Tropical and Subtropical Agroecosystems, 13 (2011): 233 – 241

WATER QUALITY IN WELLS FROM COZUMEL ISLAND, MEXICO

[CALIDAD DEL AGUA EN POZOS DE ISLA COZUMEL, MÉXICO]

Lourdes Coronado-Álvarez[1], Martha Angélica Gutiérrez-Aguirre[2]
and Adrián Cervantes-Martínez[2]

[1]SAGARPA Delegación Federal en Quintana Roo; km. 3.5 de la carretera
Chetumal-Bacalar Col. Fovisste V Etapa, C. P. 77040. Chetumal, Quintana Roo.
e-mail luz.coronado@qur.sagarpa.gob.mx
.[2] Universidad de Quintana Roo, Unidad Académica Cozumel, Departamento de
Ciencias y Humanidades, C. P. 77642, Cozumel, Quintana Roo, México. e-mail
margutierrez@uqroo.mx, adcervantes@uqroo.mx.
**Corresponding Author*

SUMMARY

Physical and chemical variables related with groundwater quality, were surveyed in several wells from Cozumel Island, Quintana Roo, Mexico. During the annual cycle (November 2007 to October 2008), the observations were compared with local and international norms for drinking water. The goal is to determine the areas with the best water quality on the Island, through the evaluation of both geographic information, and physical and chemical features through all seasons. Significant differences were found between wells in the annual cycle with a Kruskal-Wallis test ($p<0.05$). On the other hand, the result of a cluster analysis (UPGMA, Euclidian distances) suggests spatial discontinuities between the systems related with ionic content in the surveyed area. Ionic concentration was smaller (with better water quality) in the central-northern wells of the island, intermediate in the east, and higher in the west (low water quality). Therefore, the central-northern region of the Island is proposed as an important zone of fresh water supply because of the low electrical conductance, and low chloride concentration. The evidence supports the hypothesis that the temporal behavior of some groundwater variables is related to meteorological, or seasonal changes. This information could be useful for resource management and conservation of drinking water on the Island.

Key words: groundwater; karstic; hydrology; island; water chemistry.

RESUMEN

Se analizaron *in situ* y en el laboratorio, variables físicas y químicas informativas de la calidad de agua subterránea de 14 pozos ubicados en el área de mayor uso de agua dulce de la isla Cozumel, Quintana Roo, México durante un ciclo anual (noviembre 2007 a octubre 2008). Se contrastaron los valores obtenidos con la normatividad nacional e internacional de calidad de agua para uso potable; contribuyendo con información que por un lado permitió determinar áreas con mejor calidad de agua y por otro, evaluar el comportamiento de las variables a escala temporal. Con una prueba de Kruskal-Wallis ($p<0.05$) se determinó que existieron diferencias significativas entre los pozos analizados en el ciclo anual y un análisis multivariado (UPGMA, distancias euclidianas) sugiere la existencia de discontinuidades entre los pozos a escala espacial: la concentración iónica fue menor (con agua de mejor calidad) en aquellos encontrados en la región centro-norte de la Isla, intermedia en el este y elevada hacia el oeste (menor calidad). La región centro-norte de la Isla se propone como zona importante con buena calidad de agua dulce por la baja conductividad eléctrica y concentración de cloruros. Se encontró evidencia que soporta la hipótesis de que el comportamiento temporal de algunas variables fisicoquímicas del acuífero, dependen de los cambios estacionales. La información es útil para el manejo y conservación del recurso agua en la Isla.

Palabras clave: agua subterránea; cárstico; hidrología; isla; química del agua.

INTRODUCTION

The Yucatan Peninsula is a limestone plate affected by tropical climate with abundant groundwater currents (Herrera-Silveira *et al.*, 1998; Marin *et al.*, 2000) that flow through fractures or caves into the karst, and porous soil (Flores-Nava *et al.*, 1989). This aquifer is vulnerable to contamination (Zack and Lara, 2003) and easily degradable by the infiltration of soluble substances that could affect their quality (Schmitter-Soto *et al.*, 2002b).

The karstic aquifer on Cozumel Island is an entire freshwater body, located in the center of the Island;

the fresh-water layer floats on a body of marine water (Lesser and Weide, 1988). Precipitation is the only sources form its recharge (Cervantes-Martinez, 2007). The aquifer is the only source for drinking water for its inhabitants, and the only means of replenishing this water supply is trough precipitation.

Only a few works related with the groundwater assessment from Cozumel Island have been published in the last decade. Under direction from the municipal administration, these sporadic works have been done in deep wells (Wurl and Giese, 2005), or urban and suburban systems (Cervantes-Martinez 2007, 2008; Gutiérrez-Aguirre *et al.*, 2008). It is still poorly understood how the water quality in the shallow aquifer is affected due to seasonal or spatial variability (Zack and Lara, 2003). The surveyed systems here, know regionally as "pozos" (wells), were built by local residents in recent decades through 1-5 m soil perforations, to ensure contact with the aquifer (Appello and Postma, 1996). The analyzed boreholes are in ranches, and small properties; they are the main source of water supply, and they are located within the largest freshwater reserve on the island (Lesser and Weidie, 1988).

Due to the urgent need for hydrologic knowledge on the island, physical and chemical water quality variables were withdrawn from the largest area of freshwater, and were analyzed and confronted with local (SSA, 1995) and international (WHO, 2008) regulations, in order to evaluate its quality, and to identify areas with salt water influence.

MATERIAL AND METHODS

Fourteen wells were selected as points of sampling on Cozumel Island (in the Yucatan Peninsula, Mexico). The island ´s surface is 647.33 km^2 (Orellana *et al.*, 2008), and the study area is located at 20° 30' 30" LN and 86º 58' 00" LW (Fig. 1).

During the annual cycle (November 2007-October 2008) monthly collections were made. The variability of physical and chemical groundwater features was recorded, over the course of three tropical climatic seasons: dry season from February to May, rainy season from June to October, and winter storm season from November to January (Schmitter-Soto *et al.*, 2002a, Orellana, *et al.*, 2008). Highest average rainfall was recorded in September (460 mm), followed by October (340 mm). In general, total precipitation did not exceed the 100 mm in the winter storm and dry seasons. Minimal temperature was recorded in the winter storm season (21-23° C), while maximum during the rainy season with 28° C; in the dry season the environmental temperature ranged from 25 to 27° C.

Water samples were taken by duplicate. After showing stabilized values to ensure appropriate groundwater analysis, data was collected at the intermediate region of the water column (Appello and Postma, 1996). To determine the classification, quality, and environmental performance of the sampled water in comparison with local and international regulations for drinking water (SSA, 1995; WHO, 2008), field parameters were measured *in situ* [pH, water temperature, dissolved oxygen concentration (DO), chloride concentration (Cl$^-$) and electrical conductivity (EC)] with the aid of a calibrated Hydrolab DS5x (after APHA, 1996).

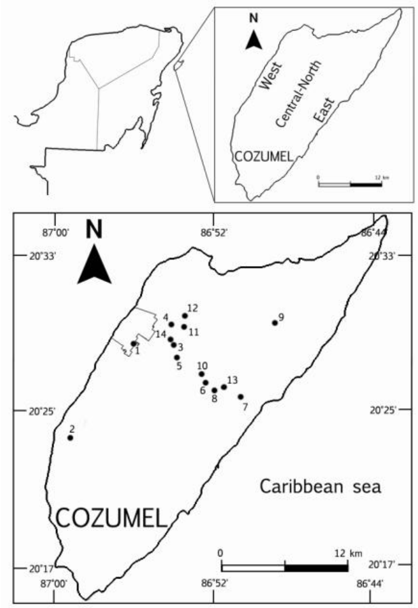

Figure 1. Study area and sampled points. 1 Sin Barda; 2 Chankanaab III; 3 Pozo el poblano; 4 Gallinas; 5 Palmas; 6 Casa verde; 7 Moscas; 8 Sarapes mojados; 9 San Gervasio I; 10 San Gervasio III; 11 Manuel Morales; 12 José Argaez; 13 San Nicolás; 14 El Poblano. Polygonal form is the urbanized area into the Island.

The water column depth (m) is the difference between both, the bottom and the water surface height in each well (Cervantes-Martinez *et al.*, 2002). In addition, water samples were collected with the aid of a van Dorn bottle to determine the total dissolved solids concentration (TDS) according to legal standards (NMX, 2001).

A Spearman rank correlation (Statgraphics, Vers. 7.0) was performed to observe if the environmental variables (temperature and monthly precipitation average), had influenced on physical and chemical variables. Physical and chemical water features between wells, were statistically compared with a Kruskal-Wallis test. A cluster analysis (UPGMA, Euclidian distances) was carried out to classify the surveyed wells according to the water quality.

RESULTS

Significant differences were found between wells in the annual cycle (Kruskal-Wallis $p < 0.05$; pH, H = 55.05; water temperature, H = 71.84; DO, H = 134.90; Cl$^-$, H = 215.80; EC, H = 215.80; TDS, H = 116.12 and water column depth, H = 128.80). With the aid of a cluster analysis (UPGMA, Euclidian distances), four groups of systems were recognized (Fig. 2). Annual variability in physical and chemical features of one well of each group is presented in Figs. 3-6, to facilitate the description.

Group 1 (Palmas, Casa Verde, San Gervasio III and Sarapes Mojados). Boreholes with oxygen concentration ranged from 0.1 to 6.2 mg L^{-1} (Table I). A considerable increase in oxygen concentration was observed in the transition from the rainy to the winter storm season (greater than 5.5 mg L^{-1}). Water temperature was almost constant (around 25° C), but in the rainy season higher values were recorded, which then decreased in the winter storm season (Fig. 3A).

Wells from this group with low EC values (274.9 to 604.8 µS cm^{-1}), TDS (110.0 to 710.0 mg L^{-1}), and Cl$^-$ (35.4 to 300.6 mg L^{-1}), and water column depth variable (Table I). Ionic content maintained stable in the winter storm and dry seasons, but varied in the rainy season: the EC and the pH decreased but along the surveyed cycle, basic waters were found in these wells (Fig. 3B).

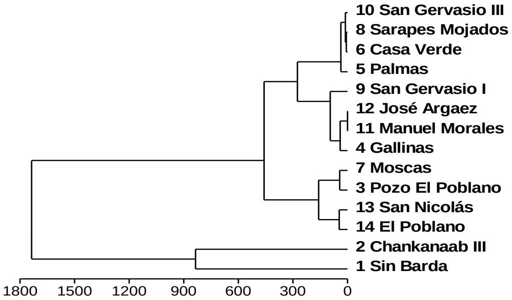

Figure 2. Dendrogram (UPGMA, Euclidian distances). The numbers represent the sampled points.

Group 2 (Gallinas, San Gervasio I, Manuel Morales and José Argaez). The trends in the temporal variations in the surveyed parameters were similar to those described from the previous group (Figs. 4A and 4B). Differences lie in the pH (slightly acid) and the EC (highest than in the Group 1). Oxygen concentration ranged from 0.1 to 5.7 mg L^{-1}, the water temperature from 25.0 to 27.0° C, the pH from 6.7 to 8.4, the EC was 543.8 to 867.0 µS cm^{-1}, the TDS concentrations from 250.0 to 688.0 mg L^{-1}, Cl$^-$ from 251.5 to 511.4 mg L^{-1}, and the depth water column from 0.2 to 2.7 m (Table I).

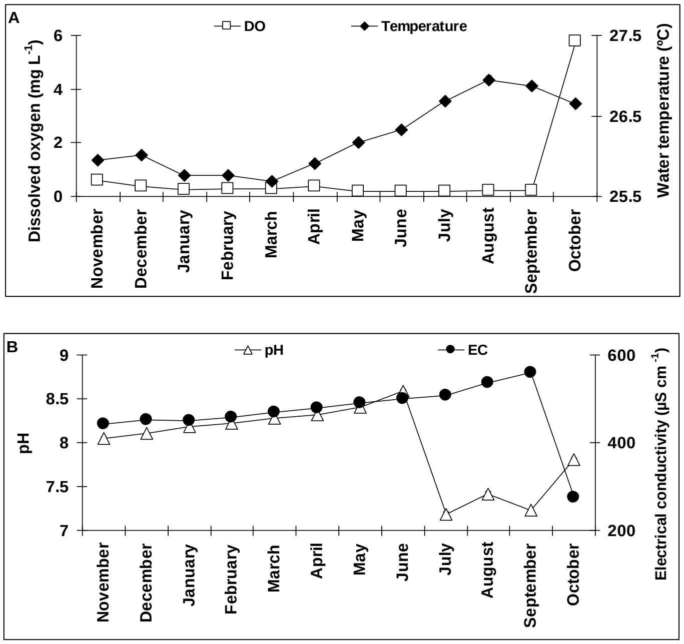

Figure 3. Monthly change in physical and chemical parameters in water from "Sarapes mojados" well (November 2007-October 2008). A = dissolved oxygen and water temperature, B = pH and electrical conductivity.

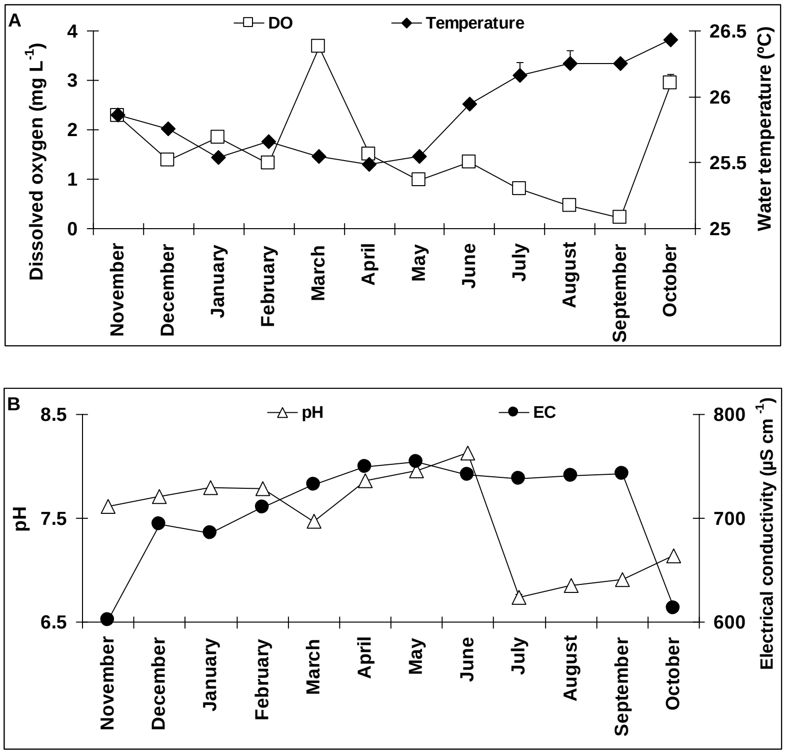

Figure 4. Monthly change in physical and chemical parameters in water from "Manuel Morales" well (November 2007-October 2008). A = dissolved oxygen and water temperature, B = pH and electrical conductivity.

Group 3 (El Poblano, Pozo el Poblano, Moscas and San Nicolás). The values of dissolved oxygen concentration (0.2 to 6.3 mg L^{-1}) and water temperature (23.7 to 27.2° C) were stable, except in the transition from the rainy to winter storm season: the oxygen concentration increased (from less of 2 mg L^{-1} to 6 mg L^{-1}). The lowest water temperature recorded in the winter storm (23.5-24.5º C) increased in dry season (Fig. 5A).

In general, alkaline pH values (around 8 units) were recorded in the wells of the group; neutral pH was found at the beginning of the rainy season. The EC was found close to 1500 µS cm^{-1}, with two lower values in the transition from the rainy to winter storm season (Fig. 5B). The wells of this group reached acid values (pH= 6.6 to 6.9) during the rainy season, with TDS concentration ranging from 226.0-850 mg L^{-1} and Cl^- from 87.5-1058.8 mg L^{-1}along the surveyed cycle; water depth ranged between 0.6 to 4.1 m (Table I).

Group 4 (Sin Barda and Chankanaab III). Dissolved oxygen concentration widely varied from 0.09 to 7.2 mg L^{-1}. Water temperature was lower in winter storm (around 25° C) and higher in the dry and rainy seasons with a temperature of 28.4° C (Fig. 6A). The recorded pH was basic in the dry and winter storm seasons, but values were close to neutral conditions in the rainy season (Fig. 6B). These wells were distinguishable because of their higher EC records, from 1000.0 to 5000.0 µS cm^{-1}; the high TDS concentration (520.0 to 1581.0 mg L^{-1}) and the high Cl^-concentration (666.5 to 2157.1 mg L^{-1}), with a depth of the water column between 1.2 and 2 m (Table 1).

On the other hand, significant differences were found in several parameters (Table 2) between climatic seasons (within each system), except in El Poblano and San Nicolás, where all the surveyed variables were homogeneous along the annual cycle. In all the surveyed systems non–significant differences were found in TDS concentration and water depth between climatic seasons. Spearman rank correlation showed that the average temperature was significantly correlated ($p < 0.05$) with several variables, for instance, with dissolved oxygen in Sin Barda (r_S = -0.67) and Chankanab III (r_S = 0.84), with the water temperature in most systems (r_S = 0.86 Sin Barda, r_S = 0.72 Chankanaab III; r_S = 0.85 Pozo el Poblano, r_S = 0.69 Casa Verde, r_S = 0.89 Moscas, r_S = 0.79 Sarapes Mojados, r_S = 0.62 San Gervasio III, and r_S = 0.81 José Argaez), and with the EC in Palmas (r_S = 0.93), Casa Verde (r_S = 0.79), Moscas (r_S = 0.82), San Gervasio I (r_S = -0.60) and José Argaez (r_S = 0.79). On the other hand, the average rainfall was significantly correlated ($p < 0.05$) with the dissolved oxygen concentration in the Pozo el Poblano (r_S = 0.60).

Table 1. Annual average and standard deviation of the surveyed variables. Maximum and minimum values in brackets. Maximum allowable concentrations for drinking water *sensu* SSA (1995) and WHO (2008) are in the last row.

System	Dissolved oxygen (mg L^{-1})	Water temperature (°C)	pH	Electrical conductivity (µS cm^{-1})	Total Dissolved Solids (mg L^{-1})	Chloride (mg L^{-1})	Depth (m)
Palmas	0.9±1.7	25.7±0.3	8.1±0.4	498.0±41.2	309.3±125.2 (666.0,	214.8±33.1	0.9±0.1
	(6.2, 0.1)	(26.2, 25.0)	(8.7, 7.2)	(582.4, 427.3)	146.0)	(282.6, 157.9)	(1.3, 0.7)
Casa Verde	0.7±1.5	26.1±0.2	7.9±0.4	461.8±61.8	296.8±107.2	185.6±49.7	2.5±0.2
	(5.6, 0.1)	(26.7, 25.1)	(8.5, 7.0)	(525.1, 293.8)	(594.0, 132.0)	(236.5, 50.6)	(3.0, 2.2)
San Gervasio III	0.7±1.7	25.9±0.3	7.8±0.5	453.0±90.7	225.8±47.7	178.5±72.9	1.6±0.1
	(6.2, 0.1)	(26.9, 25.6)	(8.6, 7.0)	(604.8, 347.4)	(276.0, 110.0)	(300.6, 93.6)	(1.8, 1.2)
Sarapes Mojados	0.7±1.5	26.2±0.4	7.9±0.4	468.3±70.7	300.5±135.9	190.9±56.8	1.2±0.1
	(5.8, 0.1)	(26.9, 25.6)	(8.6, 7.1)	(560.3, 274.9)	(710.0, 152.0)	(264.8, 35.4)	(1.5, 1.0)
Gallinas	4.0±1.5	25.8±0.5	7.8±0.4	748.7±47.8	436.0±124.9	416.3±38.4	0.6±0.3
	(5.7, 1.6)	(26.6, 25.1)	(8.4, 6.9)	(867.0, 709.7)	(688.0, 250.0)	(511.4, 384.9)	(1.3, 0.2)
San Gervasio I	4.1±0.4	25.5±0.1	7.5±0.4	816.7±27.6	512.8±86.4	471.0±22.2	1.5±0.4
	(5.0, 3.5)	(25.8, 25.2)	(8.2, 6.7)	(835.6, 731.5)	(646.0, 390.0)	(486.1, 402.4)	(2.3, 0.6)
Manuel Morales	1.5±1.0	25.8±0.3	7.4±0.4	708.8±52.0	428.3±99.6	384.2±41.5	0.9±0.2
	(3.6, 0.2)	(26.4, 25.4)	(8.1, 6.7)	(754.5, 601.8)	(622.0, 259.8)	(420.9, 298.2)	(1.5, 0.7)
José Argáez	0.6±0.7	25.7±0.6	7.6±0.4	709.0±90.5	412.8±65.3	384.4±72.7	2.1±0.3
	(2.4, 0.1)	(27.0, 25.0)	(8.1, 6.8)	(784.8, 543.8)	(502.0, 316.0)	(445.3, 251.5)	(2.7, 1.4)
El Poblano	1.7±1.8	24.7±0.5	7.8±0.4	1168.5±280.7	595.1±192.1	753.7±225.7	0.7±0.1
	(5.9, 0.2)	(25.5, 23.7)	(8.3, 6.9)	(1548.0, 531.4)	(786.0, 266.0)	(1058.8, 241.6)	(0.9, 0.6)
Pozo el Poblano	2.3±1.4	25.6±0.4	8.1±0.5	1010.7±419.8	539.6±204.2	626.9±337.5	1.4±0.4
	(5.3, 0.2)	(26.5, 25.0)	(8.7, 7.0)	(1534.0, 339.7)	(850.0, 226.0)	(1047.6, 87.5)	(2.4, 1.0)
Moscas	2.2±1.1	26.3±0.5	7.5±0.5	966.5±195.7	548.6±133.2	591.4±157.3	1.4±0.8
	(5.1, 1.2)	(27.2, 25.4)	(8.1, 6.6)	(1107.0, 508.9)	(686.0, 282.0)	(704.3, 223.5)	(4.1, 0.9)
San Nicolás	3.4±1.6	26.3±0.3	7.8±0.4	1124.2±106.0	653.0.±84.7	718.1±85.2	1.1±0.2
	(6.3, 1.2)	(26.9, 25.8)	(8.2, 6.9)	(1278.0, 836.1)	(776.0, 418.0)	(841.8, 486.6)	(1.8, 0.7)
Sin Barda	0.6±0.5	26.1±1.2	8.0±0.5	2079.4±853.7	1081.0±355.0	1486.0±686.3	1.4±0.2
	(2.2, 0.09)	(28.4, 24.6)	(8.5, 7.0)	(4581.0, 1112.0)	(1846.0, 578)	(3497.0, 708.3)	(2.0, 1.2)
Chankanaab III	3.2±1.9	25.8±1.3	8.2±0.4 (8.8, 7.5)	2914.1±611.7	1581.0±388.5	2157.1±491.8	2.0±0.1
	(7.2, 0.9)	(27.9, 24.1)		(3520.0, 1061.0)	(1870.0, 520.0)	(2644.1, 666.5)	(2.3, 1.7)
Maximum allowable			6.5-8.5	1500.0	1000.0	250.0	

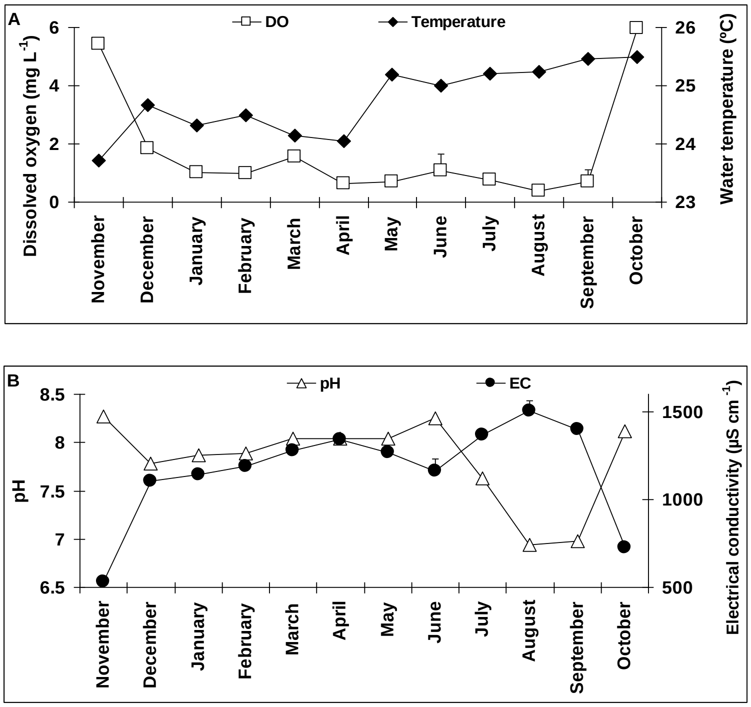

Figure 5. Monthly change in physical and chemical parameters in water from "Poblano" well (November 2007-October 2008). A = dissolved oxygen and water temperature, B = pH and electrical conductivity.

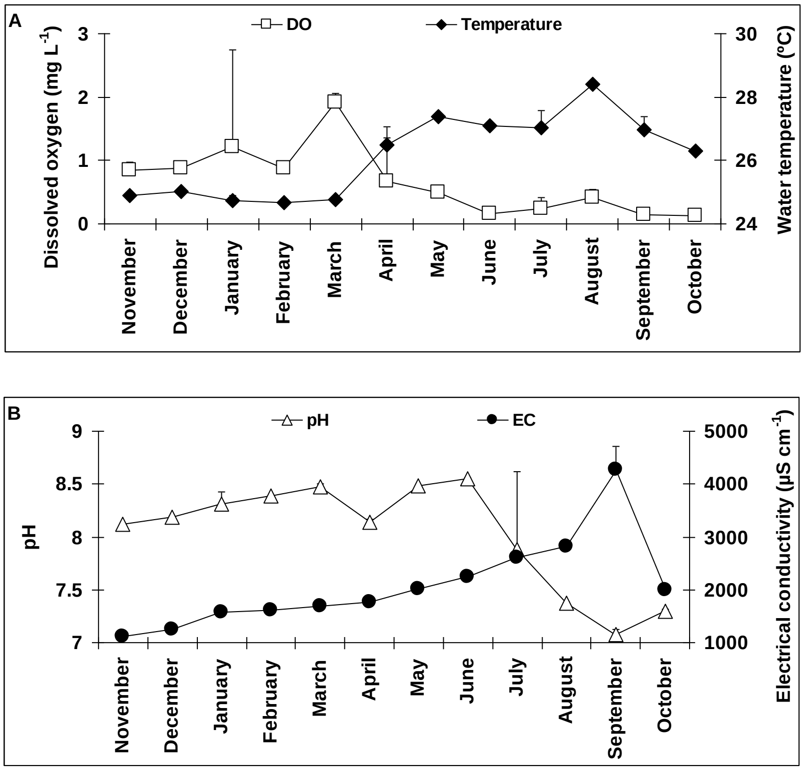

Figure 6. Monthly change in physical and chemical parameters in water from "Sin Barda" well (November 2007-October 2008). A = dissolved oxygen and water temperature, B = pH and electrical conductivity.

Table 2. Kruskal-Wallis test for water quality variables between seasons. H is presented on the first line, and p on the second line of each row. Only are showed those data where statistical differences were founded.

	1	2	3	4	5	6	7	8	9	10	11	12
Dissolved oxygen	11.62	6.73	7.31									
(mg L^{-1})	0.002	0.03	0.02									
Water temperature	11.48	16.15	10.43	6.37		1.33	12.03	12.79	8.87	7.67	12.87	11.24
(°C)	0.003	0.003	0.005	0.04		.0001	0.002	0.001	0.01	0.02	0.001	0.003
pH		7.39										
		0.02										
Electrical					12.27	6.92	6.21		7.51			7.29
conductivity (μS/cm)					0.002	0.03	0.04		0.02			0.02
Chloride (mg L^{-1})					12.27	6.92	6.21		7.51			7.29
					0.002	0.03	0.04		0.02			0.02

1 Sin Barda; 2 Chankanaab III; 3 Pozo el poblano; 4 Gallinas; 5 Palmas; 6 Casa verde; 7 Moscas; 8 Sarapes mojados; 9 San Gervasio I; 10 San Gervasio III; 11 Manuel Morales; 12 José Argaez.

DISCUSSION

The ranges recorded in electrical conductivity, chloride concentration and total dissolved solids suggests differences in the boreholes at the spatial scale: ionic concentration was significantly lower in the wells of groups 1 and 2, which are located at central-northern region of the island. The wells located in the east (such as San Nicolás and Moscas), showed intermediate ionic content (Group 3), while wells of the fourth group at the west of the island have the highest ionic content.

According to national and international regulations, the best water quality was contained in wells from groups 1 and 2, where the average records of pH, EC and TDS did not exceed the maximum allowable concentrations throughout the annual cycle (except for the pH values 8.6 to 8.7 recorded in June). However, due to the month with the highest rainfall, the minimum values of chloride in these wells were above the maximum allowable. In the region, high Cl$^-$ records such as 300 to 500 mg L^{-1} on average, are common (Wurl and Giese, 2005; Gutiérrez-Aguirre *et al.*, 2008; Matthes, 2008). These records are related to the Cozumel geology: the Tertiary and Quaternary limestone and coastal sediments from the island (Villasuso and Mendez, 2000), together with the intrusion of salt water (Wurl and Giese, 2005), and natural high rainfall rates, produces groundwater with high ionic content (White *et al.*, 1995).

In addition to the high Cl$^-$ concentration, the water quality in the third group is also affected because of the high EC, beyond the allowable limits in the rainy season (Fig. 4B). The systems of the fourth group had lower quality water, considering the standards for potable use because in general, the annual averages of pH, EC, TDS and Cl$^-$ were found beyond the maximum allowable concentrations. The ranges of the above variables, in conjunction with the records of oxygen concentration and water temperature, suggests that Chankanaab III has salt water intrusion (see Alcocer *et al.*, 1998; Perry *et al.*, 2002; Matthes, 2008).

In contrast, the records from Sin Barda, especially the water temperature records (higher in each collection, in comparison with other systems), the low oxygen concentration (Fig. 5A) and the smell of hydrogen sulfide in the dry and rainy seasons (personal observation, LCA), suggests that this is a superficial system, with little or no influence from the aquifer (Flores-Nava, 1994; Schmitter-Soto *et al.*, 2002a).

On the other hand, published records in the region have shown that the groundwater features are similar at temporal scale in some variables (Alcocer *et al.*, 1998). In this study, temporal homogeneity was observed in the water column depth, the TDS concentration, as well as the pH levels. The stable behavior of the latter is associated with the balance between carbon dioxide and carbonate and bicarbonate ions, which function as buffer system (Stoessell *et al.*, 1989).

The correlation between the ambient and the water temperature is noticeable in most analyzed wells, because there is influence from the meteorological conditions of the groundwater temperature in the superficial aquifer of Cozumel, were the freshwater table was found at 3.08 ± 1.06 m.

The ion dilution by precipitation was observed on the chloride concentration, EC, and total dissolved solids (values were lower after the month with highest rainfall, because of the water exchange); however, statistical tools showed that only the chloride concentration was significantly different between climatic seasons in some wells, which supports the hypothesis that the groundwater behavior depends on seasonal changes (Villasuso-Pino, 2006).

With this data it is possible to suggest that the area with the best water quality in Cozumel is located in the central-northern region, which is susceptible to contamination in rainy season, just like another karstic areas in Quintana Roo state (Beddows *et al*., 2002).

CONCLUSIONS

Four groups of boreholes, according to their water quality, were found with the cluster analysis. The first group has the highest water quality standards and is located towards the central-northern region of Cozumel. The groundwater from these surveyed boreholes, effectively respond to seasonal climate changes: during the rainy season the records related with the ionic content were higher than in the rest of the year.

Wells with intermediate water quality are located at east of such area. The water of the wells located at west of the island, were classified as the minor quality, exceeding the allowable limits established by international and national norms for human use and consumption; and had saline intrusion.

ACKNOWLEDGEMENTS

Aaron Canché-Canché, Koh-Pasos Coral, José Guadalupe Chan-Quijano, Omar Martinez-Zapata, and Veronica Prado-Aguilar for the support in the field work. To Jorge Sulub Tolosa for his help in making figures. Universidad de Quintana Roo UA-Cozumel (Programa de Manejo de Recursos Naturales), granted facilities to perform laboratory analysis. The Programa de Mejoramiento del Profesorado (PROMEP) gave financial support, budget No. 50732. We thank Lisa Cannon for her assistance with the English, and two anonymous reviewers for helpful comments on the manuscript.

REFERENCES

APHA. 1996. Standard methods for the examination of water and wastewater. 19a ed. American Publishing Health Association. USA.

Alcocer, J., Lugo, A., Marín, L. and Escobar, E. 1998. Hydrochemistry of waters from five cenotes and evaluation of their suitability of drinking water supplies, northeastern Yucatan, Mexico. Hydrology. 6:293-301.

Appello, C.A.J. and Postma, D. 1996. Geochemistry, groundwater and pollution. A. A. Balkema. Holanda.

Beddows, P., Smart, P., Whitaker, F. and Smith, S. 2002. Density stratified groundwater circulation on the Caribbean Coast of the Yucatan Peninsula, Mexico. Karst Front. 7:129-135.

Cervantes-Martínez, A. 2007. El balance hídrico en cuerpos de agua cársticos de la Península de Yucatán: realidades y retos. Teoría y Praxis. 3:163-172.

Cervantes-Martínez, A. 2008. Estudios limnológicos en sistemas cársticos. In: Mejía-Ortíz, L.M. (ed.). Biodiversidad acuática de la Isla de Cozumel. Universidad de Quintana Roo y Plaza y Valdés, México. pp. 349-359.

Cervantes-Martínez, A., Elías-Gutiérrez, M. and Suárez-Morales, E. 2002. Limnological and morphometrical data of eight karstic systems “cenotes” of the Yucatan Peninsula, Mexico, during the dry season (February-May, 2001). Hydrobiologia. 482:167-177.

Flores-Nava, A. 1994. Some limnological data from five water bodies of Yucatan as a basis for aquaculture development. Anales del Instituto de Ciencias del Mar y Limnología de la Universidad Nacional Autónoma de México. 21:87-98.

Flores-Nava, A., Valdéz-Lozano, D. y Sánchez-Crespo, M. 1989. Comportamiento físico químico de una manifestación cárstica de Yucatán. Anales del Instituto de Ciencias del Mar y Limnología de la Universidad Nacional Autónoma de México. 16:223-229.

Gutiérrez-Aguirre, M.A., Cervantes-Martínez, A. and Coronado-Álvarez, L. 2008. Limnology of groundwater exposures with urban influence in Cozumel Island, Mexico. Verhandlungen der Internationalen Vereinigung für Theorestische und Angewandte Limnologie. 30:493-496.

Herrera-Silveira, J., Schmitter-Soto, J.J., Comín, F., Escobar-Briones, E., Alcocer, J., Suárez-Morales, E., Elías-Gutiérrez, M., Díaz-Arce, V., Marín, L. and Steinich, B. 1998. Limnological characterization of aquatic ecosystems in Yucatan Peninsula (SE Mexico). Verhandlungen der Internationalen Vereinigung für Theorestische und Angewandte Limnologie. 26:1348-1351.

Lesser, J. and Weide, A. 1988. Region 25. Yucatan Peninsula. In: Back, W., Rosenshein, J. and Seaber, P. (eds.). The Geology of North

America. Hidrogeology. Geological Society of America, USA. pp. 237-241.

Marín, L., Steinich, B., Pacheco, J. and Escolero, O. 2000. Hydrogeology of a contaminated sole-source karst aquifer, Mérida, Yucatán, Mexico. Geofísica Instituto. 39:359-365.

Matthes, L. 2008. Analysis and evaluation of ground and surface water quality and groundwater flow in the northern aquifer of Quintana Roo, Mexico. In: Gutiérrez-Aguirre, M.A. y Cervantes-Martínez, A. (comps.). Estudio geohidrológico del norte de Quintana Roo, México. Universidad de Quintana Roo y Consejo Nacional de Ciencia y Tecnología, México. pp. 67-106.

NMX, 2001. Norma Mexicana NMX-AA-034-SCFI-2001. Determinación de sólidos y sales disueltas en aguas naturales, residuales y residuales tratadas método de prueba. Secretaría de Economía. Diario Oficial de la Federación. 1 de Agosto de 2000.

Orellana, R., Nava, F. y Espadas, C. 2008. El clima de Cozumel y la Riviera Maya. In: Mejía-Ortíz, L.M. (ed.). Biodiversidad acuática de la Isla de Cozumel. Universidad de Quintana Roo y Plaza y Valdés, México. pp. 23-32.

Perry, E., Velázquez-Oliman, G. and Marín, L. 2002. The hydrogeochemistry of the Karst Aquifer System of the Northern Yucatan Peninsula, Mexico. International Geology Review. 44:191-221.

Schmitter-Soto, J.J., Comín, F., Escobar-Briones, E., Herrera-Silveira, J., Alcocer, J., Suárez-Morales, E., Elías-Gutiérrez, M., Díaz-Arce, V., Marín, L. and Steinich, B. 2002a. Hydrogeochemical and biological characteristics of cenotes in Yucatan Peninsula (SE Mexico). Hydrobiologia. 467:215-228.

Schmitter-Soto, J.J., Escobar-Briones, E., Alcocer, J., Suárez-Morales, E., Elías-Gutiérrez, M. and Marín, L. 2002b. Los cenotes de la Península de Yucatán. En: De la Lanza-Espino, G. y García-Calderón, J.L. (eds.). Lagos y presas de México. AGT, México D. F. pp. 337-381.

SSA, 1995. Norma Oficial Mexicana NOM-127-SSA1-1994. Salud ambiental, agua para uso y consumo humano – Límites permisibles de calidad y tratamientos a que debe someterse el agua para su potabilización. Secretaría de Salud Ambiental. Diario Oficial de la Federación. 20 de Octubre de 1995.

Stoessell, R., Ward, W., Ford, B. and Schuffert, J. 1989. Water chemistry and $CaCO_3$ dissolution in the saline part of an open-flow mixing zone, coastal Yucatan Peninsula, Mexico. Geological Society of America Bulletin. 101:159-169.

Villasuso-Pino, M.J. 2006. Estudios geohidrológicos en los acuíferos cársticos costeros del norte de Quintana Roo. Memorias. Foro Estatal de Investigación Científica y Desarrollo Tecnológico El Sistema hidrológico de Quintana Roo. Playa del Carmen, Q. Roo. 30 al 31 de octubre, 2006.

Villasuso, M. and Méndez, R. 2000. A conceptual model of the aquifer of the Yucatan Peninsula. In: Lutz, W., Prieto, L. and Sanderson, W. (eds.). Population, development and environment of Yucatan Peninsula: from ancient maya to 2030. International Institute for Applied Systems Analysis, Luxemburgo. pp. 120-139.

White, W.B., Culver, D.C., Hernan, J.S., Kane, T.C. and Mylroie, J.E. 1995. Karst Lands. American Scientist. 83:450-459.

WHO, 2008. Guidelines for Drinking-water quality. 3a ed. World Healt Organization. Suiza.

Wurl, G. and Giese, S. 2005. Ground Water Quality Research on Cozumel Island, State of Quintana Roo, Mexico. In: Frausto-Martínez, O. (ed.). Desarrollo sustentable: Turismo, costas y educación. Universidad de Quintana Roo, México. pp. 171-176.

Zack, A. and Lara, F. 2003. Optimizing fresh groundwater withdrawals in Cozumel, Quintana Roo, Mexico. In: Voss, C y Konikow, L. (eds.). Second International Conference on Saltwater Intrusion and Coastal Aquifers-monitoring, modeling, and management. SWAT, México. pp. 1-10.

Submitted February 18, 2011 – February 18, 2011
Revised received February 18, 2011