Sociedad y Ambiente

Evaluation of water quality through the distribution system in Cancún, Mexico

Evaluación de la calidad de agua a través del sistema de distribución en Cancún, México

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Abstract

A water distribution system must maintain water quality throughout the entire network to guarantee public health. Although several studies have focused on changes in water quality along distribution systems, very few have evaluated the entire process from the water source to household containers. The aim of this study was to evaluate the effectiveness of bacteriological control and to determine the critical points of potential contamination along the distribution system in Cancún, Mexico. We addressed three aspects: 1) physicochemical and bacteriological analysis of water, 2) biochemical oxygen demand (BOD_5) and nitrate-nitrite associated with organic matter, and 3) trihalometanes (THMs) as chlorine by-products from the disinfection process. The results showed that the water supply met the required quality standards in most parts of the distribution system but that there are critical points that could increase the risk of recontamination, specifically the geological setting and the critical aspects in irregular urban development in the area of water extraction. Mexico and any other country that relies on groundwater as a drinking water source must review and reinforce the regulations to protect areas with extraction wells and encourage the maintenance of containers to ensure water quality.

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Key words: quality; groundwater; distribution system; potable water; control;

Abstract

Un sistema de distribución de agua debe mantener la calidad del agua en toda la red en beneficio de la salud pública. Varios estudios se han enfocado en cambios en la calidad del agua en el sistema de distribución, pero pocos han evaluado todo el proceso desde la fuente de agua hasta los contenedores residenciales. El objetivo de este estudio fue evaluar la efectividad del control bacteriológico y determinar los puntos críticos de contaminación potencial a lo largo del sistema de distribución en Cancún, México. Se abordaron tres aspectos: 1) análisis físico-químicos y bacteriológicos del agua, 2) demanda bioquímica de oxígeno (DBO_5) y nitritos-nitratos asociados a materia orgánica, y 3) trihalometanos (THM) como subproductos de desinfección por cloración. Los resultados muestran que se cumplen los estándares de calidad en la mayor parte del sistema de distribución, pero existen puntos críticos que incrementan el riesgo de recontaminación; específicamente, debido a las condiciones geológicas y el incremento de desarrollos urbanos irregulares en el área de extracción. México, como cualquier otro país que dependa del agua subterránea como fuente de agua potable, requiere revisar y reforzar las regulaciones de protección en zonas de pozos de extracción, y fomentar el mantenimiento de los contenedores para asegurar la calidad del agua.

Palabras clave: calidad; agua subterránea; sistema de distribución; agua potable; protección;

Introduction

Water supply systems throughout the world must meet quality standards to ensure the health of the populations served, especially to prevent gastrointestinal illness. The Worldwide Health Organization (WHO, 2007) reported that variations in water quality in distribution systems were due to fecal contamination from broken pipes, storage tanks, or open containers. Moreover, some researchers have observed that storing water in the household leads to a deterioration of water quality due to poor hygiene and water-handling practices (*e.g.* Levy *et al.,* 2008). Other researchers have found that factors that propitiate recontamination of water in the home included size of the storage vessel mouth, transfer of water between containers from collection to storage, hand-to-water contact, dipping of utensils in contaminated water, and bacterial regrowth within the storage container (Hammad and Dirar, 1982; Lindskog and Lindskog, 1988; Mintz *et al.*, 1995; Momba and Kaleni, 2002; Trevett *et al.*, 2005). Pruss *et al.* (2002) and Grundy *et al.* (2006) mentioned that water contamination could be present at any point in the distribution and collection system.

In Mexico, federal guidelines for bacteriological control are set by the Health Ministry and the National Water Commission (spanish acronym CONAGUA). Organizations tasked with local water distribution, including state agencies, county committees, and/or operators of privately managed systems are required to monitor bacteriological load and to use chlorination to assure that federal regulations are achieved and maintained. For instance, Cisneros (2011) indicated that the water distributed in the Mexico City Metropolitan Area fulfilled 64 % of the physicochemical and 71 % of the bacteriological federal standards in 1994 but that by 1996, quality had decreased. Another study in Mérida, Yucatán examined the quality of potable water from the distribution system (outdoors) to domestic storage (indoors) (Flores-Abuxapqui *et al.*, 1995) and found that the water sampled met the quality standards. However, Pacheco *et al.* (2000) noted the deterioration of water quality in samples collected in supply wells north of Mérida City.

Escalona and Jiménez (2010) observed that in Mexico, “tandeo” (periodic changes of hydrostatic pressure) is a regular practice among distributors to prevent breaks and leaks in water pipes and to reach the farthest point in the system. These interruptions occur regularly, either on the basis of a schedule, or irregularly. The resulting discontinuity of water pumping has led to an increase in household water storage, which poses the greatest risk of water recontamination . This raises a number of questions:

- Does water distributed from the extraction point (well) to households maintain its quality?
- Is there a bacteriological and physicochemical difference along the distribution system?
- Does disinfection through the addition of chloride suffice to decrease the bacteria from groundwater and maintain these levels in residential storage containers (households)?

The aim of the study was to evaluate the water quality of a portion of the distribution system in Cancún, Quintana Roo, from the extraction site to the mixing point where chlorine is added, and in a selected set of residential storage containers. The study sought to determine the changes in water quality from the source to the end point and to determine whether recontamination occurred in the system during the rainy and dry seasons of 2011 and 2013. The study will establish whether the disinfection process effectively decreases the bacteriological load in groundwater once it has been transferred to residential storage containers and households.

Materials and methods

Characteristics of the study zone and water distribution system

Quintana Roo is the fastest-growing state due to tourist activity with a mean population increase of 4.1 % compared with the national rate of 1.4 % (INEGI, 2010). The main tourist attractions and developments in the northeastern part of the peninsula (Cancún, Playa del Carmen, Tulum and Costa Maya) have led to extraordinary population growth. This increase in the number of visitors and residents has placed an enormous strain on the area's resources, as well as the ability to locate and supply sufficient fresh water to meet the extraordinary demand created by large hotels, resorts, and sprawling residential development.

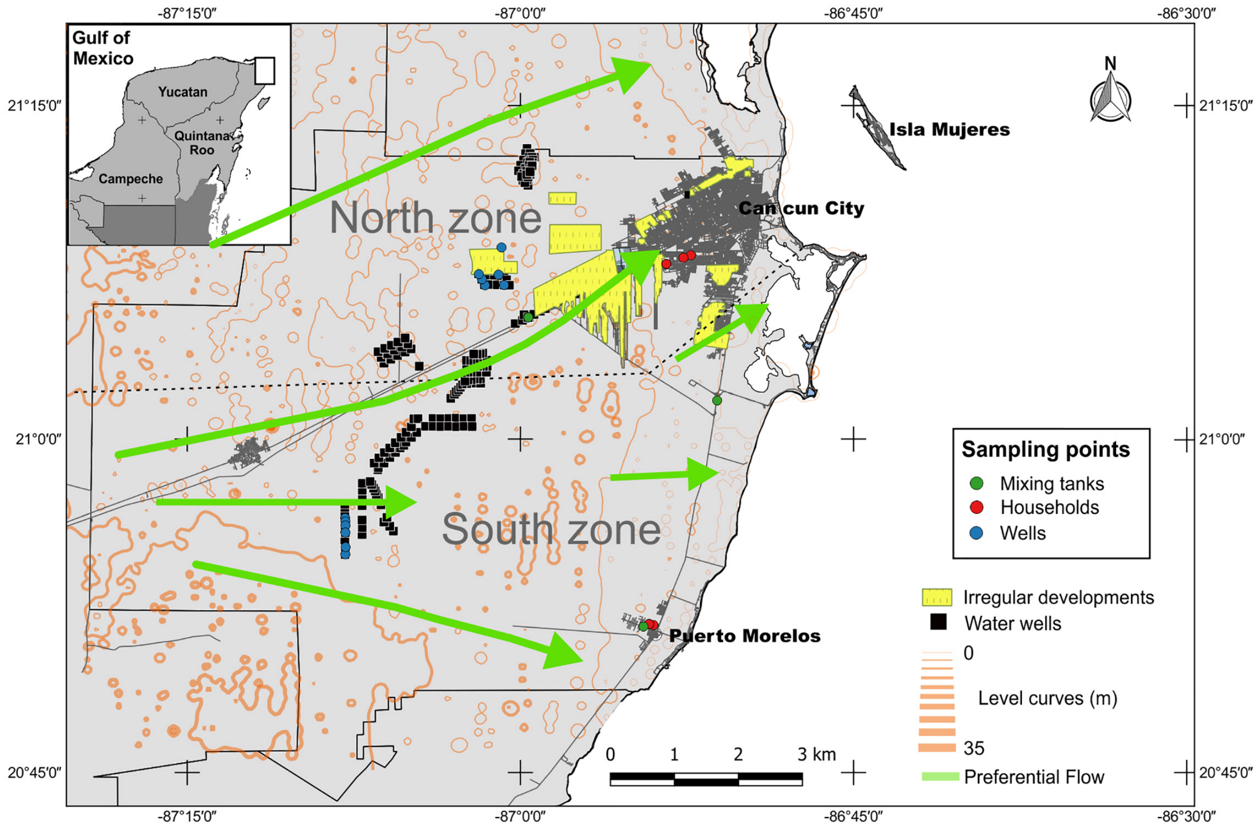
In Quintana Roo, the state water agency is the Drinking Water and Sewage System (Spanish acronym CAPA), which is required to monitor the water quality of distribution systems. The goal of municipal water distribution systems is to achieve 0.0 MPN of *Escherichia coli* as specified by the Mexican Official Standard NOM-127-SSA1-1994 (DOF, 2000). In the county of Benito Juárez, Quintana Roo, water distribution and water quality testing are provided by a private distribution company: DHC-Aguakan, which serves the urban zone of Cancún City, Alfredo B. Bonfil, the Cancún hotel zone, Puerto Morelos, Leona Vicario, and part of Isla Mujeres (DHC-Aguakan, 2011). Benito Juárez county, located in the northeast of the Yucatán Peninsula, has an area of 1644 km^2 and 661,176 inhabitants. In 2011, the distribution system comprised 160 wells, 2,200 km of pipes, and 47 mixing tanks distributed throughout Cancún city and the tourist areas (the hotel zone and Puerto Morelos). In 2013, the system was expanded to include 167 wells, 2400 km of pipes, and 48 mixing tanks. The company reported an average usage rate of 230 ℓ per day per inhabitant.

The unconfined aquifer used by CAPA and DHC-Aquakan is located in karst, which is highly vulnerable to contamination (Perry *et al.*, 2002). The Yucatán Peninsula is a large, emergent carbonate platform with developed karst features. Dissolution of carbonate material along fractures is common, leading to karstic features such as sinkholes, caves of varying width and depth. The area has the following characteristics: 1) beneath almost the entire northern region, the fresh water lens is underlain by marine saline intrusion in close hydraulic contact with the ocean, 2) the freshwater lens is approximately 10 m thick near the coast, reaching a depth of approximately 60 m, 3) precipitation across Quintana Roo ranges from 1,100 mm to 1,500 mm annually. Rainwater is the main source of aquifer recharge, with 15 % of total precipitation percolating down to the water table (Moore, 1992). Precipitation rapidly penetrates the surface layer of caliche through fractures and moves through a highly permeable vadose zone to the water table. As a result, there are no surface streams more than few hundred meters long in the northern and northeast peninsula.

Sampling design

For this study, two well-fields were selected: North zone (Nuevos Horizontes 2 NH2) with 33 wells, and South zone with 64 wells (Figure 1). The whole system comprises over 1690 wells and 49 mixing tanks. These areas supply water to the north part of the city where most of the irregular urban development has taken place, while the south zone supplies part of the city and hotel tourist zone (Figure 1). Collection was undertaken during the rainy season (June and July) in 2011 and the dry (March) and rainy season (July) in 2013. Water samples were collected throughout the distribution system, which included supply wells, mixing tanks (where chlorination takes place) and urban household containers (Figure 1).

Figure 1. Map of study area and location of sampling points*

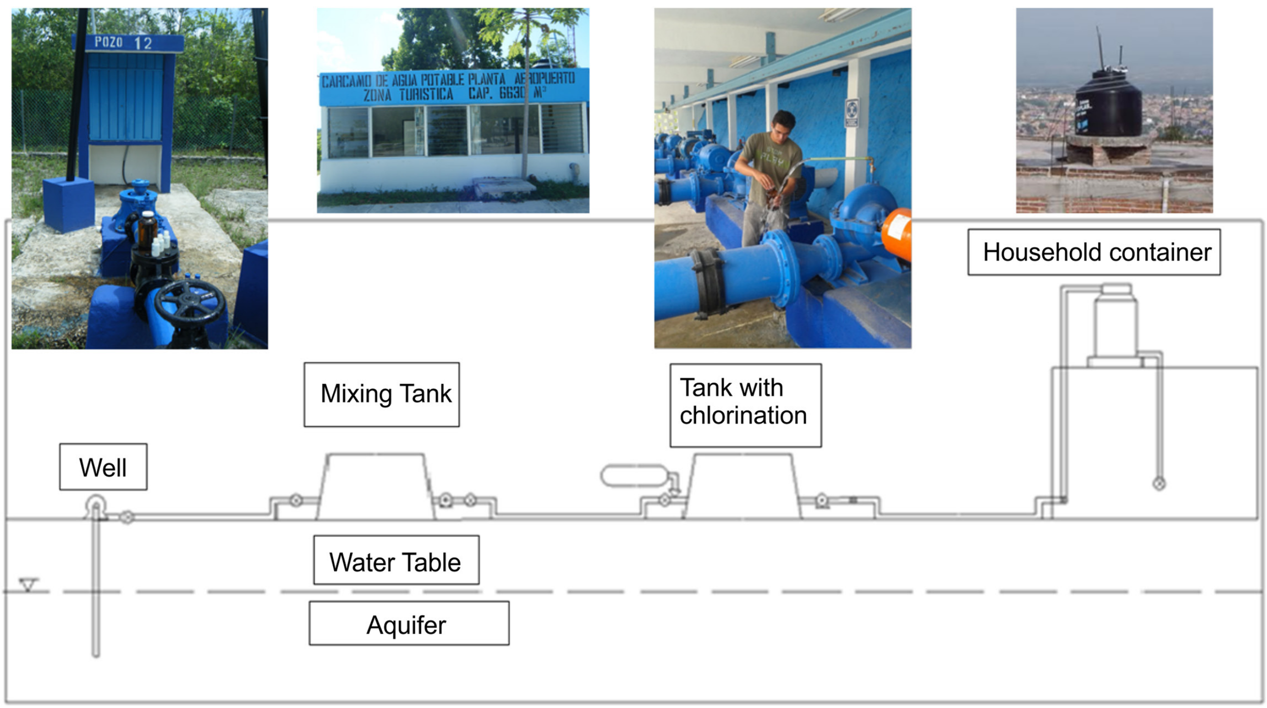


* Preferential flows show that the hydraulic gradient directs the groundwater flow from west to east. Note that the well field zones are upstream above all possible Wastewater Treatment Plants.

Source: Drought Prevention and Mitigation Measures Program (Spanish acronym PMPMS) 2014, National Commission for Biodiversity (Spanish acronym CONABIO) (http://www.conabio.gob.mx/informacion/gis/) and National Institute of Statistics and Geography (Spanish acronym INEGI) (http://www.inegi.gob.mx).

Although the wells and household containers were randomly selected, the selection of water mixing tanks was constrained by the requirement that they should receive water from the selected wells (Figure 2). However, in 2013, the sampling process selected wells from 2011, either because some wells were out of service due to maintenance or because they were the next closest wells in operation. Accordingly, the sample was drawn from the same set of wells in order to maintain the same geochemical characteristics. During these periods, 12 wells (six in each zone), four mixing tanks (two in each zone) and 23 (15 north and 8 south) households were evaluated for 2011 and 2013. In 2012, since several mechanical adjustments were made by CAPA, it was decided to wait for the end of this activity in order to resume the evaluation. The Mexican Official Standard NOM-127-SSA1-1994 (DOF, 2000) was used as reference for human water consumption, as well as the CONAGUA Water Classification.

Figure 2. Diagram of distribution system, including critical points: well (extraction of groundwater), mixing tank connected to chlorination process, and household containers



Source: modified from Diaz Cruz, 2013.

Parameters measured

At each collection site, water was flushed through the sampling valve and tubing for five minutes, after which physical-chemical data were measured for temperature, specific electrical conductivity (EC), total dissolved solids (TDS), and pH by a multiparametric portable sonde (Hach, model k156) to determine conditions in the field. After the flushing and measurement of field parameters, water was collected from the wells in the following order: 1) microbiology, one liter (collected in a sterile, amber-colored glass bottle) to carry out the physicochemical and bacteriological analysis, 2) BOD_5 in a HDPE container kept inside a black plastic bag with 60 mL HDPE water for nitrate-nitrite associated with organic matter: and 3) trihalometanes (THMs) as chlorine by-products from the disinfection process (collected in 45 ml EPA-vials mL). All containers were kept at 4 °C and transported to the laboratory.

Total coliforms, fecal coliform, and *E. coli* were assessed in triplicate using the chromogenic method (Idexx Colilert) following the manufacturers' instructions. For the Biochemical Oxygen Demand (BOD_5), analyses were performed using the Water Standard Methods (5210 Biochemical Oxygen Demand 5 Day BOD_5 test) (APHA, 1999). Samples for alkalinity, nitrate, and nitrite were vacuum-filtered through 0.2 µm filters, and collected with plastic bottles to analyze them in triplicate. Alkalinity was analyzed by the Gran method (Gran, 1952) using a digital Titler HACH brand model 16900 with vials of sulfuric acid (H_2SO_4) to 0.1600 ± 0.0008 N and a potentiometer Fisher Scientific® Accumet model Excel XL60. Nitrate and nitrite were analyzed following the APHA procedures (APHA, 1999). The samples for organics were collected in 40 ml EPA vials (VOA) and analyzed using 7 µm polydimethylsiloxane (PDMS) SPME fiber to concentrate the organic compounds and analyzed by gas chromatographic techniques, with an electron capture detector (GC/ECD), using a Thermo Finnigan Trace GC Ultra, with a 30 m x 0.32 mm x 0.25 µm Injector temperature at 280 °C splitless, ramp1 at 40 °C for 1 minute, 100 °C by 4 °C/min for one minute, ramp 2 at 200 °C by 20 °C/minute for one minute, ECD at 260 °C with Nitrogen as the carrier gas at 1 m ℓ / minute. Since all the data showed either presence/absence or were obtained from a single sampling point, there was no statistical analysis of the data.

Results

Physicochemical analysis

In general, the results showed data overlap (Table 1). Between wells in the north and south zones, the temperatures ranged from 25.5-28.5 °C (2011) and 23.3-28.7 °C (2013), the pH ranged from 6.53-7.77 (2011) and 7.07- 7.73 (2013); and the EC ranged from 974-1230 µS/cm (2011) and 1089-

1345 µS/cm (2013) which are similar values to groundwater in other parts of the region (Pacheco *et al.*, 2000; Perry *et al.*, 2002). The alkalinity values of the wells in the north were 276.37-316.71 HCO_3 mg/ ℓ (2011) and 503.96-524.81 HCO_3 mg/ ℓ (2013), and in the south they were 320.21-329.27 HCO_3 mg/ ℓ (2011) and 535.58-568.50 HCO_3 mg/ ℓ (2013).

In the mixing tanks, temperatures ranged from 27.4-28.7 °C (2011) and 23.5-29.5 °C (2013), the pH 5.21-7.0, and the EC ranged from 1017-1164 µS/cm (2011) and 1096-1326 µS/cm (2013). The variation in the mixing tanks could be due to the different wells being used. Alkalinity values in the mixing tanks were similar in the north, 295.49-322.29 HCO_3 mg/ ℓ, and in the south, 289.9-314.28 HCO_3 mg/ ℓ, for 2011, and in 2013, values in the north were 510.28-559.66 HCO_3 mg/ ℓ and 539.34-558.61 HCO_3 mg/ ℓ in the south.

The temperatures in the household containers ranged from 26.8-32.4 °C (2011) and 23.5-31.6 °C (2013), the pH ranged from 7.27-8.28 (2011) and 7.15-9.8 (2013), and the EC values ranged from 251-1070 µS/cm (2011) to 886-1507 µS/cm (2013). Alkalinity varied from 118.24-293.68 HCO_3 mg/ ℓ (2011) and 520.03-560.40 HCO_3 mg/ ℓ (2013) in the north to 91.6 -289.85 HCO_3 mg/ ℓ (2011) and 496.08-544.34 HCO_3 mg/ ℓ (2013) in the south. The temperature and pH changed after the water had been transported by pipe. The low EC value (251 µS/cm) is related to the source of the groundwater or the influence of rain in open household containers, which reduces the ion content (Sule *et al.*, 2011).

Table 1. Physicochemical results of samples collected in 2011 and 2013

NORTH											
2011						2013					
CODE	TYPE	Temp °C	pH	SpC uS/cm	Alkalinity HCO_3 mg/ ℓ	CODE	TYPE	Temp °C	pH	SpC uS/cm	Alkalinity HCO_3 mg/ ℓ
P-2 NH2	Well	26.8	6.91	1164	276.37	1PP-7	Well	28.1	7.17	1261	517.45
P-5 NH2	Well	26.7	7.29	1023	290.48	1P-11A	Well	26	7.49	1289	521.25
P-7 NH2	Well	26.7	6.53	1236	295.77	1P-11	Well	26.3	7.48	1117	524.81
P-10 NH2	Well	26.8	7.10	991	282.79	1P-2	Well	25.5	7.27	1089	521.59
P-12 NH2	Well	28.5	7.05	1132	279.54	2P-11	Well	25.5	7.19	1182	522.49
P-15 NH2	Well	26.5	6.98	974	316.71	2P-6	Well	25.4	7.22	1188	503.96
Ca-5	Mixing-tank	27.8	6.61	1115	295.49	2P-1	Well	25.6	7.43	1095	540.28
Ca- NH2	Mixing-tank	27.6	6.59	1164	322.29	2P-8	Well	23.5	7.34	1326	559.66
ITZ-335	Household	28.7	8.25	830	118.24	Ca-5	Mixing-tank	26.5	7.21	1230	538.73
ITZ-337	Household	28	7.54	1050	268.50	Ca-NH2	Mixing-tank	26.4	7.15	1210	537.72
BEL-518	Household	26.6	7.61	1006	270.68	103-1	Household	24	7.81	1332	520.03

						103-2	Household	23.5	9.86	1343	478.31
						103-3	Household	24.1	7.61	1312	548.63
						103-4	Household	27.2	7.58	1249	535.30
						PM-1a	Household	26	7.26	1268	535.30
						PM-1b	Household	26.6	7.7	1228	517.33
						PM-2	Household	25.2	7.69	1245	545.95
						PM-3	Household	25.5	7.58	1186	552.10
SOUTH											
2011						2013					
CODE	TYPE	Temp °C	pH	SpC uS/cm	Alkalinity HCO_3 mg/ ℓ	CODE	TYPE	Temp °C	pH	SpC uS/cm	Alkalinity HCO_3 mg/ ℓ
RC-50	Well	25.8	7.12	1066	323.77	RC-48A	Well	23.4	7.61	1345	565.40
RC-50A	Well	25.5	7.16	1069	329.27	RC-50	Well	23.5	7.66	1196	535.58
RC-51	Well	28.2	7.07	1067	324.74	RC-51	Well	23.8	7.62	1114	550.43
RC-55	Well	26.2	7.14	1209	327.15	RC-52	Well	23.4	7.73	1254	568.50
RC-54	Well	25.6	7.37	1176	320.31	RC-53	Well	23.3	7.72	1294	540.28
RC-52	Well	26.3	6.95	1062	328.80	C-10 E	Mixing-tank	28.7	7.63	1307	558.61
Ca-10 E	Mixing-tank	28.7	5.21	1017	314.28	C-10 S	Mixing-tank	29.1	7.56	1269	539.34
C-10 S	Mixing-tank	27.4	7	1068	289.92	BG	Household	29.5	7.76	1175	514.22
VM-H1	House hold	31.9	7.27	1070	289.85	UTC	Household	27.8	7.62	1244	533.15
VM-V1	House hold	32.1	7.35	1042	268.83	BV	Household	31.5	7.21	1215	544.34
VM-C1	House hold	31.2	7.64	836	173.07	CE-64	Household	26.8	7.43	1302	519.06
VM-C2	House hold	31.3	7.64	999	219.72	UTe	Household	27.8	7.41	1441	509.99
VM-C3	House hold	32.4	8.28	251	91.60	UTs	Household	30.5	7.75	1507	496.08

Bacteriological analysis

The bacteriological results indicated the presence of total coliforms at the well and in household containers (Table 2 and 3). In 2011, fecal coliforms were present in four wells and two household containers but none at the mixing tanks; moreover, none of the samples were positive for *E. coli*. In 2013, total coliforms was confirmed at the groundwater source (wells) where fecal coliforms were detected in three wells. However, after the chlorination process, the total number of coliforms was 0 MPN/100 mℓ for the wells. In 2011, fecal coliforms were detected in two households (3 and 6 MPN/100 mℓ) at the exit valve of containers. In 2013, only one household container reported the presence of fecal coliforms, also at the exit valve of the container.

Table 2. Bacteriological results (MPN/100 mℓ) in groundwater samples (wells) from 2011 and 2013

NORTH				SOUTH			
CODE	Total coliforms	Fecal coliforms	*E. coli*	CODE	Total coliforms	Fecal coliforms	*E. coli*
2011							
P-2 NH2	***1***	***2***	<1	RC-P50	<1	<1	<1
P-5 NH2	<1	<1	<1	RC-P50A	<1	<1	<1
P-7 NH2	***1***	<1	<1	RC-P51	<1	<1	<1
P-10 NH2	***5***	***2***	<1	RC-P55	<1	<1	<1
P-12 NH2	***1***	***1***	<1	RC-P54	***2***	<1	<1
P-15 NH2	***1***	***2***	<1	RC-P52	***2***	<1	<1
2013							
1PP-7	***2.6***	***1***	<1	RC-P48A	***0.5***	<1	<1
1P-11A	<1	<1	<1	RC-P50	***3.6***	<1	<1
1P-11	***1***	<1	<1	RC-P51	***5.8***	***1***	<1
1P-2	***4.1***	***2***	<1	RC-P52	***9.1***	<1	<1
2P-11	***0***	<1	<1	RC-P53	***10.9***	***3***	<1
2P-6	***3.6***	***2***	<1				
2P-1	***1.6***	<1	<1				
2P-8	<1	<1	<1				

Table 3. Bacteriological results (MPN/100 mℓ) in households from 2011 and 2013

NORTH				SOUTH			
CODE	Total coliforms	Fecal Coliforms	*E. coli*	CODE	Total coliforms	Fecal Coliforms	*E. coli*
2011							
103-1	***14***	***6.1***	***2***	ITZ-335	***8***	***3***	***3***
103-2	***1***	***0.15***	<1	ITZ-337	***4***	***1***	<1
103-3	***19.1***	***14.9***	***1***	BS-MIG	***1***	<1	<1
103-4	<1	<1	<1	BEL-518	<1	<1	<1
PM-1a	<1	<1	<1	VM-H1	<1	<1	<1
PM-2	<1	<1	<1	VM-V1	<1	<1	<1
PM-3	<1	<1	<1	VM-C1	<1	<1	<1
PM-4	<1	<1	<1	VM-C2	***1***	***1***	<1
				VM-C3	<1	<1	<1

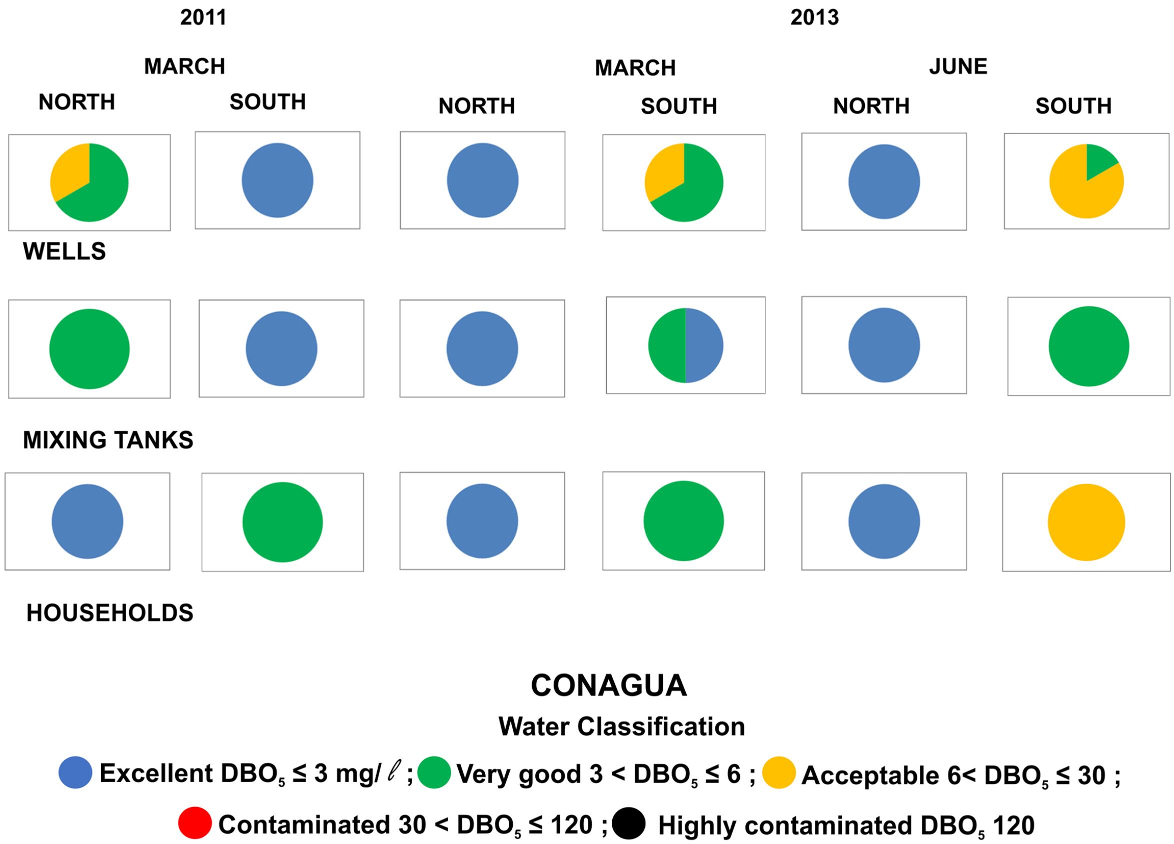
2013							
103-1	***17.9***	***7.6***	<1	ITZ-335	***16***	***3***	<1
103-2	***1***	***2***	<1	ITZ-337	***2***	***1***	<1
103-3	<1	<1	<1	BS-MIG	***1***	<1	<1
BG	<1	<1	<1	BEL-518	<1	<1	<1
UTC	<1	<1	<1	VM-H1	<1	<1	<1
BV	<1	<1	<1	VM-V1	<1	<1	<1
CE-64	<1	<1	<1	VM-C1	<1	<1	<1
UTe	<1	<1	<1	VM-C2	***1***	***1***	<1
UTs	<1	<1	<1	VM-C3	<1	<1	<1

Biochemical Oxygen Demand (BOD_5)

Biochemical Oxygen Demand (BOD_5) was considered a factor in the production of THMs due to its relationship with organic matter and temperature increase (Freire *et al.*, 2008; Navalon, 2009). In general, BOD_5 ranges from 4.11 to 7.12 mg/ ℓ for wells and 5.12 to 6.14 mg/ ℓ for mixing tanks at the north zone, whereas in household containers, BOD_5 ranges from 5.60 to 6.24 mg/ ℓ (Figure 3). This indicates that organic matter remains in the system from its initial critical point (wells). The well fields naturally have organic matter that increased during the rainy season from 2011 to 2013, possibly due to runoff and infiltration.

According to the CONAGUA water classification (Figure 3), in 2011, water in the north and south zone was classified as excellent to very good in the household containers and mixing tanks, whereas the wells in the south classified as very good to excellent. In 2013, water was classified as excellent for both the north and south zones in March, but in June (the rainy season), the classification decreased to acceptable.

Figure 3. Biochemical Oxygen Demand (BOD_5)*

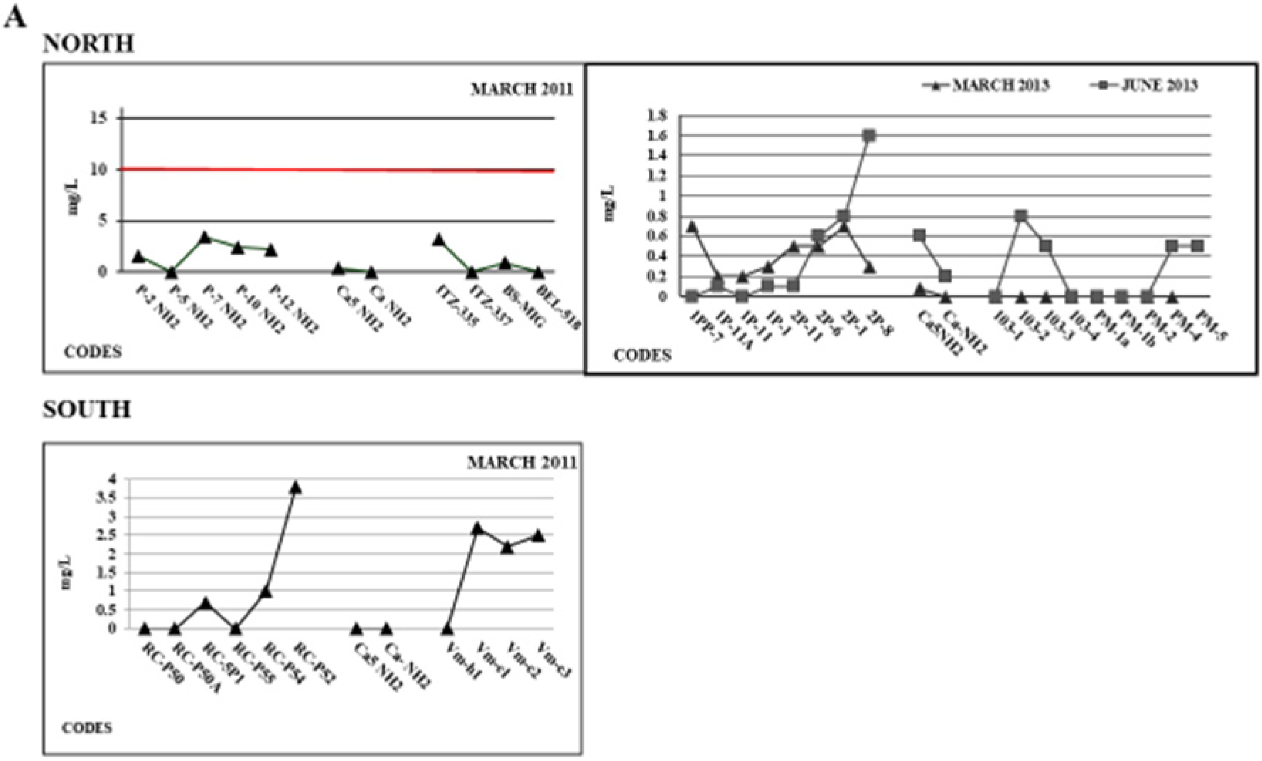


* The entire number of household samples had excellent quality in 2011 in March, and in 2013, the entire number of samples were classified as excellent in March, yet by June, this classification had deteriorated.
Source: graphics generated from our own data.

Nitrates and Nitrites

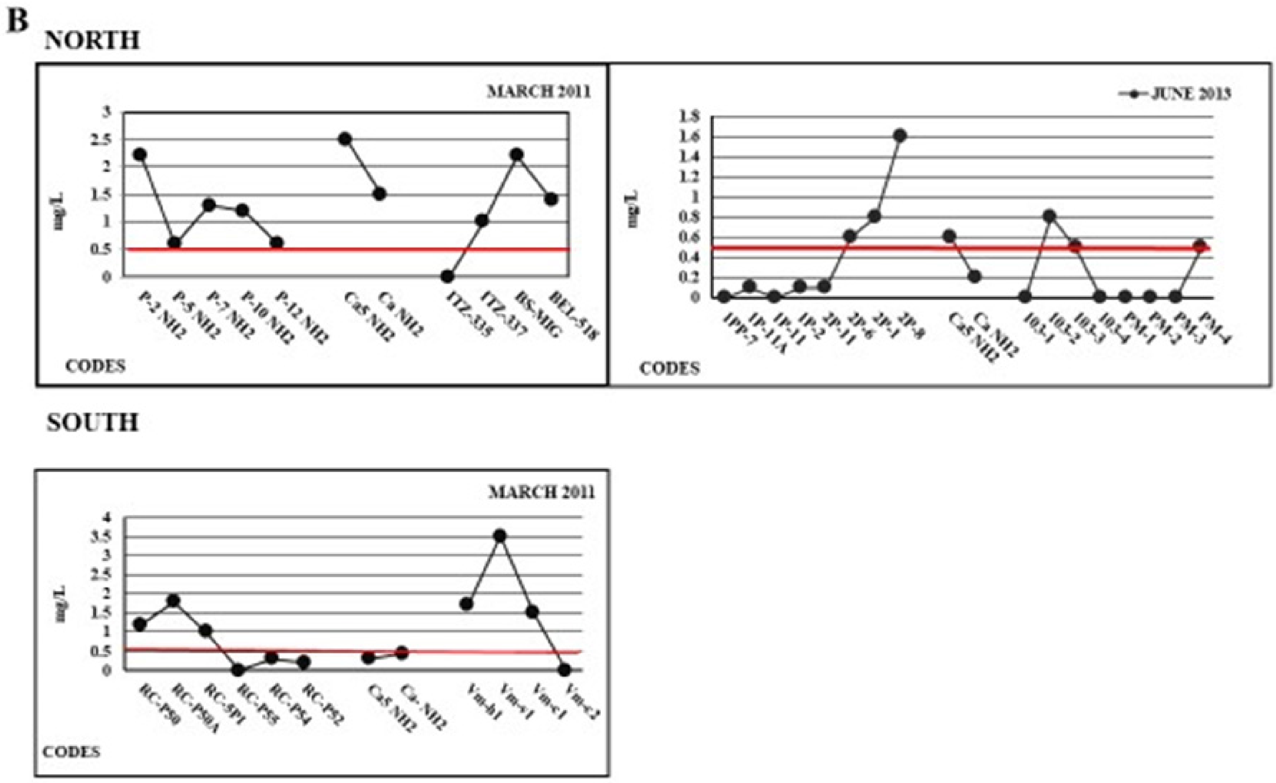
One parameter that scored above the norms was nitrite. Since the Mexican Official Standard indicates a maximum contaminated level of 0.5 mg/ ℓ, nitrite levels fail to comply, as can be seen in Figure 4A, where household containers showed the highest values detected (0 to 3.6 mg/ ℓ). Groundwater and water from the mixing tanks have similar nitrite levels; (for wells the range was from 0.2 to 2.3 mg/ ℓ, whereas for pumping mixing tanks it ranged from 3 to 25 mg/ ℓ), and in household containers, nitrite increased from 0 to 3.6 mg/ ℓ. Nitrate (Figure 4B) ranged from 0 to 16 mg/ ℓ, while groundwater showed the highest presence of nitrate (for wells, the range was from 0 to 15.5 mg/ ℓ), and values for pumping mixing tanks decreased from 0 to 0.4 mg/ ℓ, and for households from 0 to 3.2 mg/ ℓ. Since the Mexican Official Standard stipulates a maximum contaminated level of 10 mg/ ℓ, it is only in the wells zone that levels are out of compliance.

Figure 4A) Although nitrite compounds were undetected in March of 2013 in both zones, conditions in wells and household containers were above the Mexican Official Standard of 0.5 mg/ ℓ



Source: graphics generated from our own data.

Figure 4B) In 2011, nitrate levels above the Mexican Official Standard of 10 mg/ ℓ were detected and even though nitrate was detected in both March and June of 2013, it failed to be detected in the south zone

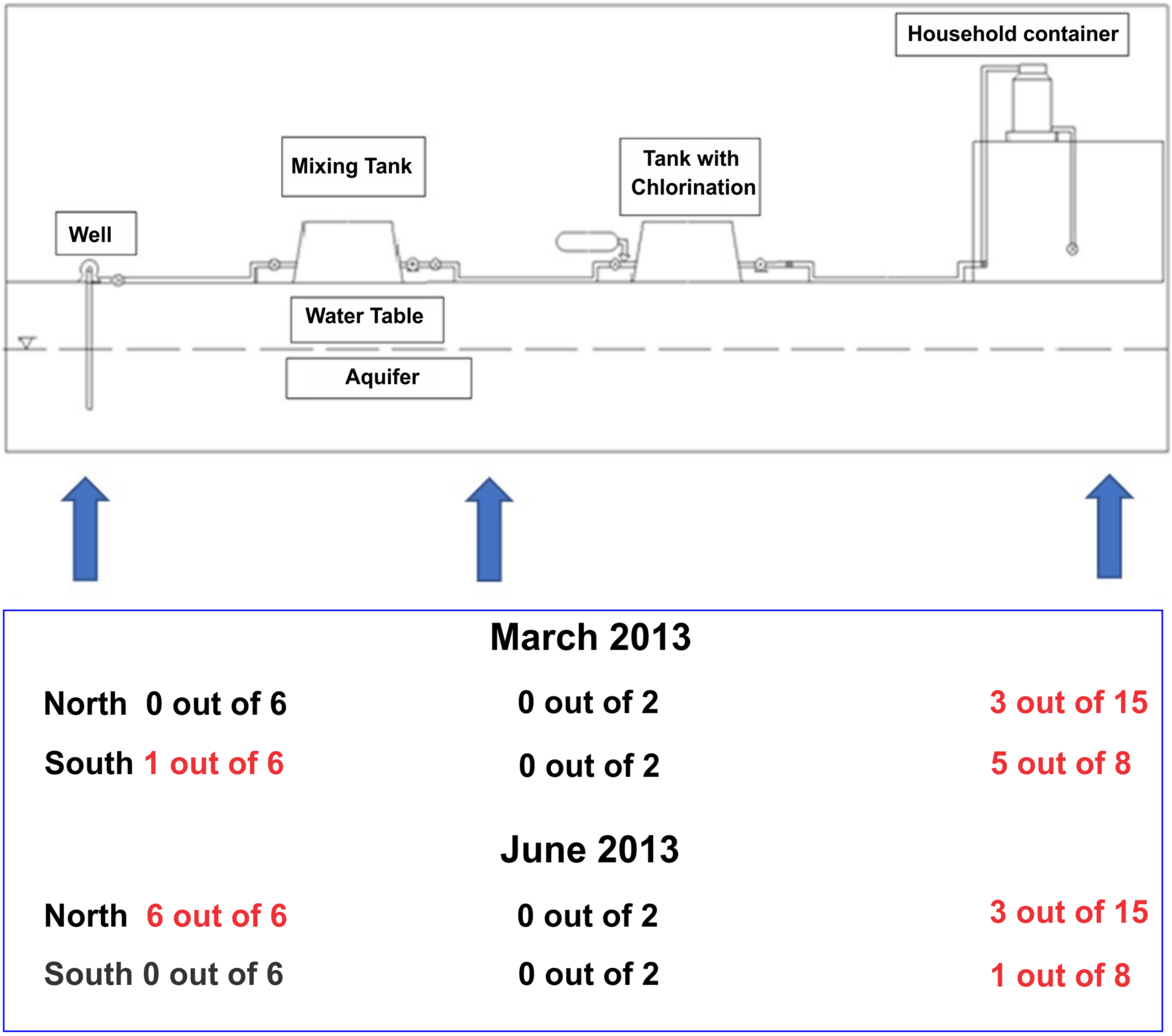


Source: graphics generated from our own data.

Organic compounds: trihalometanes (THMs) as chlorine by-products from the disinfection process

The presence of semi-volatile compounds in household containers underlined the importance of evaluating the influence of the different materials and water storage conditions. In 2011, there were positive detections at one well in the south, two mixing tanks, and three household containers made of plastic but they were not detected in concrete cisterns. These positive peaks were identified as Chloroethane, Tribromomethane, Bromochloromethane and Bromomethane. However, by 2013 the situation had changed drastically (Figure 5), with three out of 15 households reporting the presence of THMs in the north zone; and five out of eight households indicating the presence of THMs in the south zone.

Figure 5. Critical points in the distribution system where the detection of THMs compounds was positive for 2013. Note that THMs are present in wells and households containers



Source: modifed from Diaz Cruz, 2013.

Table 4. Identified organic compounds detected in a specific part of THMs in the distribution process

CODE	Type	Organic compound
2011		
Rc-p54	South well	Bromochloromethane
Ca-5	Mixing tank	Chloroethane Tribromomethane Bromochloromethane
Ca-NH2	Mixing tank	Chloroethane Tribromomethane Bromochloromethane Bromomethane
ITZ-335	Household container	Chloroethane Bromochloromethane
BS-MIG	Household container	Chloromethane
VM-C1	Household container	Chloroethane Bromomethane
2013		
P-2-NH2	North well	Chloromethane Bromodichloromethane
P-7-NH2	North well	Chloromethane
P-10-NH2	North well	Bromodichlorometane Dibromochlorometane
P-12-NH2	North well	Dibromochlorometane
ITZ-335	Household container	Bromophorme
BS-MIG	Household container	Dibromochlorometane
BEL-518	Household container	Bromophorme
RC-51	South well	Bromophorme
RC-54	South well	Chlorodibromomethane
VMH1	Household container	Bromodichloromethane
VM-V1	Household container	Bromodichloromethane
VM-C1	Household container	Chlorodibromomethane
VM_C2	Household container	Chlorodibromomethane

Source: table generated with our own data.

Discussion

Several studies have focused on possible changes in water quality in distribution systems. However, describing physicochemical and bacteriological parameters to determine whether the distribution system is in compliance with water quality standards from the water source to household containers had not been done until now. This research analyzed water quality throughout the entire distribution system to determine whether it ensured the water quality the population requires. It also examined whether the entire process including chlorination sufficed to supply water that meets quality standards.

Aqueous chemistry showed that the water supply met the required quality standards in most parts of the distribution system. Chemical conditions such as pH, specific conductivity, and alkalinity become homogenized at the pumping mixing tanks, which serve as temporary well water storage for the supply company. However, the bacteriological standards were not met. This coincides with reports by Pacheco *et al.* (2000), on high densities of total and fecal coliform in groundwater in the northwest of the Yucatán Peninsula. These authors suggest that the sources of the bacteriologically contaminated groundwater samples collected north of the city of Mérida are related to the leaching of animal and human waste near the sampled wells in this area. In our study, we believe the increase is due to irregular urban development, which has limited access to proper sewage disposal.

The presence of fecal coliforms indicates that the groundwater at the well did not comply with the bacteriological quality norms (specifically in the north well field), thus justifying the need for a disinfection process. As protection against waterborne diseases, water is chlorinated several times along the distribution system, before reaching the farthest point. After the drinking water treatment, values for organic nitrogen were still above the limit established in the Mexican Official Standard (DOF, 2000). These facts may explain the high presence of THM compounds found at this site. Residual chlorine must be sufficient to maintain disinfection throughout the distribution system and can lead to the formation of THMs. As Gelover *et al.* (2000) reported, the highest concentration of THMs in the water distribution system in the five Mexican cities evaluated was found in Cancun City, mainly bromoform.

Results shows that nitrate and nitrite were found in all the samples collected, and that nitrite levels are above the Mexican Official Standard (Gelover *et al.,* 2000). Nitrate or nitrite levels can rise when the area surrounding the well is heavily developed, due to either agriculture or sewage. Nitrite, which is not stable, has a short residence time in groundwater. Thus a high presence of nitrite generally indicates that the activity which produced it is very recent and/or very close by (Null *et al.,* 2014). Because nitrite is present in all the samples (some of which also contained nitrate), the recent introduction of nitrogen may be related to the increase in urban development, which creates points of solid waste deposits, particularly around the north wells field. The presence of nutrients may also suggest the re-growth of biofilms in the pipeline of the distribution system (Lethola *et al.,* 2006).

As mentioned before, THM groups were detected in wells during both periods and in eight household containers during the dry season in 2011 and 2013. There are two main reasons for this detection: 1) percolation of water from the surface into the aquifers in the well field occurs where there are irregular urban developments, and 2) an increase in BOD_5 indicates a higher concentration of dissolved organic matter in household containers, which could lead to THMs as byproducts of residual chlorine (Garrido and Fonseca, 2009). Up to this point, the occurrence of THM compounds in wells indicates their relationship with anthropogenic activity due to infiltration into the aquifer, while confirmation of their presence in household containers could be related to their persistence and accumulation as a result of the increase in organic matter and total dissolved solids through the distribution system. This confirms the vulnerability of well fields where recharge control enables the infiltration of these compounds from irregular urban developments.

This presence of coliforms, nitrate, and THMs at the water source (groundwater) points to a combination of situations: a) infiltration is occurring through a region with new urban developments, which encourages waste deposits similar to the situation reported by Leal-Bautista *et al.* (2013) in Tulum's well field, and b) the accumulation of organic matter in household containers, which promotes the presence of biofilms and leads to the presence of coliforms and *E. coli* and an increase in THMs. The occurrence of THMs in wells points to their association with anthropogenic activity. At the same time, it also provides confirmation that THMs in household containers could be related to the persistence and accumulation of organic matter and increased chlorine through the distribution system (LeChavallier *et al.,* 1987; Geldrich, 1996; Sadiq and Rodriguez, 2004).

Improvements in the distribution system since the 1990s have led to a decrease in diarrheal diseases and improved the water supply and sanitation (through the chlorination of drinking water, increased distribution of potable water among the population, greater access to proper sewage disposal, and restrictions on the use of contaminated water for agriculture). However, regulations stop at the house connection and does not include the maintenance or protection of household containers. Thus, either the *E. coli* or THMs detected in household containers have implications for human health related not to the lack of sanitation but rather to the maintenance and operation of the system. The presence of coliforms and *E. coli* in households could be related to: a) the "tandeo" or cycles which flush sediments and biofilms developed along the pipes and b) the importance of the maintenance and hygiene of household containers (which is the responsibility of consumers), which plays an important role in the change in water quality at the household level.

Even though the Mexican Official Standard does not require the evaluation of BOD_5 for human water consumption, CONAGUA uses this parameter to indicate whether a hydric-system (groundwater or surface water) has suitable water quality for any use. The range reported in both well fields is suitable for use and ranges are similar to those reported by Mantilla *et al.* (2002). In general, the samples showed a decrease in water quality yet still in compliance with its classification. This indicates that organic matter remained in the system from its initial critical point (wells) at both field wells and increased during the rainy season from 2011 to 2013 due to runoff and infiltration. However, the presence of organic matter encourages the development of THMs at high temperatures and residual chlorine, which affects household containers and human health. This confirms the vulnerability of the recharge zone where changes in the rainy and dry season could cause differences that warrant further assessment.

Since the water table is not deep (2.5-46 m; Perry *et al.,* 2002) and most groundwater is pumped from a depth of just 11 to 14 m, the increase in irregular urban developments where groundwater is extracted has a major impact on water quality. These developments do not have wastewater treatment plant or even sewage pipes. This means untreated water may infiltrate the aquifer via unmonitored latrines, or direct wastewater discharge into sinkholes, which is compounded by the presence of dumps and irregular animal activities such as unregistered chicken farms. This situation requires an extension of the sewerage system to serve irregular urban developments and above all, to encourage households to connect to this service since Mexican law only promotes the regulation of the sewage pipes by the municipality but has no mechanism compelling owners to connect to the system

Conclusions

1. Does water distribution from the extraction point (well) to households maintain its quality? No, this could change, particularly in household containers.
2. Is there a bacteriological and physicochemical difference along the distribution system? The disinfection process fulfills bacteriological Mexican requirements along the whole distribution system and there is no difference in physicochemical water quality once it is transported though the system because it becomes homogenized.

3. Is the disinfection process by the addition of chloride sufficient to decrease the bacteriological presence from the groundwater and maintain it in residential storage containers (households)? The disinfection process fulfills Mexican bacteriological requirements by reducing the bacteriological presence detected in groundwater; however, it was found that changes in microbiology occur in household containers.

This study shows that water distribution promotes better water quality control and fulfills the quality norms established by the federal government. However, Mexico needs well protection regulations because of the rise in the number of developments around well fields. Policies for protecting these areas surrounding wells must be reviewed and enforced to protect the quality of the water supply. Aqueous chemistry shows that water supplies meets the required quality standards in most parts of the distribution process. Once water undergoes the chlorine addition process, the physicochemical parameters, including alkalinity, became similar. Nevertheless, the karstic characteristics are clearly allowing rapid infiltration of contaminants (nitrate and nitrites) into the aquifer.

The presence of THMs at the water source (wells fields) suggests that recharge is an important form of control of well water quality, not that the well fields are geochemically different. In addition, this study shows that there is a need for a culture of maintenance of household containers to reduce the risk of bacteriological contamination that will affect public health. These changes will make it possible to maintain the high quality of drinking water and allow better development of the region. Although local and state water committees such as Basin Committees are attempting to improve water quality assessment, this is usually undertaken at the point of extraction or after disinfection, when in fact, the whole distribution system should be examined.

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