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Comparison of the Water Quality of Two Aquifers Established in Different Development Zones of Mexico

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Abstract

The rapid growth of urban areas has further affected groundwater quality due to over-exploitation of resources and improper waste disposal practices. The over-exploitation of aquifers, which reduces natural recharge due to high urbanization and anthropogenic activities, has caused a decrease in groundwater quality in many areas. The objective of this research was to determine and compare the bacteriological and physicochemical quality of the Mexico City and Tepalcingo-Axochiapan, Morelos aquifers. Groundwater samples were collected every two months for one year. The bacteriological and physicochemical parameters were analyzed in accordance with Standard Methods for the Examination of Water and Wastewater. The Tepalcingo-Axochiapan, Morelos aquifer had higher concentrations of total and fecal coliforms in most wells and samplings than the Mexico City aquifer. Fecal coliform values of the two aquifers were lower than the maximum permissible limit indicated in the Mexican Ecological Criteria of Water Quality (1000 colony forming units (CFU)/100 ml of fecal coliforms) for public supply sources. Average values of electrical conductivity and dissolved solids in the Tepalcingo-Axochiapan aquifer were higher than average values from the Mexico City aquifer. ANOVA analysis showed significant differences ($p < 0.05$) only for hardness and sulfates, they were the physicochemical parameters that showed the biggest difference between the two aquifers, the concentrations of both parameters being higher in the Tepalcingo-Axochiapan aquifer than in the Mexico City aquifer. In general, the average values of the physicochemical parameters were below the maximum permissible limits indicated in the Mexican Official Norm (NOM-127-SSA1-1994) for drinking water.

Keywords: Aquifers, Groundwater, Microbiological Quality, Physico-Chemical Quality

1.0 Introduction

Pure groundwater does not exist in nature; as it flows over or through the surface layers of the earth, it dissolves and carries with it some of almost everything it touches, including that dumped into it by man. Groundwater, therefore, naturally contains mineral ions. These ions slowly dissolve from soil particles, sediments, and rocks as the water travels along mineral surfaces in the pores or fractures of the unsaturated zone and the aquifer (Erah *et al*., 2002; Harter, 2003). Groundwater quality includes the physical, chemical and biological characteristics of groundwater and depends on natural processes as well as anthropogenic activities. Human activities can alter the natural composition of ground water through the disposal or dissemination of chemical and microbial matter at ground surface and into soil or through the injection of waste directly into the groundwater. During the last few years, it has been observed that groundwater gets drastically polluted because of the increase in human activities. Thus, groundwater pollution is defined as an undesirable change in groundwater quality resulting from human activities (Harter, 2003; Bhalla *et al*., 2010; Kale *et al*., 2010; Lewis and Liljedahl, 2010; Bhupinder, 2011).

Groundwater represents an important source of drinking water and its quality is currently threatened by a combination of microbiological and chemical contamination. The consequence of urbanization and industrialization leads to water pollution. In rural areas groundwater is used for agricultural purposes, especially where other sources of water are not available. The rapid growth of urban areas has further affected groundwater quality due to over-exploitation of resources and improper waste disposal practices (Granel and Galez, 2002; Jameel and Sirajudeen, 2006; Aydin, 2007; Ozler and Aydin, 2008). In Mexico, nearly 50% of water used for domestic, industrial and agricultural activities comes from groundwater sources, and wells are positioned indiscriminately; in many cases little is known about the geology, the volume of water available and its quality. In addition, the over-exploitation of aquifers, which reduces natural recharge due to high urbanization and anthropogenic activities, has caused a decrease in groundwater quality in many areas (Granel and Galez, 2002; Ramirez, 2010). The decrease of the microbiological and chemical quality has been reported in several aquifers around the country (Munoz *et al*., 2004; Pacheco *et al*., 2004; Perez y Pacheco, 2004; Jimenez *et al.*, 2006; Ramirez *et al*., 2009, 2010; Robles *et al.*, 2009, 2010). The objective of this research was to compare the bacteriological and physicochemical quality of the Mexico City and Tepalcingo–Axochiapan, Morelos aquifers.

2.0 Materials and methods

2.1 Mexico City (MC) Aquifer

The Mexico City aquifer is located southwest of the Valley of Mexico (Figure 1); it occupies 17% of the basin surface area, which covers 9600 km^2. The Mexico basin is endorheic, where the earth's crust has been subjected to great force, causing intensive fracturing. Mexico City and its suburbs depend fundamentally on the aquifer for drinking water, which has resulted in its over-exploitation. The weather is warm sub-humid (Cb (Wo) (W)), which is the least humid of the warm weathers with summer rains, with an annual average rainfall of 1003 mm, and an annual average temperature of 20 °C.

The Mexico City aquifer is semi-confined. The impermeable substrate is made of volcanic rock and limestone. The sedimentary package produces a complex aquifer system comprising three large bodies: in the upper part a clay package of high porosity, low permeability and largely heterogeneous, constitutes an aquitard of variable thickness which is semi-confined in the middle of the basin. Under this package is the aquifer currently being exploited, made up of thicker granular material than the aquitard, namely pyroclastics and volcanic conglomerates. Its thickness is variable, generally greater than 200 m, as are its hydraulic properties. In the lower part there are fractured volcanic rocks, which reach 200 m in the middle, decreasing towards the basin borders. The three units show a wide range of hydrodynamic parameters (permeability, storage coefficient, transmissivity). The units are communicated, particularly the last two (one made up of volcanic rock and the other, granular material).

Natural and induced recharge of the aquifer is almost zero due to the zone having the highest number of habitants in the country, and those areas where natural recharge could occur are either paved or the sites of shanty towns. Practically the only water entry is by horizontal flow with 279,000 m^3 annually. The extraction of groundwater from the Mexico City Basin is around 507,364 m^3 per year, from wells up to 100 m deep. Groundwater extraction accounts for about 70% of the city's supply, so the aquifer is considerably over-exploited. Every year a total of 448,499,000 m^3 is used for urban municipal use, 49,419,000 m^3 for industrial use and 6,540,000 m^3 for commercial use. The zone has the main services such as drainage and drinking water supply. Of the thirteen Federal District boroughs served by the Mexico City aquifer, the three selected for this research were those with the highest population, about 3,500,000 inhabitants (30% of the total) and the highest groundwater extraction volume, about 200,000 m^3 (41 % of the total) (CONAGUA, 2002a).

2.2 Tepalcingo-Axochiapan (TA) Aquifer

The Tepalcingo-Axochiapan Valley aquifer is one of the four aquifer of Morelos State in Central Mexico and is located in the western portion of the state (Figure 1). It has a surface area of 1,353.7 km^2 of which 495.9 km^2 correspond to the recharge area in the high ground to the north, and 857.8 km^2 to the aquifer area in the valley to the south. The prevailing weather is warm sub-humid with summer rains, an annual average temperature of 20.3°C and annual average precipitation of 910 mm.

The water passes downwards from the Nevada Sierra to the Tepalcingo-Axochiapan Valley. The geological structure determines the direction of groundwater flow, giving a preferred direction of north to south. The geology of the aquifer is represented by different rock units; the materials comprising these units are igneous, intrusive and extrusive rocks; and large outcroppings of sea, continental and sedimentary rocks. The Sierra Nevada (Popocatepetl volcano, 5,452 mosl) is one of the main aquifer recharge zones. It is made up of tephra formed by basaltic, andesitic or rhyolitic lava interspersed with pyroclasts. The tephra layer has a high degree of secondary permeability caused by intense fracturing; and the volcanic slag (tezontle) allows the infiltration of rainwater.

The aquifer is set in the Nexapa River Basin, where the large number of deep wells bored for agriculture has resulted in its over-exploitation. The water quality has been mainly deteriorated by the use of fertilizers, septic tank effluents, disposal of sewage effluents, and solid waste. Seven municipalities of Morelos with a population of 118,844 inhabitants are in the zone of the Tepalcingo-Axochiapan aquifer; (CONAGUA, 2002b).

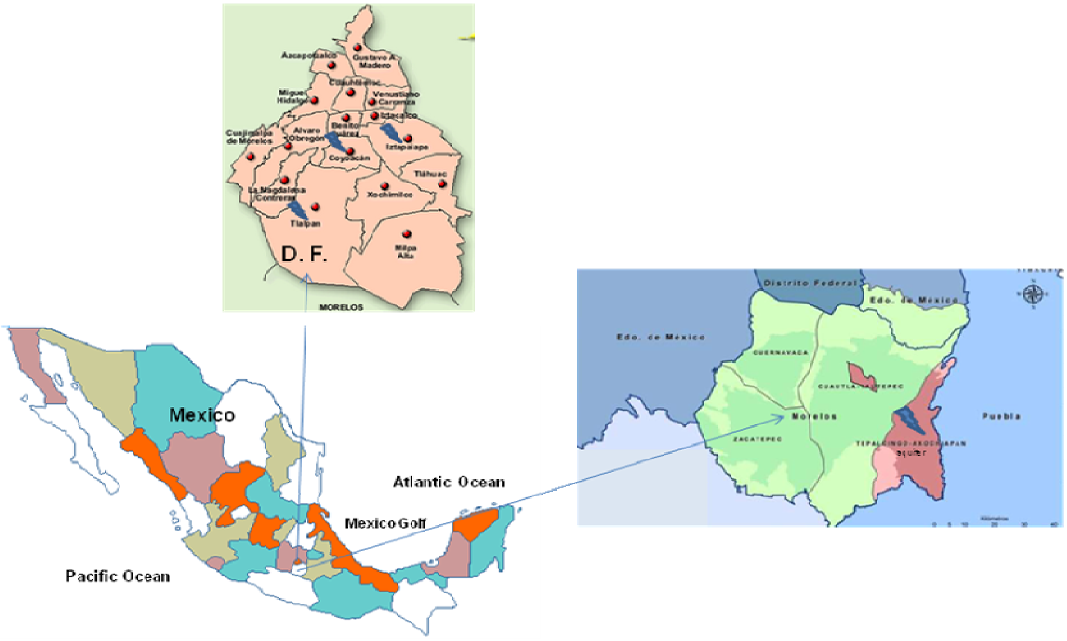

Figure 1: Location of City Mexico and Tepancingo-Axochiapan Morelos aquifers

2.3 Sampling procedure

Eight wells (W) and two springs (S) were sampled in the south and east areas of the MC aquifer and eight wells and one spring distributed along the TA aquifer. Sites were sampled every two months for one year. The samples were taken before the chlorine injection point to determine the natural conditions of the aquifer. The pH level, dissolved oxygen (DO) and temperature were determined *in situ*.

2.4 Laboratory analysis

The bacteriological parameters analyzed were: total coliforms and fecal coliforms. These were analyzed using the membrane filter technique according to Standard Methods for the Examination of Water and Wastewater (1998). The physicochemical parameters were: biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), ammonia nitrogen, total alkalinity, phenolphthalein alkalinity, total hardness, calcium hardness, chloride, sulfate, dissolved solids, nitrates, nitrite, methylene blue active substances (MBAS) and turbidity, according to Standard Methods for the Examination of Water and Wastewater (1998).

3.0 Results and Discussion

The Tepalcingo-Axochiapan, Morelos aquifer had higher concentrations of total and fecal coliforms in most wells and samplings than the Mexico City aquifer (Tables 1, 2 and 3). The high bacterial contamination shown in the TA aquifer may be due to the zone having no drainage system, the use of septic tanks for waste disposal, and because the aquifer runs through material with a high degree of permeability, which allows the infiltration of contaminants.

Table 1: Values (geometric means) of Total and Fecal Coliforms from the Aquifers

	Mexico City aquifer			**Tepalcingo-Axochiapan, Morelos aquifer**	
	Total Coliform	**Fecal Coliform**		**Total Coliform**	**Fecal Coliform**
W1	0	0	W1	502	287
W2	0.16	0.16	W2	1.1	0.63
W3	56.7	6.1	W3	77.3	47.7
W4	11.09	1.5	W4	183439	60183
W5	0.196	0.119	W5	229	140
W6	0.151	0.110	W6	0.898	0.195
W7	0.098	0.098	W7	1.79	0.98
W8	1.08	0.09	W8	1.02	0.51
S1	0	0	S1	2064	1923
S2	0.221	0.061			

Fecal coliform values in the two aquifers were lower than the maximum permissible limit indicated in the Mexican Ecological Criteria of Water Quality (1000 colony forming units (CFU)/100 ml of fecal coliforms) for public supply sources (SEDUE, 1989), with the exception of one well and the spring of the TA aquifer. If we consider that the well water must be chlorinated after extraction, it would meet the Mexican regulations for drinking water (total and fecal coliforms must be absent) (SSA, 1999); however, the water from some wells of the TA aquifer is not chlorinated.

Table 2: Sample Number with Total and Fecal Coliforms from Mexico City aquifer

A) Total Coliforms

CFU/100 ml	W1	W2	W3	W4	W5	W6	W7	W8	S1	S2
0	6	4	5	4	5	3	6	4		
1 -10		2		2	1	2		2	2	3
11 -100			1			1			1	3
> 100									3	

B) Fecal Coliforms

CFU/100 ml	W1	W2	W3	W4	W5	W6	W7	W8	S1	S2
0	6	4	5	5	5	4	6	4	2	2
1 -10		2	1	1	1	2		2	2	2
11 -100										2
> 100									2	

Table 3: Sample number with Total and Fecal Coliforms from Tepalcingo-Axochiapan, Morelos aquifer

A) Total Coliforms

CFU/100 ml	W1	W2	W3	W4	W5	W6	W7	W8	S1
0		2/5				2	1	1	
1 -10		2/5				4	5	4	
11 -100		1/5	4					1	
> 100	6		2	6	6				6

B) Fecal Coliforms

CFU/100 ml	W1	W2	W3	W4	W5	W6	W7	W8	S1
0		3/5				4	1	2	
1 -10		1/5	1			2	5	4	
11 -100		1/5	4		2				
> 100	6		1	6	4				6

In the two aquifers BOD_5, COD, ammonia nitrogen and MBAS were below the detection limit of the techniques, suggesting that organic matter is either absent or present in very low amounts (Robles *et al*., 2004; Romero, 1999).

Most of the sampled wells in the Mexico City aquifer are hard water (average = 157 mg/L $CaCO_3$): varying some wells from very hard to soft. The aquifer water has carbonate hardness and only in a few cases, non-carbonate hardness (Table 4). This is in contrast to the Tepalcingo-Axochiapan, aquifer, where all well and spring water can be considered very hard in both carbonate and non-carbonate hardness (Table 4). Carbonate hardness can be precipitated by prolonged boiling but non-carbonate is more difficult to remove; this hardness is usually caused by the presence of calcium and magnesium sulfates, chlorides and/or nitrates in the water (Robles *et al*., 2004; Romero, 1999). The high values of sulfates obtained in the Tepalcingo-Axochiapan aquifer explain the high values of non-carbonate hardness. Alkalinity was also due to bicarbonates.

Table 4: Water Classification According Hardness

Area		Total Alkalinity (mg/L $CaCO_3$)	Total Hardness (mg/L $CaCO_3$)	Carbonated Hardness (mg/L $CaCO_3$)	No Carbonated Hardness (mg/L $CaCO_3$)
Mexico City Aquifer	Average	219	157	157	0
	Maximum value	613	522	522	0
	Minimum value	46	53	43	10
Tepalcingo-Axochiapan, Mor. Aquifer	Average	211	357	211	146
	Maximum value	304	736	304	432
	Minimum value	132	145	132	13

Table 5: ANOVA Test of Physicochemical Parameters

Parameter	F o	Ft	Probability
Dissolved solids	0.732	4.45	0.404
Total Hardness	7.3	4.45	0.015
Total Alkalinity	0.009	4.45	0.924
Chloride	3.34	4.45	0.085
Sulfates	8.67	4.45	0.009
Turbidity	1.01	4.45	0.328
pH	0.70	4.45	0.413
Nitrates	0.039	4.45	0.844

Hardness and sulfates were the physicochemical parameters that showed the most marked difference between the two aquifers, the concentrations of both parameters being higher in the TA aquifer than in the MC aquifer (Table 5 and 6). The difference was confirmed by ANOVA analysis, which showed significant differences ($p< 0.05$) only for these two physicochemical parameters (Table 5). Electrical conductivity values found in the Tepalcingo-Axochiapan aquifer were in a range from 410 to 1642 µs/cm, which were lower than those found in a study done by the National Water Commission (CONAGUA) in 2002 (400 to 2,500 µs/cm); while in the Mexico City aquifer, values ranged from 139 to 2510 µs/cm.

Dissolved solids detected in the Tepalcingo-Axochiapan aquifer were in the range from 297 to 1198 mg/L, with the highest values being found in the southern area of the aquifer, probably due to the water flowing from north to south, and the groundwater dissolving soil salts as it flows downhill (CONAGUA, 2002b). In the Mexico City aquifer, dissolved solids ranged from 129 to 1469 mg/L; in both aquifers some values were above the permissible limit of the Mexican Standard for drinking water (Table 6).

Table 6: Comparison of the Physicochemical Mean Values with the Mexican Standard (SSA, 1999) Values in mg/L except pH and turbidity (NTU)

Parameter	Mexico City Aquifer			Tepalcingo-Axochiapan, Mor. Aquifer			Maximum permissible limits
	Average	Minimum value	Maximum value	Average	Minimum value	Maximum value	
pH	7.2 ± 0.59	6.3	8.3	6.9 ± 0.52	6	7.6	6.5-8.5
Total Hardness	157 ± 134	53	522	357 ± 187	145	736	500
Nitrites	0	0	0	0	0	0	1.0
Nitrates	1.75 ± 1.25	0.023	2.9	1.67 ± 0.55	0.8	2.2	10
Ammonia nitrogen	0	0	0	0	0	0	0.5
Chloride	71.7 ± 91.5	3.4	265	15.3 ± 9	3.8	30.1	250
Sulfates	60.8 ± 73.7	2.8	248	273 ± 214	49.8	740	400
Methylene blue active substances SAAM	0	0	0	0	0	0	0.5
Dissolved solids	499 ±454	129	1469	653 ± 303	297	1198	1000
Turbidity	3.6 ± 9.8	0.16	31.4	0.28 ± 0.19	0.15	0.77	5

Average values of electrical conductivity and dissolved solids in the TA aquifer were higher than average values from the MC aquifer, although two sites in the MC aquifer had the highest values (Figure 2). Electrical conductivity is water's ability to conduct an electric current and is used to estimate the amount of total salts (dissolved ions). A high concentration of dissolved solids greatly affects the taste of the water and thus has a significant negative impact on its use as drinking water (Jameel and Sirajudeen, 2006).
Chloride concentrations were between 3.4 and 71.7 mg/L in the Mexico City aquifer, with the exception of two wells with concentrations of 211 and 265 mg/L, the last value exceeds Mexican regulations for drinking water. Concentrations in the Tepalcingo-Axochiapan aquifer were in a range from 3.8 to 30.1 mg/L (Table 6). Chloride in water results from agricultural activities, industries, the discharge of domestic waste and disposal by human activities. Geological formations in the area may also influence the high chloride values (Jameel and Sirajudeen, 2006).

In general, the average values of the physicochemical parameters were below the maximum permissible limits indicated in the Mexican Official Standard (NOM-127-SSA1-1994) for drinking water, although some individual values were outside the limits, specifically, in the MC aquifer pH (6.3), total hardness (522 mg/L), chloride (265 mg/L), dissolved solids (1469 mg/L) and turbidity (31.4 NTU); and in the TA aquifer pH (6.0), total hardness (736 mg/L), sulfates (740 mg/L) and dissolved solids (1198 mg/L) (Table 6).

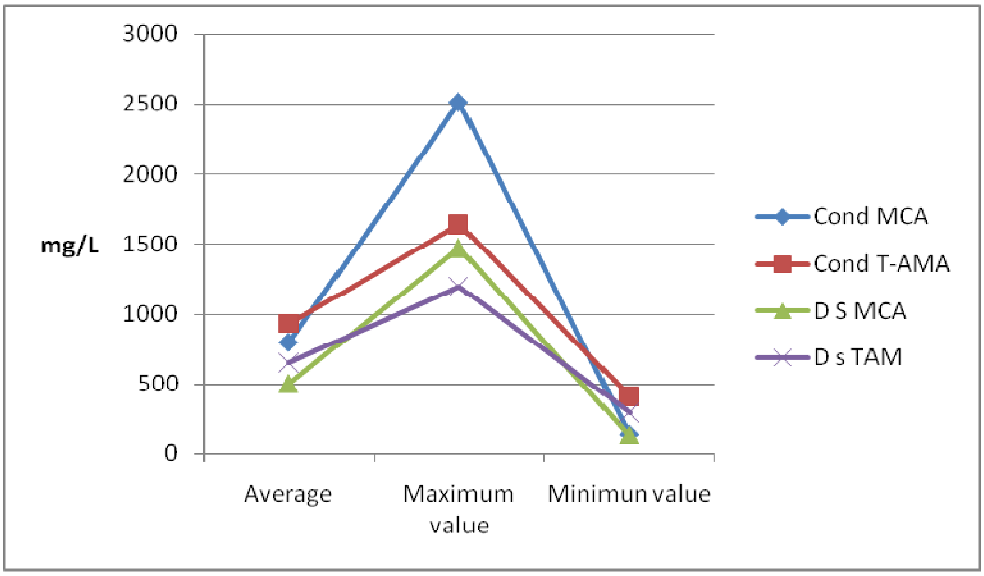

Figure 2: Conductivity and dissolved Solids

4.0 Conclusions:

Sulfates and hardness were the most important physicochemical parameters that differentiated the aquifers and these were determined by permeability degradation, fracturing and the substrate type of the aquifers. Some bacteriological and physicochemical parameters of the aquifers were outside the maximum permissible limit for the water to be used as a public supply source. Sanitary measures are necessary, therefore, to comply with regulations and avoid health risks. There was a significance difference in the bacteriological quality between the Tepalcingo-Axochiapan aquifer and the Mexico City aquifer, due mainly to the TA aquifer being established in an agriculture zone and wastewater going to septic tanks or being discharged into soil; the MC aquifer is established in an urban area with drainage and this avoids the direct discharge of wastewater into soil. The occurrence of total and fecal coliforms in some samples of the Tepalcingo-Axochiapan aquifer is an indication that contamination is beginning to reach the aquifer. For this reason, we recommended avoiding discharges of untreated wastewater, mainly from septic tanks, which are extensively used in the area.

5.0 Acknowledgments

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