Tropical and Subtropical Agroecosystems, 13 (2011): 187 - 197

AN ASSESSMENT OF WATER QUALITY (NH_4^+, NO_2^-, NO_3^-, TP, SO_4, COLIFORM BACTERIA AND HEAVY METALS) OF THE MAIN WATER SUPPLIES IN THE STATE OF CAMPECHE

[DIAGNÓSTICO DE LA CALIDAD DEL AGUA (NH_4^+, NO_2^-, NO_3^-, TP, SO_4, BACTERIAS COLIFORMES Y METALES PESADOS) DE LAS PRINCIPALES FUENTES DE ABASTECIMIENTO DE AGUA EN EL ESTADO DE CAMPECHE]

Jorge A. Benítez, Maurilio Lara-Flores, Leonel Amábilis, Joshua Ben-Arie, Jimmy A. Vidal-Maldonado, Brenda T. Cen-Poot, Víctor M. Acevedo, Jaime Rendón-Von Osten and Karina Sonda-Santos.

Centro de Ecología Pesquerías y Oceanografía del Golfo de México, Universidad Autónoma de Campeche, Av. Agustín Melgar s/n entre Juan de la Barrera y Calle 20. Colonia Buenavista. San Francisco de Campeche, Campeche, México. C.P. 24039

Email: jabenite@uacam.mx

**Corresponding Author*

SUMMARY

Water quality testing (*in situ* and in laboratory) was conducted on 50 wells across the state of Campeche. Further to this (to aid in water quality management and policy), a GIS was implemented to i) approximate Zones of Contribution (ZOC) for well recharge which in turn supplies water for main cities in the state and ii) perform predictive land change modeling on these ZOC's to predict the future effect of non-point source pollution. Due to natural geohydrological conditions, values of TDS, pH, and SO_4 exceeded Mexican regulations in roughly one third of the wells. Although most wells do not exceed the permissible limits of nutrients and heavy metals, some wells show worryingly high levels of NO_2^-, TP, and Pb, indicators of pollution from anthropogenic sources. All wells were contaminated by coliform bacteria. Poor water quality in some of the main water sources in the state is mainly due to the proliferation of open dumps and the lack of sewage infrastructure, as well as the ongoing conversion of vegetated land to agriculture into the ZOC's. It is shown that unless remedial measures are implemented, human activities will continue to extend into these areas, placing the state's water supply at even higher risk of contamination.

Key Words: Wroundwater, pollution, Yucatan Peninsula, GIS

RESUMEN

Se analizó la calidad del agua (*in situ* y laboratorio) de 50 pozos en todo el Estado. Además, se implemento un SIG (para establecer políticas y pautas de manejo de la calidad del agua), consistente en i) delimitar de manera preliminar la zona que contribuye agua a los pozos (ZOC) que abastecen las principales ciudades y ii) modelar las tendencias del uso del suelo para predecir el efecto futuro de las fuentes dispersas de contaminación. Debido a condiciones naturales geohidrológicas, los valores de STD, pH y SO_4 rebasaron los límites permisibles de la normatividad mexicana en alrededor de un tercio de los pozos. Aunque la mayoría de los sitos no excedieron los límites permisibles para nutrientes y metales pesados, algunos pozos mostraron niveles de NO_2^-, TP, SO_4, y Pb preocupantemente altos, lo cual es un indicador de contaminación antropogénica. Todos los pozos presentaron contaminación por bacterias coliformes. La baja calidad del agua en algunas de las principales fuentes de abastecimiento del Estado se debe principalmente a la proliferación de basureros a cielo abierto y la deficiente red de alcantarillado, así como al cambio de uso del suelo dentro de la ZOC. Si no se implementan las medidas adecuadas, las actividades humanas continuaran extendiéndose dentro de estas áreas colocando a las fuentes de agua en un mayor riesgo de ser contaminadas.

Palabras Clave: Agua subterránea, contaminación, Península de Yucatán, SIG

INTRODUCTION

Like the majority of people in the Yucatan Peninsula, communities in the state of Campeche depend entirely on groundwater as a water supply source, mainly from unconfined aquifers (CONAGUA, 2008). It is estimated that this groundwater supply is not a problem since consumption is minimal compared to the average annual recharge of approximately 74,712 million m^3 yr^{-1} (Villasuso y Mendez). However, the

water quality depends on the proper management of human activities within their recharge areas.
Due to the karstic nature of the Peninsula, the shallow depth of static groundwater levels, high rainfall and high hydraulic conductivity, the water supply sources in this region are at high risk from contamination by both point source and non-point source pollution (Escolero *et al.*, 2000; Escolero *et al*., 2002; Escolero *et al*., 2007). This is particularly true for the state of Campeche, which lacks proper landfills for municipal waste disposal (thereby creating an open dump problem) as well as lacking in sufficient sewage infrastructure (currently sewage goes into the ground without treatment). Additionally, high rates of land use conversion by replacing natural vegetation with agriculture is a further threat to the quality of recharge waters.

Despite these ecological, social and public health concerns, the state of Campeche has no systematic studies on groundwater quality and is also lacking in assessing land use in groundwater recharge areas of the main water supply sources. This study was therefore done to establish pollution levels and their relation to human activities as a first step toward protecting water quality.

Study Area

The state of Campeche is located in the southeast of Mexico (Fig. 1). It is bordered on the north by the state of Yucatan, in the south by the state of Tabasco and Guatemala, in the west by the Gulf of Mexico and in the east by the state of Quintana Roo. It covers an area of roughly 60,000 km^2 with a population of about 760,000 inhabitants (INEGI, 2005).

From a climatic perspective, the state has a rainfall gradient running from the north (800-1200 mm yr^{-1}) near the border with the state of Yucatan to the southeast border with Tabasco (2000 mm yr^{-1}; Fig. 2A). The average annual temperature has an upward gradient from east to west, with values of 23˚C (border with Quintana Roo) to 28˚C (Gulf of Mexico; Fig. 2B). The average annual evapotranspiration is about 1500 mm across the state, with values ranging from 1700 mm in the north to 1400 mm in the south (CONAGUA, 2000).

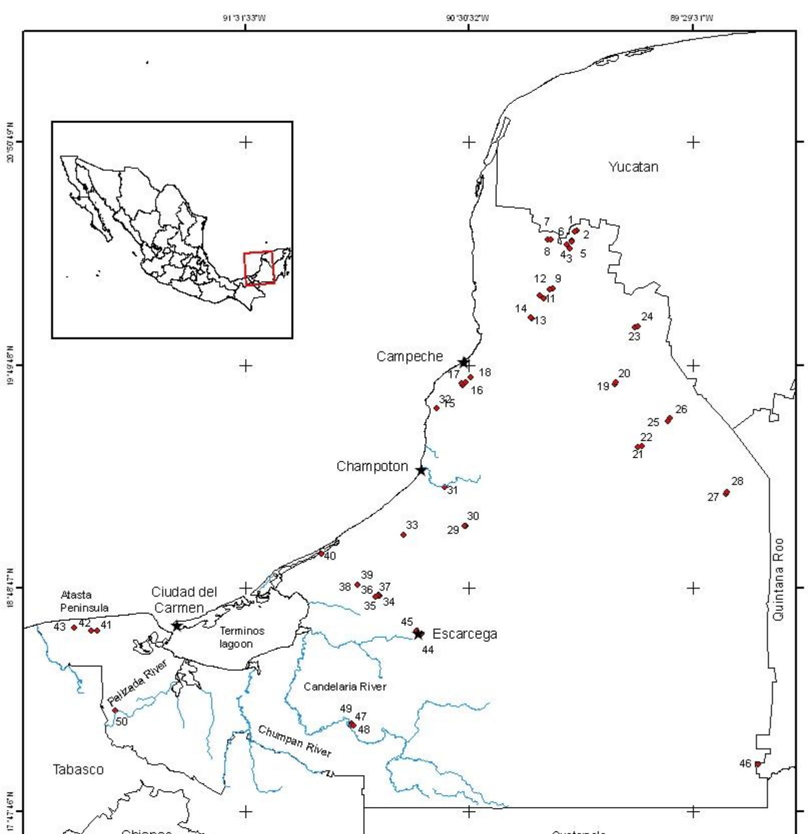

Figure 1. Study Area, showing the location of the main water supplies (wells) of the state of Campeche.

This pattern of temperature and precipitation gives rise to two climatic types according to the Köppen Climate Classification and modified by García (1964). The warm humid zone (Am) located in the southwest of Campeche (Fig. 2C), between Terminos Lagoon and Tabasco, and the warm sub-humid zone (Aw) comprising the rest of the state. The latter type is further divided into warm sub-humid dry (the driest of the sub-humid, Aw_0), located in the northern portion, warm sub-humid intermediate (Aw_1), located in the central portion and warm sub-humid wettest (wettest of the sub-humid, Aw_2), located in the south.

Geologically, Campeche is located on a platform of stratified carbonate (dolomite and limestone) and evaporites (gypsum and anhydrite) of up to six km thick, the product of biological marine activity that gave rise to the entire Yucatan Block (Graham, 2003). Depending on the geology (SGM, 2007), geomorphology (Lugo-Hubp *et al*., 1992) and groundwater geochemistry (CONAGUA, 2000; Perry *et al*., 2009; Heredia y Farfán, 2004), one can distinguish three main geohydrological regions in the state (Fig. 2D).

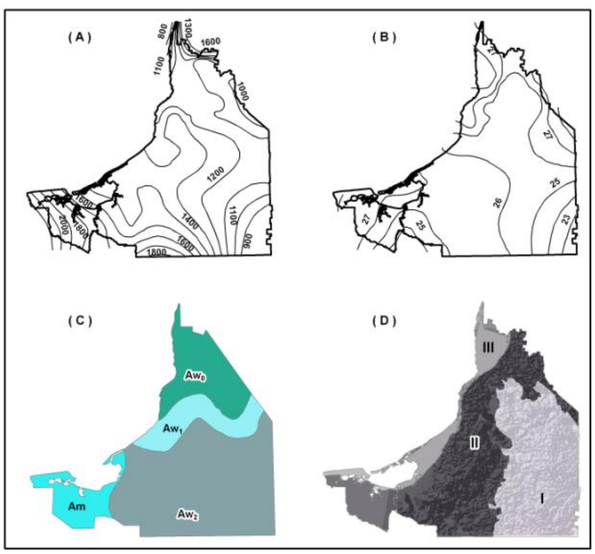

Figure 2. Weather Conditions and Geological Characteristics of the study area. (A) Isohyetal lines (mm year^{-1}), (B) Isothermal lines (˚C), (C) Climatic types and (D) Geohydrological regions

The first region covers almost 40% of Campeche and is located in the southeast. Containing evaporitic deposits from the Paleocene (ca. 67 myr) with hills from 200 to 400 m above sea level as well as deposits of gypsum, this result in low aquifer productivity and poor water quality. The static groundwater levels vary from 50 to 150 m deep.

The second region runs across the state from northeast to southwest and covers about 35% of its surface. This region consists of fractured limestone from the Eocene (ca. 55 myr), with elevations of 100 to 200 m above sea level. The southwestern portion of this region has large deposits from the Quaternary, resulting from the deposition of the Usumacinta River. It contains large reserves of water with static groundwater levels typically between 10 and 50 m deep but in parts there are extreme values of 3 m (very shallow) and 165 m (very deep).

The third region is located along the entire coastal area of state and mainly consists of Quaternary deposits (ca. 10,000 yr) and some fractured limestone from the Miocene (ca. 24 myr) in the farthest portion of the northern coastal zone. Elevation ranges from 0 to 25 m above sea level, static groundwater levels are less than 10 m and groundwater quality is medium to poor.

Due the karstic nature of this area allowing for a great amount rainwater infiltration, surface water currents are intermittent and rare. Permanent channels occur mainly in the south of the state of Campeche (Fig. 1), leaving the rest of the landscape without significant riparian zones.

Methodology

Water Quality Sampling

Between June and September 2009 (corresponding to the rainy season), 50 wells were sampled that supply the most important communities in the state of Campeche. All samples were taken before passing through the chlorinator system as well as waiting five minutes after using the pumps in order for the original water in the pipe to vacate completely (Cuevas *et al*., 2002; Pacheco *et al*., 2004). Measurements were made of Total Dissolved Solids (TDS) and pH *in situ* with a multiparametric HANNA (HI 98286). Water samples were preserved according to the recommendations of the Environmental Protection Agency (EPA, 1997).

Water samples were transported to the laboratory for determination of Ammonium (NH_4^+), Nitrite (NO_2^-), Nitrate (NO_3^-), Total Phosphorous (TP), Sulfate (SO_4), Total Coliform (TC) and Fecal Coliform (FC), following the techniques of the EPA (1997) and the corresponding Official Mexican Standards (NOM-127-SSA1-1994). Also determined were the heavy metals Cadmium (Cd), Zinc (Zn), Lead (Pb), Arsenic (As), Copper (Cu) and Total Chromium (Cr) using the voltamperometer VA-797 Computrace. Water samples were also tested for organochlorine pesticides using the technique of Fatoki and Awofolu (2003) using a Varian 3800 chromatographer.

Determining the ZOC and Land Use Trends

The land surface area over which water can infiltrate and move toward wells (called the zone of influence; ZOC) was defined for the wells that supply water for the four main cities of Campeche: San Francisco de Campeche (population 230,000), Ciudad del Carmen (pop. 195,000), Champotón (pop. 75,000) and Escárcega (pop. 50,000), together representing nearly 80% of the total population of the state. ZOC's were produced by i) delineating a superficial watershed basin for each well based on topography and ii) the assessment of a zone of influence based on groundwater travel times.

To delineate each superficial watershed (using ArcGIS 9.2 Spatial Analyst), a Digital Elevation Model (30 m resolution) was corrected and enhanced by a "burning" process (Saunders, 2000) using topographic stream data from INEGI (1982). Sinks were removed in the resulting *Flow Direction* raster and then a *Flow Accumulation* raster was calculated. Watersheds representing the preliminary recharge area of each well were automatically delineated with the *Watershed* tool and well locations were used as pour points.

ArcGIS 9.2 was used to map zones of influence based on groundwater velocity. Continuous buffers around each well site was created with a radius based on groundwater travel time, which were calculated from hydraulic conductivity values (K) as reported in Muldoon and Payton (1993). A grid map of K values (Table 1) was created based on soil texture properties (INEGI, 2002). This map was used to estimate the time needed by superficial water to reach the static levels of groundwater reported by CONAGUA (2000). A grid map of horizontal travel time was then created using mean K values given for carbonated rocks in the Yucatan peninsula (Worthington, 2003). The addition of these two grids produced a third grid map where each cell contributes water to the well within a specified amount of time.

Table 1. K values used to estimate groundwater travel time to wells

Travel Time	Horizon Depth	Texture	K (m day^{-1})
Vertical	0-0.5 m	Fine	0.005
		Medium	0.0075
		Coarse	1.8
	0.5m-Static Level	Sandy	2.65
Horizontal	Static Level	Carbonate Rock	362

The delineated watersheds (polygons) along with the travel time map were superimposed on a geological map of the region (SGM, 2007) as well as the geomorphology as described by Lugo *et al*., (1992) and soil maps from INEGI (2002). In combining all of this data, adjustments were made to watershed boundaries in order to determine the ZOC.

In each delineated ZOC, GIS analysis was performed to determine land use, present population and the location of open landfills. According to studies conducted by SEMARNAT (2005), it is assumed that each resident produces an average of 0.5 kg of garbage daily, an amount that is multiplied by the number of individuals to determine the annual production of solid waste. We used average population grow rate reported for the state of Campeche (INEGI 2008) to predict future population and solid waste production in 2020 and 2030.

To predict future changes in vegetation cover, the module Land Change Modeler (LCM) was used (an IDRISI product used within ArcGIS). LCM is based on the potential transition of land use change (Eastman *et al*., 2005). This module allows for the analysis of land use change between two time periods (that have passed) and then to develop a spatial predictive model. These future models are based on land use cover and vegetation for 1993 and 2003 of the same area (series II and III respectively from INEGI), where the gains and losses of the area were modeled as well as the transition of forested and deforested areas.

For the transition potential of each class, independent variables were used as a proxy for deforestation of such factors as distance from road, distance to population centers and distance from previously disturbed areas. In this way, the model spatially estimates vegetation in 2020 and 2030, assuming that these trends remained equal to those occurring between 1993 and 2003.

RESULTS

Water Quality

The concentration of total dissolved solids (TDS) ranged between 210 and 2121 mg L^{-1} and for pH between 7.17 and 10.05 (Table 2). Based on these two parameters more than half of the sampled wells rated as poor quality, showing roughly 40% of their values above NOM-127-SSA1-1994 standards, which establishes an upper limit of 1000 mg L^{-1} TDS and a pH range of 6.5 - 8.5. The area in the north of the state of Campeche is where most of the wells exceeding values of TDS and pH are concentrated (Fig. 3a).

For nutrients levels, around 95% of sampled wells showed acceptable levels for human consumption

(Table 2, Fig. 3b). NO_3^- values ranged between 3.24 and 8.6 mg L^{-1} and nitrite showed values from Not Detectable (ND) up to 0.1 mg L^{-1}. NH_4^+ values fluctuated between 0.004 mg L^{-1} to 0.442 mg L^{-1}. In only one well, located in the recharge area of San Francisco de Campeche, nitrite levels were above the official Mexican regulations (NOM-127-SSA1-1994) with a value of 0.05 mg L^{-1}. Most of the wells in the Atasta Peninsula (located in the southeast portion of the state) had ammonia nitrogen values close to NOM-127-SSA1-1994 upper limits. This law does not set a limit for Total Phosphorous (TP). However, another Mexican law, the Federal Law of Rights (*Ley Federal de Derechos*; DOF 27-11-2009), establishes a maximum level of 0.1 mg L^{-1}. Taking this law into account 76% of the wells exceeded the limit of TP, with values ranking from 0.01 mg L^{-1} to 4.603 mg L^{-1} (Table 2, Fig. 3c). SO_4^- values ranged between 4.0 and 674.5 mg L^{-1}, resulting 20% of the wells above the limit (400.0 mg L^{-1}) imposed by NOM-127-SSA1-1994.

Because NOM-127-SSA1-1994 establishes zero as a limit for both total and fecal coliform, 100% of the wells in the state exceeded such limits (Table 3, Fig. 3d), with values ranging from 2 to 240,000 MPN 100 ml^{-1}. Water supply for the city of Candelaria (well no. 48, Fig. 1) presented the highest concentration of both total and fecal coliform. However, most of the wells (84%) had concentrations below 1000 MPN 100 ml^{-1}, the maximum level established for fecal coliform by DOF 27-11-2009 standards.

Table 2. Values for pH, Total Dissolved Solids (TDS), Ammonium (NH_4^+), Nitrites (NO_2^-), Nitrates (NO_3^-), and Total Phosphorous (TP) and wells grouped into four categories. For the location of wells, refer to Fig. 1.

pH	6.5 – 7.16	7.17 – 7.82	7.83 – 8.5	Exceeding
		15, 34, 40, 46, 49, (10%)	3, 6, 7, 8, 16, 17, 18, 23, 24, 29, 30, 31, 32, 35, 36, 37, 38, 39, 41, 42, 43, 47, 48, (46%)	5,10, 1,2,4, 9, 11, 12, 13, 14, 19, 20, 21, 22, 25, 26, 27, 28, 33, 44, 45, 50 (44%)
TDS	0 – 333 mg L^{-1}	334 - 667 mg L^{-1}	668 - 1000 mg L^{-1}	Exceeding
	29,30,33,35,36, 37,40,50 (16%)	15,19,20,24,25,31,34,38,39,41,44,45,46, 47,48 (30%)	9,11,12,13,18,21,22, 23,26,28,32,42,49, (26%)	1,2,3,4,5,6,7,8,10,14,16,17, 27,43, (28%)
NH_4^+	0 – 0.166 mg L^{-1}	0.167 – 0.333 mg L^{-1}	0.334 – 0.500 mg L^{-1}	Exceeding
	1-40, 44-50 (94%)		41,42,43 (6%)	
NO_2^-	0 – 0.016 mg L^{-1}	0.017 – 0.033 mg L^{-1}	0.034 – 0.050 mg L^{-1}	Exceeding
	1-15, 17-31, 33-36, 38, 43-49 (84%)	32, 37, 40,41,42,50 (12%)	39 (2%)	16 (2%)
NO_3^-	0 – 3.33 mg L^{-1}	3.34 – 6.66 mg L^{-1}	6.67 – 10.00 mg L^{-1}	Exceeding
	31, (2%)	1-14,16-30, 32,34-50 (94%)	15, 33 (4%)	
TP	0 – 0.033 mg L^{-1}	0.034 – 0.066 mg L^{-1}	0.067 – 0.1 mg L^{-1}	Exceeding
	23, 25, 29, 33, (8%)	15, 20, 22, 30, (8%)	16, 18, 19, 24, (8 %)	1,2,3,4,5,6,7,8,9,10, 11,12,13,14,17,21, 26,27,28,31,32,34, 35,36,37,38,39,40, 41,42,43,44,45,46, 47, 48,49,50 (76%)
SO_4^-	0 – 133 mg L^{-1}	134 – 266 mg L^{-1}	266 – 400 mg L^{-1}	Exceeding
	15,16,17,19,20,23,24,25,26,29,30, 31,32,33,34,35,36,37,38,39,40,41, 42,43,44,45,48 (54%)	7,11,18,50 (8%)	5,6,8,9,10,12,13,21,46, (18%)	1,2,3,4,14,22,27, 28,47,49 (20 %)

Levels of heavy metal (Table 4) were below what is established in the regulations for human consumption in 49 of 50 wells sampled. There were no detectable levels of Cd or As. Zn levels ranged from ND to 2.016 mg L^{-1}. Cu levels ranged from ND to 0.035 mg L^{-1} and Pb levels ranged from ND to 0.026 mg L^{-1} (the latter value exceeds the standard for human use and consumption which is 0,025 mg L^{-1}). The single well contaminated by Pb is found in the ZOC of Escárcega (Fig. 3C).

None of the 50 wells tested presented detected levels of chlorine pesticides (Aldrin, Dieldrin, chlordane, DDT, Gamma-HCH, Hexachlorobenzene, Methoxychlor, Heptachlor and Heptachlor-epoxi).

ZOC Delineation and Land Use Trends

ZOC areas identified for major urban areas in the state of Campeche is shown in figure 4. These contribution areas cover 26,500 ha for San Francisco de Campeche, 35,000 ha for Champotón, 56,600 ha for Ciudad del Carmen and 20,500 ha for Escárcega. Groundwater travel time in these areas is rapid. The GIS model estimated that water falling in locations up to 15 km from wells would reach the water supply in less than six months.

Human activities within these areas cover between 18 to 35% of its surface (Table 4). According to the analysis of land use trends, it is estimated that unless remedial measure are implemented, these human activities will extend to about 40% of the recharge area by 2030.

Based on the current number of inhabitants, it is estimated that within the ZOC of the water supply sources for San Francisco de Campeche, 823 tons year^{1} of solid waste is deposited without any control or sanitation measures (Table 5). In the case of Champotón, this volume of solid waste is 719 tons year^{-1} and Ciudad del Carmen deposits more than 778 tons year^{-1} Noticeably higher, Escárcega's ZOC deposits 5,085 tons year^{-1} (the latter three cities also without any control or sanitation measures). Considering the current population grow rate, solid waste will more than double by 2030, considerably increasing the risk to contaminated groundwater.

Table 3. Parameters for Total Coliform (Total), and Fecal Coliform (Fecal) and wells grouped into three categories. For the location of wells, refer to Fig. 1.

Coliform	**0 – 80000 MPN 100 ml^{-1}**	**90000 – 160000 MPN 100 ml^{-1}**	**170000 – 240000 MPN 100 ml^{-1}**
Total	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16, 17,18,19,20,21,22, 23,24,25,26,27,28, 31,32,34,35,36,37, 38, 39,41,42,43,44, 45,46,47,49,50 (90%)	30 (2%)	29, 33,40, 48, (8%)
Fecal	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16, 17,18,19,20,21,22, 23,24,25,26,27,28, 29,30,31,32,33,34, 35,36,37,38,39,41, 42, 43,44,45,46,49, 50 (96 %)	40 (2 %)	48 (2 %)

Table 4. Heavy metal concentrations and wells grouped into four categories. Cadmium and Arsenic were not detected. For the location of wells, refer to Fig. 1.

Zn	**0 – 1.666 mg L^{-1}** 1-28, 30-50 (98%)	**1.667 – 3.334 mg L^{-1}** 29 (2%)	**3.335 – 5.00 mg L^{-1}**	**Exceeding**
Pb	0-0.0083 mg L^{-1} 1-14, 16, 18-28, 30, 32,34-43,46-50 (86%)	0.0084- 0.0166 mg L^{-1} 15, 17,29,31,33,44 (12 %)	0.0167 0.025 mg L^{-1}	Exceeding 45 (2%)
Cu	0-0.6666 mg L^{-1} 1-50 (100 %)	0.6667-1.3333 mg L^{-1}	1.3334-2.00 mg L^{-1}	Exceeding
Cr	0 – 0.016 mg L^{-1} 1-50 (100 %)	0.017 – 0.033 mg L^{-1}	0.034 – 0.050 mg L^{-1}	Exceeding

DISCUSSION

The high pH and TDS values found in 40% of wells monitored in the state of Campeche seems to be a consequence of the existing hydrogeological conditions, which may also account for the high concentrations of SO_4 found in 20% of wells, exceeding the limits set by NOM-SSA-127-1994. These wells, located in the north, are constructed on evaporitic deposits from the Paleocene (Heredia and Farfan, 2004). These rocks are part of the ejecta blanket produced by the terminal Cretaceous Chicxulub bolid impact (Perry *et al*., 2009 and references therein). In these areas, the groundwater derives its particular ionic chemistry from deposits of gypsum ($CaSO_4{\bullet}2H_2O$), calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), and celestite ($SrSO_4$) (Perry 2002).

Besides these geological characteristics, infiltration is negligible in the north due to high levels of evapo-transpiration (1500-1600 mm yr^{-1}) compared with precipitation (950-1015 mm yr^{-1}). These hydrological conditions may prevent local recharge and dilution and therefore water taken from these wells come from the central part of the state where evaporitc deposits are abundant too.

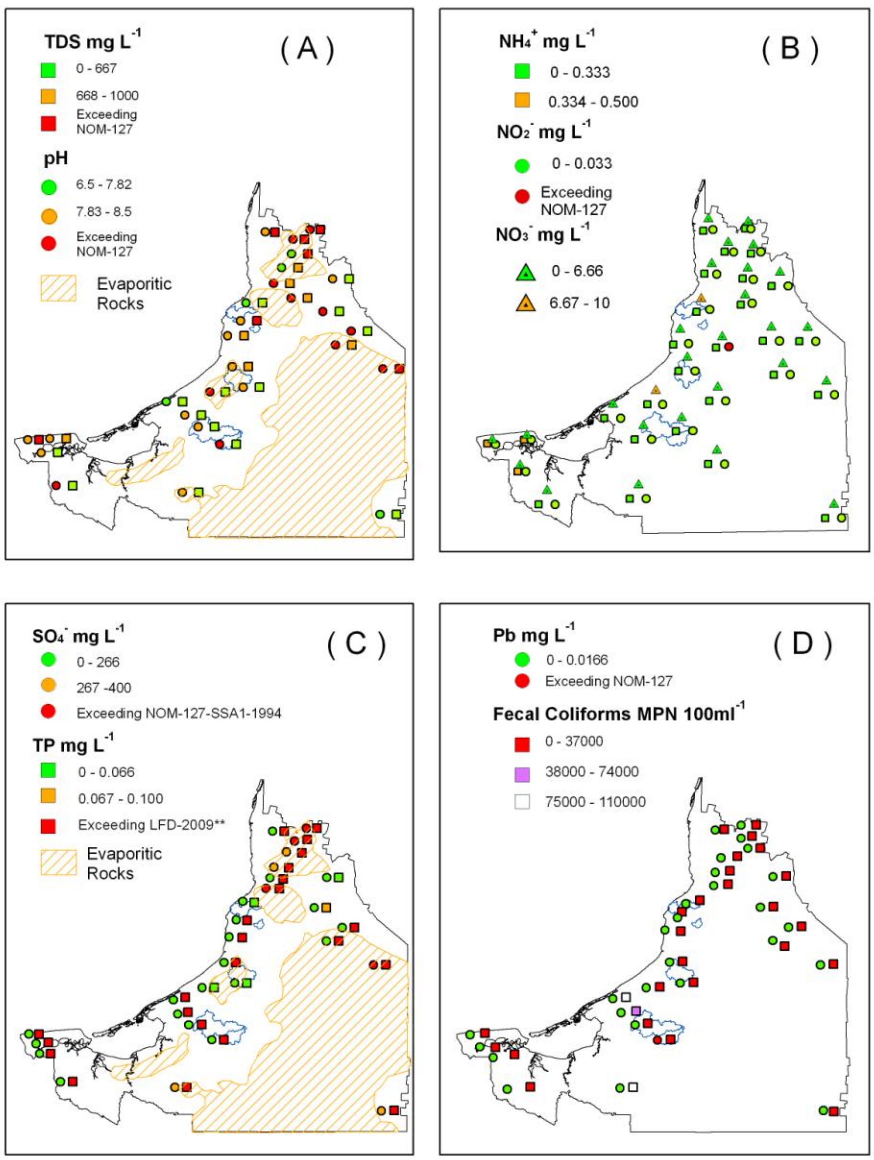

Figure 3. Water quality for wells grouped into categories (See tables 1-3 for identification of wells and fig. 1 for the location of the wells). Boundaries of evaporitic rocks from Heredia and Farfan (2004).

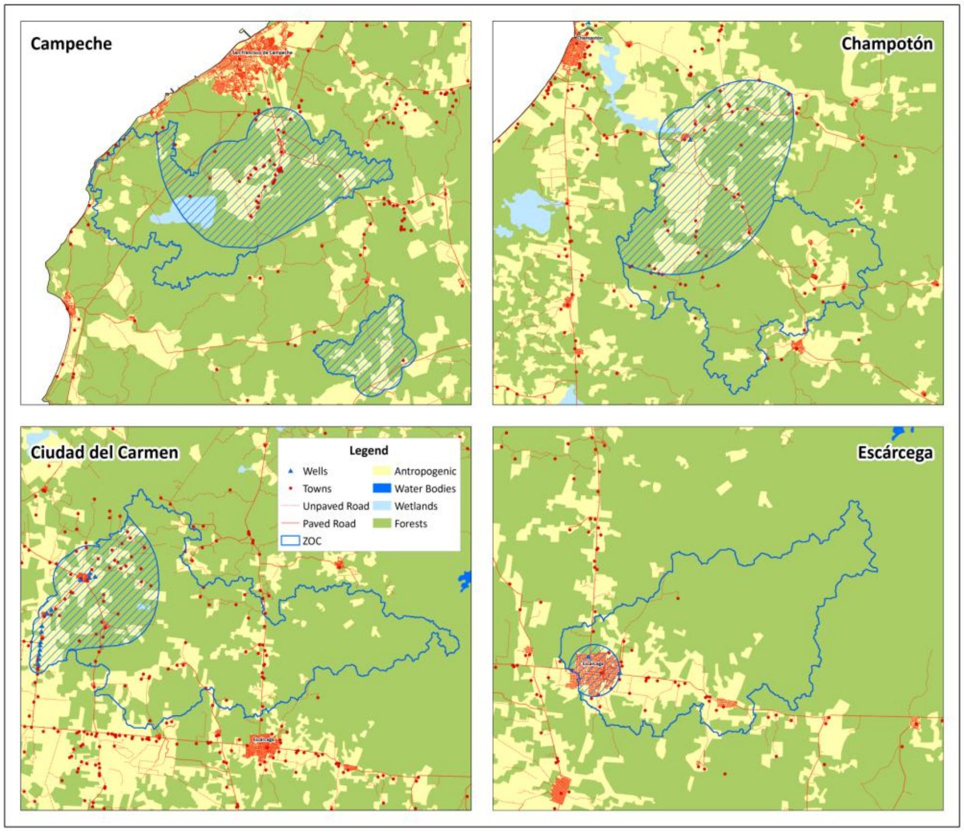

Figure 4. Zone of contribution of the wells for the cities of San Francisco de Campeche, Champotón, Ciudad del Carmen, and Escárcega, showing road network, urban areas, land cover and land use for 2005. Shaded zones represent the area where water travel time to wells is less than six months.

In examining nutrient levels, most of the wells tested do not exceed values established by Mexican regulations, though the Atasta Peninsula wells had the highest values of NH_4^+ (Mean = 0.4 mg L^{-1}) and TDS (Mean = 1128 mg L^{-1}), together with negative redox values of -31.1 mV, which is illustrative of wastewater disturbance (Crites and Tchobanoglous, 2001). Disturbance allows for higher oxygen levels, creating high negative redox values and resulting in low levels of NO_3^- and high levels of NH_4^+ (Masters and Ela, 2007).

A problem that is common to all water sources in the state is the presence of coliform bacteria. Some sources from rural areas reached values of up to 240,000 MPN 100 ml^{-1}, which puts them in the category of "heavily polluted waters" (WHO, 2008). However, it must be noted that samples were taken before water reached the chlorination system.

For the results of heavy metals in the water sources, the values found in the majority of wells are typical for areas of semi-rural populations and low industrial activity (Martin, 2001; Herrera and Comín, 2000). However, about 12% of the water sources showed Pb values between 0.0084 and 0.0166 mg L^{-1}. These values, although below Mexican regulation limits, are above those reported for natural waters and (one must conclude) a product of anthropogenic pollution. This is particularly true for the ZOC of Escárcega, where one of the water sources showed a Pb value slightly above the maximum allowable limit for human consumption. Given the absence of major industrial activity, it is likely that the origins of these pollutants are open dumps located within the ZOC.

In carbonate environments such as that found in the state of Campeche, surface flows are not necessarily determined by topography, making it necessary to use tracer methods to accurately determine water flow and the watershed limits of a particular water source (Prussian and Baichtal, 2007). However, it is possible to approximate recharge areas of a particular water supply based on alternative methods (Muldoon and Payton, 1993).

If we consider that the ZOC's established in this study are good approximations of reality, it is evident that the water supply sources in the state are under high risk of contamination. This is especially true for

Escárcega, whose water supply source is located within its urban area and that the production of solid waste and sewage from its 50,000 residents are discharged without any sanitation controls directly over aquifers with a depth of 35 m.

Table 5. Land cover changes trends into the ZOC of the cities of San Francisco de Campeche, Champotón, Ciudad del Carmen, and Escárcega.

	Land Use	1990	2005	2020	2030
CAMPECHE	Anthropogenic %	12.6	18.4	27.1	39.3
	Forests %	87.4	81.6	72.9	60.7
	Solid Waste ton year $^{-1}$	-	823	1352	1786
CHAMPOTÓN	Anthropogenic %	20.2	35.2	33.7	36.8
	Forests %	79.8	64.8	66.3	63.2
	Solid Waste ton year $^{-1}$	-	719	1181	1560
CARMEN	Anthropogenic %	8.9	19.3	20.2	28.3
	Forests %	91.1	80.7	79.8	71.7
	Solid Waste ton year $^{-1}$	-	778	1277	1687
ESCÁRCEGA	Anthropogenic %	18	25	37	40
	Forests %	82	75	63	60
	Solid Waste ton year $^{-1}$	-	5,085	8,351	11,033

CONCLUSION

It is shown that, aside from heavy metals resulting from urban pollution and open dumps, the values for TDS, pH, and SO_4 are governed by the hydrogeological nature of the region. Although most well parameters do not exceed the permissible limits for human consumption, some show worryingly high levels of nutrients and Pb, an indicator of anthropogenic contamination.

The recharge areas that supply the water sources for the principal urban areas of the state of Campeche pose a significant source of non-point source pollution. This jeopardizes the quality and quantity of water needed for the socioeconomic development of the cities, not to mention the general health and wellbeing of the local residents, in the next two decades.

It is necessary to implement an effective sewage system, along with a water treatment system (such as chlorination and reverse-osmosis), to reduce coliform bacteria counts, TDS, and SO_4. It is also necessary to carry out a detailed geohydrological study to delineate the precise recharge areas for the water supply sources of the cities of San Francisco de Campeche, Champotón, Ciudad del Carmen and Escárcega. Once this study is complete, one can then implement a program of protection and monitoring to ensure as high water quality as possible for human consumption.

ACKNOWLEDGEMENT

This research (ongoing) is financed by the National Water Commission (Comisión Nacional del Agua - CONAGUA) and the state government of Campeche (2003-2009). We thank Juan C. Lavalle, David Montcouquiol, and Rafael Chan for allowing access to the CONAGUA database. We also thank Daniel Samarron and Ricardo Trejo for assisting with the GIS analysis, to Rodolfo Dzul for laboratory analysis, and to Martin Memije and Marcos L. Ehuan for field data collection.

REFERENCES

CONAGUA. 2000. Panorama Geohidrológico e Hidroquímico del Estado de Campeche. Gerencia Estatal Campeche. Subgerencia Técnica. Comisión Nacional del Agua. 463p.

CONAGUA. 2008. Estadísticas del agua en México. SEMARNAT. Edición 2008. México, Distrito Federal. 20 pp.

Cuevas, E., Pacheco, J., Cabrera, A., Coronado, V., Vázquez, J., Comas, M. 2002. Calidad Química y Bacteriológica del agua subterránea en el principal campo de pozos para el abastecimiento de Mérida, Yucatán, México. Federación Mexicana de Ingeniería Sanitaria y Ciencias del Ambiente; AIDIS. Memorias. México, D.F., FEMISCA 2002, p.1-10 Ilus., tab

Crites, R., Tchobanoglous, G. 2001. Tratamiento de aguas residuales en pequeñas poblaciones. Mc Graw Hill. Bogotá Colombia. 223-226 pp.

Environmental Protection Agency (EPA). 1997. Methods for the Analysis of Chemical Substances in Marine and Estuarine Environmental Matrices. Environmental Protection Agency. EPA Pub., 2nd Edition. EPAA/600/R-97/072.

Escolero, O., Marin, L., Steinich, B., Pacheco, J. 2000. Delimitation of a hydrogeological reserve for a city within a karstic aquifer: the Merida

Yucatan. Lanscape and Urban Planning 51: 53-62.

Escolero, O. Marin, L., Steinich, Pacheco, J., Alcocer, J. 2002. Development of a protection Strategy of Karst limestone Aquifers: The Merida Yucatan, Mexico Case Study. Water Resources Management. 16: 351–367

Escolero, O., Marin, L., Dominguez-Mariani, E., Torres-Onofre, S. 2007. Dynamic of the freshwater-saltwater interface in a karstic aquifer under extraordinary recharge action: the Merida Yucatan case study. Environmental Geology. 51: 719-723

Eastman, J.R., Solorzano, L., Van Fossen, M. 2005. Transition Potential Modeling for Land-Cover Change. In *GIS, Spatial Analysis and Modeling*, edited by David J. Maguire, Michael Batty and Michael F. Goodchild, 357-385. Redlands, CA: ESRI Press.

Fatoki OS, Awofolu RO. 2003. Methods for selective determination of persistent organochlorine pesticide residues in water and sediments by capillary gas chromatography and electron-capture detection. Journal of Chromatography A 983(1-2):225-236.

García, E. 1964. Modificaciones al Sistema de Clasificación Climática de Köppen (para adaptarlo a las condiciones de la Republica Mexicana). Tercera Edición. Offset Larios. México, D.F.

Graham, A., 2003. In the beginning: Early Events in the Development of Mesoamerica and the Lowland Maya Area. 31-44 pp. In: Gómez-Pompa A., M.F. Allen, S.L. Fedick and J. Jiménez-Osornio (Eds.). The Lowland Maya Area; three millennia at the human-wildland interface. Food Products Press. New York. 659p.

Herrera, J., Comín, F., 2000. An introductory account of types of aquatic ecosystems of Yucatan Peninsula. Aquatic ecosystem of Mexico. Status and scope. The Netherlands: Backhuys Publishers, 213-227.

Heredia JD, and Farfán MO. 2004. Influencia de rocas evaporíticas en la calidad del agua subterránea en la porción centro-sur de la Península de Yucatán. Congress XXXIII IAH - 7º ALHSUD. Groundwater Flow Understanding from local to regional scales. Zacatecas City, México.

INEGI 2002. Conjunto de datos vectoriales del Estado de Campeche. Versión Digital.

INEGI, 2005. Censo de Población y Vivienda. Instituto Nacional de Estadística, Geografía e Informática. Versión Digital.

INEGI, 2008. Perfil Sociodemográfico de Campeche. Instituto Nacional de Estadística, Geografía e Informática. 96p.

DOF 27-11-2009. Ley Federal de Derechos. Diario Oficial de la Federación, 27 de noviembre de 2009.

Lugo-Hubp, J., Aceves-Quesada, J., Espinasa-Pereña, R. 1992. Rasgos Geomorfológicos Mayores de la Península de Yucatán. Universidad Nacional Autónoma de México. Instituto de Geología. 10 (2): 143-150

Martin, J., 2001. Exchange and matrix of conduit water in examples from a Florida aquifer. U.S. Geological survey Karst Interest Group Proceedings, water resources investigation report 01-4011, 38-44 pp.

Masters, G., Ela, W., 2007. Environmental Engineering and Science. 3rd Edition. Prentice Hall. Arizona, USA.3 pp.

Muldoon, M., Payton, J. 1993. Determining Wellhead protection Boundaries – An Introduction. Groundwater Wisconsin's Buried Treasure. Wisconsin Department of Natural Resources. Publ WR313-92. 28p.

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. Diario de la Federación. Fecha de publicación: 22 de noviembre de 2000.

Pacheco, J., Cabrera, A., Pérez, R. 2004. Diagnóstico de la calidad del agua subterránea en los sistemas municipales de abastecimiento en el Estado de Yucatán, México. Ingeniería 8(2): 165-179.

Perry, E.C., Velazquez-Oliman, G., Marin, L., 2002. The hydrogeochemistry of the karst aquifer system of the northern Yucatan Peninsula, Mexico. Int. Geol. Rev. 44, 191–221.

Perry, E., Paytan, A., Pedersen, B., Velazquez-Oliman, G. 2009. Groundwater Geochemistry of the Yucatan Peninsula, Mexico: Constraints on stratigraphy and hydrogeology. Journal of Hydrology. 367:27-40

Prussian, K., Baichtal, J., 2007. Delineation of a Karst Watershed on Prince of Wales Island, southeast Alaska. In. M Furniss, C Clifton, and K Ronnernber, eds. Advancing the Fundamental Sciences: proceedings of the Forest service National Earth Sciences Conference, San Diego, CA, 18-22 October 2004, PNW-GTR-689, Portland, OR; U.S. Deparment of Agriculture, Forest Service, Pacific Northwest Research Station. pp. 111-117

Saunders, W. 2000. Preparation of DEMs for Use in Environmental Modeling Analysis. P. 29-51, In: Maidment D, and D. Djokic (Comp). Hydrologic and Hydraulic Modelling Support with Geographic Information Systems

SGM, 2007. Carta Geológico-Minera, Estados de: Campeche, Quintana Roo, y Yucatán. Escala 1:500,000. Servicio Geológico Mexicano. Versión Digital <http://www.coremisgm.gob.mx/>.

SEMARNAT, 2005. Informe de la Situación del Medio Ambiente en México; Compendio de Estadísticas Ambientales. Secretaria de Medio Ambiente, Agricultura y recursos Naturales. Dirección General de Estadística e Informática Ambiental. 380p.

Villasuso, M.J. and R. Mendez, 2000. A conceptual model of the aquifer of the Yucatán Peninsula. Pp. 120-139, In: Lutz, W., L. Prieto, and W. Sanderson (Eds), Population, Development, and Environment on the Yucatán Peninsula; from ancient Maya to 2030. IIASA, Luxemburg, Austria. 257p.

WHO. 2008. Guidelines for drinking –water quality. Vol. 1. Third edition Incorporating the First and second Addenda”. Geneva, World Health Organization. 515p.

Worthington, S., 2003. A comprehensive strategy for understanding flow in carbonate aquifer. Speleogenesis and Evolution of Karst Aquifers. 1 (1):1-8

Submitted August 31, 2010 – Accepted November 25, 2010
Revised received January 27, 2011