Am. Ceram. Soc. **87:**286–288.

**APHA.** 1992. Standard Methods for Examination of Water and Wastewater. 18th Edition. American Public Health Association. Washington D.C.

**Barragan RM, Birkle P, Portugal ME, Arellano VM, Alvarez RJ.** 2001. Geochemical survey of medium temperature geothermal resources from the Baja California Peninsula and Sonora, Mexico. J. Volcanol. Geoth. Res. **110:**101–119.

**Brito-Castillo L, Douglas AV, Leyva-Contreras A, Lluch-Belda D.** 2003. The effect of large-scale circulation on precipitation and streamflow in the Gulf of California continental watershed. Int. J. Climatol. **23:**751–768.

**Cervantes-Rosas OD, Arredondo-García MC.** 1999. Ecological regionalization in a portion of the coast to the south of Port Peñasco, Sonora. *In* Proceedings of the VII Congreso de la Asociación de Investigadores del Mar de Cortés y Primer Simposium Internacional sobre el Mar de Cortés. Hermosillo, Sonora.

**CNA.** 1991. Comisión Nacional del Agua. Isoyetas normales anuales de la República Mexicana, período 1931–1990. Regiones hidrológicas 1 Baja California Noroeste (Ensenada); 4 Baja California Noreste (San Felipe); 7 Río Colorado y 8 Sonora Norte. Lámina I.

**DeSimone LA, Howes BL.** 1998. Nitrogen transport in shallow aquifer receiving wastewater discharge: A mass balance approach. Water Resour. Res. **34:**271–285.

**Dobrzynski D.** 2007. Chemical diversity of groundwater in the carboniferous–permian aquifer in the Unislaw Slaski – Sokolowsko area (the Sudetes, Poland); a geochemical modelling approach. Acta Geol. Polonica **57:**97–112.

**Dominguez-Mariani E, Carrillo-Chavez A, Ortega A, Orozco-Esquivel MT**. 2004. Wastewater Reuse in Valsequillo Agricultural Area, Mexico: Environmental Impact on Groundwater. Water Air Soil Poll. **155**:251–267.

**Dzik AJ.** 1989. Cerebrovascular disease mortality rates and water hardness in North Dakota. SDJ Med. **42**:5–7.

**Environmental Protection Agency**. 2002 National Recommended Water Quality Criteria. EPA/822/R-02-047. Office of Water. Office of Science and Technology (94304T). United States of America.

**Flores III A, Nisola GM, Cho E, Gwon EM, Kim H, Lee Ch, Park S, Chung WJ.** 2007. Bioaugmented sulfur-oxidzing denitrification system with Alcaligens defragrans B21 for high nitrate containing wastewater treatment. Bioprocess Biosyst. Eng. **30**:197–205.

**Griffin AE.** 1960. Significance and removal of manganese in water supplies. J. Am. Water Works Assoc. **52**:1326–1332.

**Griffioen J.** 2006. Extent of immobilization of phosphate during aeration of nutrient-rich, anoxic groundwater. J. Hydrol. **320**:359–369.

**Hearne RR.** 2004. Evolving water management institutions in Mexico Water Resour. Res. **40**: W12S04, doi:10.1029/2003WR002745

**Helena B, Pardo R, Vega M, Barrado E, Fernandez JM, Fernandez L.** 2000. Temporal evolution of groundwater composition in an alluvial aquifer (Pisuerga River, Spain) by principal component analysis. Wat. Res. **34**:807–816.

**Hem JD.** 1992. Study and interpretation of the chemical characteristics of natural water. Water-supply Paper 2254. US Geological Survey, Reston, VA.

**Hill T, Lewicki P.** 2007. STATISTICS Methods and Applications. StatSoft, Tulsa, OK.

**INEGI.** 1981a. Carta hidrológica de aguas superficiales, 1:25000, Tijuana I11–11.

**INEGI.** 1981b. Carta hidrológica de aguas subterráneas, 1:25000, Tijuana I11–11.

**INEGI.** 2000a. Anuario estadístico de Baja California. Instituto Nacional de Estadística, Geografía e Historia. Aguascalientes, México.

**INEGI.** 2000b. Anuario estadístico de Sonora. Instituto Nacional de Estadística, Geografía e Historia. Aguascalientes, México.

**Join JL, Coudray J, Longworth K.** 1997. Using principal components analysis and Na/Cl ratios to trace ground water circulation in a volcanic island: The example of Reunion. J. Hydrol. **190**:1–18.

**Kampbell DH, An YJ, Jewell KP, Masoner JR.** 2003. Groundwater quality surrounding Lake Texoma. Environ. Pollut. **125**:183–191.

**Kaplunovsky AS.** 2005. Factor analysis in environmental studies. HAIT J. Sci. Eng. **B:2**:54–94.

**Leoni V, Fabián L, Ticchiarelli L.** 1985. Water hardness and cardiovascular mortality rate in Abruzzo, Italy. Arch. Environ. Health **40**:274–278.

**Liu ChW, Lin KH, Kuo YM.** 2003. Application of factor analysis in the assessment of groundwater quality in a blackfoot disease area in Taiwan. Sci. Total Environ. **313**:77–89.

**Melloul AJ.** 1995. Use of principal components analysis for studying deep aquifers with scarce data-application to the Nubian sandstone aquifer, Egypt and Israel. Hydrol. J. **3**:19–39.

**Meybeck M.** 1982. Carbon, nitrogen and phosphorus transport by World Rivers. Am. J. Sci. **282**:401–450.

**Morell I, Giménez E, Esteller MV.** 1996. Application of the principal components analysis to the study of salinization on the Castellon Plain (Spain). Sci. Total Environ. **177**:161–171.

**Muñoz H, Armienta MA, Vera A, Ceniceros N.** 2004. Nitrate in groundwater of Huamantla Valley, Tlaxcala, Mexico. Rev. Int. Contam. Ambient. **20**:91–97.

**National Research Council.** 1977. Drinking water and health. National Academy of Sciences. Washington D.C. 940 p.

**Nolan BT, Stoner JD.** 2000. Nutrients in groundwater of the conterminous United States, 1992–1995. Environ. Sci. Technol. **37**:1156–1165.

**Panno SV, Hackley KC, Hwang HH, Greenberg SE, Krapac IG, Landsberger S, O'Kelly, DJ.** 2006. Characterization and Identification of Na-Cl Sources in Ground Water. Ground Water **44**:176–187.

**Pavia EG, Graef F.** 2002. The Recent Rainfall Climatology of the Mediterranean Californias. J. Clim. **15**:2697–2701.

**Por FD.** 1972. Hydrobiological notes on the high-salinity waters of the Sinai Peninsula. Mar. Biol. **14**:111–119.

**Richter BC, Kreitler WC.** 1993. Geochemical Techniques for Identifying Sources of Groundwater Salinization. CRC Press, New York, 258p.

**Sanchez R.** 1995. Water Quality Problems in Nogales, Sonora. Environ Health Perspect. **103**:93–97.

**Sandoval CAE.** 2003. Vulnerability due to extremes: droughts. Enzo Levi Lecture 2002 Ing. Hidraul. Mex. **18**:133–155.

**Sandoval R.** 2004. A participatory approach to integrated aquifer management: The case of Guanajuato State, Mexico. Hydrogeol. J. **12**:6–13.

**Sawyer CN, McCarty PL.** 1967. Chemistry for Sanitary Engineers. 2nd Ed. McGraw-Hill Book Co., New York, 363p.

**Scott CA, Shah T.** 2004. Groundwater Overdraft Reduction through Agricultural Energy Policy: Insights from India and Mexico. Int. J. Water Resour. D. **20**:149–164.

**Sedin R.** 2001. Environmental Quality Criteria Groundwater. Report no. 5051. Swedish Environmental Protection Agency. Stockholm, Sweden.

**Simeonov V, Stratis JA, Samara C, Zachariadis G, Voutsa D, Anthemidis AM, Sofoniou M, Kouimtzis T.** 2003. Assessment of the surface water quality in Northern Greece. Water Res. **37:**4119–4124.

**SIUE.** 1999. Programa de desarrollo Turístico de Puerto Peñásco, Sonora. Subsecretaría de Planeación Urbana y Ecología. Hermosillo, Sonora. México, 195p.

**Speiser B, Kistler C.** 2002. Field tests with a molluscicide containing iron phosphate. Crop Prot. **21:**389–394.

**Subbarao C, Subbarao NV, Chandu SN.** 1996. Characterization of groundwater contamination using factor analysis. Environ. Geol. **28:**175–180.

**WHO.** 1996. Guidelines for Drinking Water Quality, Health Criteria and Other Supporting Information, 2nd Ed. World Health Organization, Geneva, 973p.

Received: 24 May 2007; accepted: 30 April 2008.