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Relationships between urban aquifers and preserved areas south of Mexico City

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ABSTRACT

Mexico City is an example of intense socio-ecosystem interactions, particularly in water management. The groundwater under this city has complex structures and dynamics due to the coexistence of aquifers located at different depths. Through groundwater extraction, the main aquifer supports 71% of the water demand of the city. In this research, we describe the dynamics between aquifers and the surface, particularly in preserved spaces located south of the city. The results indicate the presence of a shallow aquifer that is relatively independent to the main one. The water of both aquifers has the same origin (rainwater) and the same water flow direction, but it has different recharge areas and residence times. Apparently, there is a strong interaction between the shallow aquifer and the surface, in which the small proportion of preserved green spaces (27 km^2), in relation to urbanized ones (53 km^2), may produce negative consequences on the quality and quantity of groundwater. The lack of knowledge about the dynamics of the shallow aquifer leads to its underappreciation for the water management of the city.

1. Introduction

Cities are complex systems with constant interactions between their social and ecological variables, which generate the so-called socio-ecosystems (Fischer et al., 2015). In these interactions, green spaces are relevant because they increase landscape properties (Hough, 2004) that are critical providers of direct and indirect benefits to human well-being and health (Bennett et al., 2015). These areas must be properly managed to stimulate inclusive, sustainable and resilient cities (McPhearson et al., 2014). Thus, there are two approaches used to promote the preservation of these green spaces (Tallis and Lubchenco, 2014). The first is the instrumental approach, which focuses on the benefits, i.e., ecosystem services, that the green spaces provide to the urban population (Reid, 2006), and the second is the intrinsic value approach, which is used to preserve biodiversity (Acosta and Esperanza, 2011).

Mexico City is an example of intense interactions between ecological and social variables, especially regarding water. This city, with 22 million inhabitants, has a water demand of 77 m^3/s (Mazari-Hiriart et al., 2014). Part of this demand (71%) is supplied by groundwater extraction through wells from the main aquifer. The depth of this aquifer ranges from 70 to 500 m, and it is an heterogenous unit with granular materials and fractured volcanic rocks. Previous studies have divided this aquifer into two sub-units due to an increase of clays materials at 150 m of depth: the first sub-unit at 70–180 m and the second at 180–500 m (Morales-Casique et al., 2014). The main aquifer is overexploited to satisfy the water demands of human population. According to the National Commission of Water (CONAGUA in Spanish), this overexploitation is reflected in an annual extraction of 1103.98 Mm^3, which surpasses the amount of water that is infiltrated (CONAGUA, 2015). These numbers do not consider the water required by ecosystems dynamics, and therefore, values must be recalculated to have a more realistic understanding of the watershed hydrodynamics (Rohde et al., 2017). The overexploitation of the main aquifer has different consequences, such as the draining of shallow aquifers to the main one, which can generate land subsidence in different areas of the city— and consequently, more vulnerable citizens to earthquakes—and fissures in superficial water bodies (Kralisch et al., 2012; Legorreta, 2006).

The groundwater system has a complex structure due to the coexistence of aquifers that are located at different depths. These aquifers are nourished with water from diverse ecosystems that have multiple

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types of soil; therefore, numerous groundwater dynamics are generated (Tóth, 2015). This dynamics diversity starts from the regions in which they are recharged, and includes the distance and the speed at which the water travels. Each rocky area, lake, woodland, or urban region has different fluxes dynamics, which generate differences in the quality and quantity of water that is infiltrated into the groundwater system. Shallow aquifers are the most susceptible of being polluted by surface activities because of their proximity, and according to the characteristics of the surface, these aquifers are susceptible to different type pollutants. However, most of these aquifers are interconnected and, in consequence, pollution can spread throughout the water system, and all of them can be affected by the overexploitation of the main aquifer (Lee et al., 2015). The amount of sources of groundwater pollution in Mexico City (Soto et al., 2000) increases the urgency of understanding the water flow dynamics among the overexploited aquifers.

In Mexico City, the main sources of groundwater pollution are industries, solid waste disposal, the sewage system, gas stations, fuel tanks, the urban zone, and the abandoned water extraction wells (Soto et al., 2000). Within Mexico City, three municipalities are located above the shallow aquifer: Alvaro Obregon, Coyoacan, and Tlalpan. According to Soto et al. (2000), these municipalities have several sources of pollution that could affect the groundwater. Alvaro Obregon Municipality is mainly affected by pollution, and fuel tanks represent a major threat. Tlalpan Municipality is the least affected by pollution, and the main risk is generated by solid waste. Coyoacan Municipality has an intermediate level of risk, and urbanization is the major threat (Soto et al., 2000). Therefore, managing the sources of pollution on the surface above the shallow aquifer is crucial due to groundwater susceptibility of pollution.

In Mexico City, green spaces have become a cornerstone to provide water source to feed aquifers. The Pedregal is a good example of a preserved area in Mexico City. This area was formed by basaltic rock from the Xitle volcanic eruption that occurred approximately 1670 years ago, and this rocky formation has low presence of soil, which explains its name: Pedregal (rocky area). The Pedregal has an average annual temperature of 16.1 °C and an annual accumulated precipitation of 870.2 mm (Cano-Santana et al., 2009).

Due to the urban expansion that has occurred over the last century, the Pedregal has suffered a dramatic fragmentation and area reduction from 80 km^2 in 1954 to 40 km^2 in 1984. Currently, there are only two important green spaces within the original extension of the Pedregal: the Reserva Ecológica del Pedregal de San Ángel (REPSA) and the Tlalpan's forest. The Tlalpan's forest does not have the original characteristics of the Pedregal because it suffered human-related transformations in the creation of this urban park. Therefore, the provision of ecosystem services of the Tlalpan's forest has been influenced by humans (Calderón-Contreras and Quiroz-Rosas, 2017). The REPSA is a natural protected area where the pristine characteristics of the Pedregal have been preserved (Calderón-Contreras and Quiroz-Rosas, 2017). Currently, the REPSA is considered the last remaining area of the Pedregal, with only 2.37 km^2 based at the Universidad Nacional Autonoma de México (UNAM) (Alvarez Sanchez et al., 1994; Rojo Curiel, 1994) (Fig. 1). The fragmentation and reduced area of the Pedregal has a negative impact on the biodiversity and the ecosystem dynamics. However, the Pedregal still provides ecosystem services to the population of Mexico City (Nava-López et al., 2009).

The lack of green spaces can generate a reduction in the amount water infiltration because the soil in urbanized areas is practically impermeable, and the rainwater in this area is diverted to sewage systems. This often results in floods in the lowlands of the city (Zambrano et al., 2017). Despite having a large sewage system, the rainwater diversion process in Mexico City is inefficient (Candiani, 2014), particularly under extreme storms, which will be commoner with climate change (Zambrano et al., 2017). Because of the low presence of soil and the characteristics of the subsoil, the zone of the Pedregal has high hydraulic conductivity. Since this area promotes a fast water infiltration, the REPSA provides ecosystem services related to the regulation of water quality and quantity of the aquifer (Nava-López et al., 2009).

The human population living in the Pedregal ecosystem has always used water from the shallow aquifer, using the scattered springs that occur in the area. However, this water is underappreciated by managers, possibly because of the lack of knowledge on the dynamics of the aquifer. For example, throughout the entire city, it is common to redirect the water from springs to the sewage system once it appears while an infrastructure project is being built. The lack of knowledge about the characteristics of the aquifer may result in the detrimental use of water and the pollution of this scarce and valuable resource in the city.

Therefore, the objective of this research is to understand the relationship between the aquifers and to evaluate the influence of the surface area of the preserved Pedregal in the southern part of Mexico City.

2. Methods

Geological sections provide stratigraphy information, which helps to understand how groundwater moves between aquifers. To obtain information from the geological sections, the lithological columns from the water extraction wells that surround the REPSA were analyzed (data from SACMEX, which stands for Water System of Mexico City in Spanish). The lithologies were clustered according to the geological local map of Carrillo Trueba (1995). Twelve lithological columns from wells were used in Section I (direction: northeast to southwest), and eleven lithological columns from wells were used in Section II (direction: west to east) (Fig. 1).

Water sampling was made in June 24, 2016, at seven sites within the Pedregal (Fig. 1). Four of these sites were natural springs in private spaces (i.e., D, E, F and G), and three (i.e., A, B and C) were water extraction wells that were property of SACMEX. The water field parameters [electrical conductivity (EC), total dissolved solids (TDS), pH, temperature (T), redox potential (Eh)] were measured at all sites using multi-parameter equipment (Hanna Instruments 9812).

Water samples were collected to determine the main anions (HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-, PO_4^{3-}), the main cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and the trace elements (Al, As, Ba, Cd, Cr, Cu, Fe, Mn, Na, Pb and Zn). At the collection site, samples were filtered through 0.45-μm Millipore cellulose nitrate filters. The samples collected for cation and trace element analyses were also acidified with HNO_3 to pH ~ 2 (Appelo and Postma, 2005). All samples were stored in a cooler at approximately 4 °C and transported to the Institute of Geology at UNAM. Anions and cations were analyzed by liquid chromatography in the Chromatography Laboratory, and trace elements were analyzed by inductive coupling plasma (ICP) with an optical emission spectrophotometer (OES) (ICP-OES) in the Atomic Spectroscopy Laboratory (Institute of Geology, UNAM). Cations and anions had a charge-balance error (CBE) from 0.7 to 5.3. Acceptable water analyses have CBE values less than ± 5% (U.S.G.S, 2007). Samples for stable isotopes (d18O and d2H (Wassenaar et al., 2009)) were collected and analyzed by laser spectroscopy in the Isotopic Laboratory of Davis University, California, United States of America. The results were expressed as the relative abundance with respect to the Vienna standard mean ocean water (VSMOW) and were compared to the local meteorological line. This line was determined based on rain water samples that were obtained from the *Sierra del Ajusco* at the top of the basin and complied with the equation: d2H = 7.95 d18O + 11.77 (r = 0.989) (Cortés and Farvolden, 1989). Additionally, the altitude above medium sea level where the recharge of the groundwater system occurred was calculated and complied with the equation d18O = (-2.13z – 3.2)*1000, which was based on isotopic data from Cortés and Durazo (2001).

The topographic elevation of the land was used to establish the altitude of the water table, because groundwater moves from high pressure to low pressure areas (Darcy, 1856; Domenico and Schwartz, 1990;

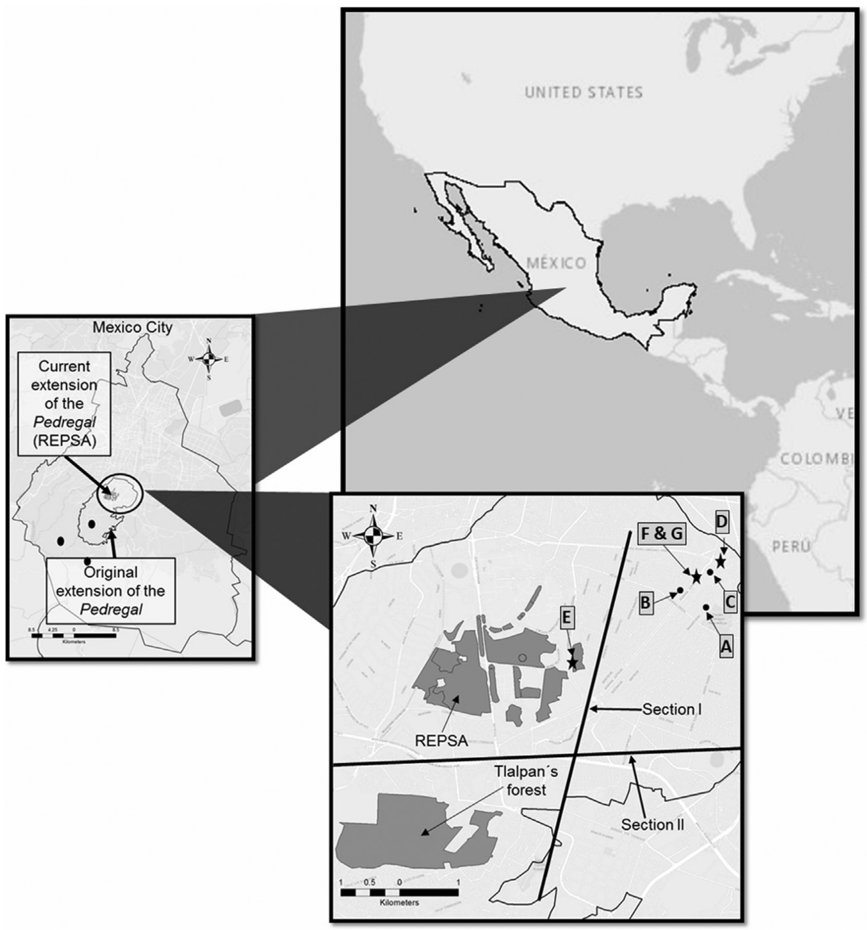

Fig. 1. The Pedregal location in Mexico City, including original and current extension. The zoom image shows the sampled sites. Water wells with dots and springs with stars. Lines are geological sections.

Tóth, 1963). The altitude of the water table was calculated with the equation: topography elevation (m.a.s.l.) – water table depth (m). The water table is where the surface water head is equal to the atmospheric pressure (Freeze and Cherry, 1979). The altitude of the water table in each well and the topographic elevation in springs were used separately to create isolines. The groundwater movement is perpendicular to these isolines. Therefore, flow network was created based on the direction of the groundwater movement and the isolines obtained from wells and springs (Domenico and Schwartz, 1990). In addition, the value of the flow was determined using the technique of Section Area and Speed at one of the sites (site E).

3. Results

Geological sections in the study area had three main layers. The first was composed of recent basalts, where the shallow aquifer was located; the second contained fluvio-lacustrine sediments and tuffs; and the third was based on andesites, where the main aquifer is located (Fig. 2). Based on these results it is possible to consider two aquifers: the shallow and the main one.

Not all the sampled springs have natural origin, springs E, F and G are outcrops of groundwater as a result of deep excavations. Spring E outcrops at 40 m depth, and springs F and G emerge at 8 m depth with respect to the original natural terrain. The average temperature of water in sampled springs was 19.4 °C, while the temperature of water from wells was 17.0 °C. pH values of the water samples fluctuated between 6.41 and 8.64 and the highest values were obtained at site D. The TDS values ranged from 154 mg/l to 347 mg/l; however, springs F and G were more similar to the water extraction wells than to the other springs, where the values were considerably lower (Table 1). Water from springs and wells has a similar chemical composition based on the concentration of major ions (Table 2). As can be seen in the Piper Diagram (Fig. 3) the samples are grouped in the central part due to this chemical similarity.

Stiff diagram (Fig. 4) shows that the water from wells A, B, C had the same behavior in the preferential cations: Na + K and Mg. Water from springs D, E, F and G was more enriched in Ca than water from wells. Anion values had a similar behavior: while springs had depleted values of Cl, wells were enriched. In addition, springs F and G, located in the excavated area site, have higher concentrations of Cl than other springs of the study area.

Isotopic results from water samples are distributed along a trend line, corresponding to the evaporation process (Fig. 5). Wells A, B and C are the closest to the local meteorological line, while springs D and E are located furthest away, suggesting that the latter two are more influenced by the evaporation process than springs A, B and C.

The direction of water flow was from southwest to northeast in both aquifers (shallow and main). The flow value (obtained only from site E) was 77.78 m^3/d in dry season and 10,160.64 m^3/d in rainy season. The results locate the REPSA and Tlalpan forest in the middle of the shallow aquifer. Therefore, their influence of these green spaces is towards the northeast region (Fig. 6a and b). Based on these results, a synthesis figure was generated to illustrate the position, the depth and the distance of both, shallow and main, aquifers (Fig. 4).

The water isotopic values of d2H ranged from −50.4‰ to −72.9‰, while the values of d18O ranged from −6.71‰ to −10.20‰. Fig. 4 shows the local meteoric line (LML - continuous line) determined by Cortés and Farvolden (1989). Here, isotopic data are

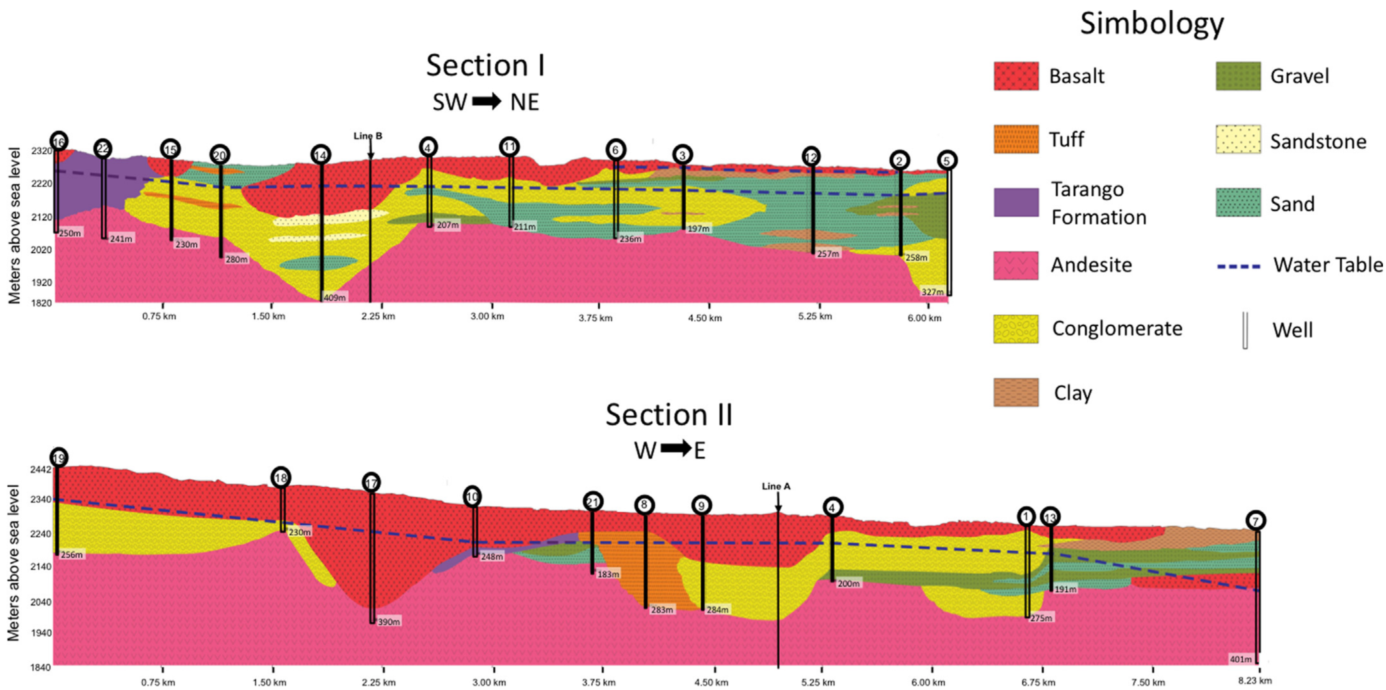

Fig. 2. Geologic sections. Section I goes from southwest to northeast and Section II goes from west to east. Circles shows the water extraction wells (Appendix 1). Intersection line shows the point in which both geologic sections cross.

Table 1
Physico-chemical parameters in study sites.

Site	Type of site	Coordinates			Temp. (°C)	pH	Eh (mV)	EC (µS/cm)	TDS (mg/l)
		x	y	z					
A	Well	484025.41	2136952.19	2260	17.03	7.16	− 12.5	684	342
B	Well	483570.14	2137232.65	2267	17.83	6.64	− 9.6	594	297
C	Well	484079.36	2137538.63	2253	16.16	6.41	− 9.5	654	327
D	Spring	484253.67	2137713.53	2244	20.32	8.64	− 13.5	308	154
E	Spring	481783.89	2135938.80	2274	17.96	7.66	− 12.4	365	183
F	Spring	483865.91	2137455.71	2251	18.7	6.72	− 3.6	660	330
G	Spring	483865.91	2137455.71	2251	20.53	6.68	− 3.9	693	347

Table 2
Major ions data of wells and springs. LOD: Limit of detection.

Site	Type of site	HCO_3^- (mg/l)	Cl^- (mg/l)	NO_3^- (mg/l)	PO_4^{2-} (mg/l)	SO_4^{2-} (mg/l)	K^+ (mg/l)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Na^+ (mg/l)
A	Well	190.1	101.6	12	< LOD	25.7	7.53	12.37	25.29	77.17
B	Well	141.9	62.4	30	< LOD	40	6.63	10.13	19.48	60.32
C	Well	151.6	59.5	28.2	< LOD	46.7	7.4	11.81	21.32	58.61
D	Spring	99.4	20.5	7.9	< LOD	34.8	10.44	20.19	8.05	24.67
E	Spring	78.3	33.6	52	< LOD	47.9	6.54	22.08	12.86	33.37
F	Spring	126.5	72.8	82.8	9.2	81	12.46	27.87	19.1	73.61
G	Spring	154.4	78.7	81.2	10.3	98.5	14.41	33.74	20.26	81.83

aligned following the trend of an evaporation line (EL - dotted line). Springs D and E showed greater evaporation, while the other sampled sites remained close to the LML, which suggests that all sites have a common water source.

Water analyzed from wells A, B and C was infiltrated at an elevation of 3200 m above sea level (Fig. 7). Water from the springs F and G was infiltrated at an elevation of 2800 m above sea level (Fig. 7). The results for springs D and E were not considered due to the apparent high influence of evaporation.

There were low concentrations of most of the trace elements (Table 3), and some elements had concentrations lower than the level of determination (LOD). A possible exception is the concentration of Fe found in water of the well A, which can be interpreted as a consequence of basalt weathering at the site that resulted in clays that are rich in this element (Hem, 1992). With the exception of the mentioned variables, there were no other chemical differences between the samples, which suggested that all the groundwater was from the same water source.

4. Discussion

After analyzing the isotopic results from springs and wells (Appendix 2), two different components of the groundwater systems were identified: the shallow component and the main one. The main groundwater component was reported by Morales-Casique et al. (2015). However, the shallow component has never been reported before. Contrary to the main aquifer, this shallow component is unconfined.

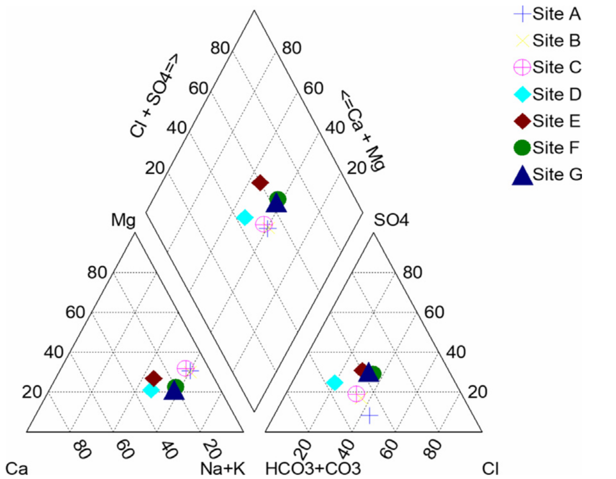

Fig. 3. Water classification diagram (Piper, 1944).

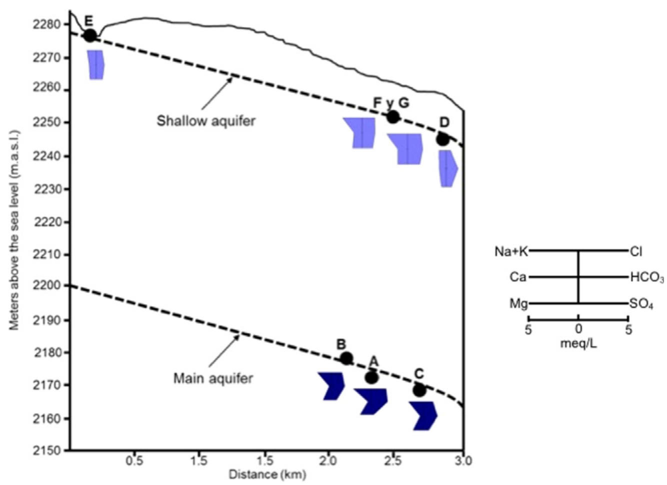

Fig. 4. On the left side the topographic profile and Stiff diagrams of each sampled and on the right side the general Stiff diagram (Stiff, 1951).

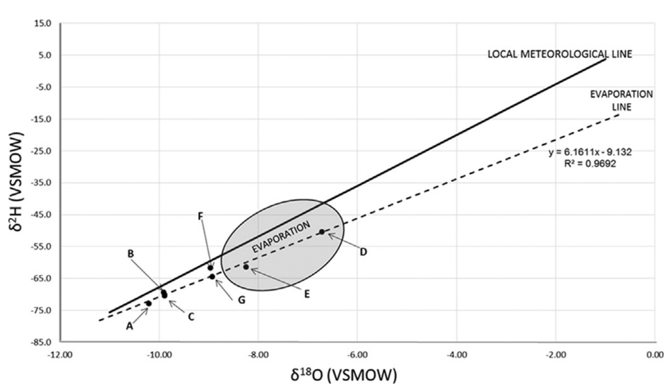

Fig. 5. Correlation between d2H and d18O and its relationship with the local meteorological line. The sample sites with dots.

A combination of conglomerate, tuff and clay layers separate these two components (geological sections, Fig. 2). This separation is due to the low hydraulic conductivity in these materials. The hydraulic conductivity assigned to clay is 0.000006 m/d (Based on data from Fetter, 2001), However, the aquifers can be hydraulically connected in zones where there is no presence of the layer with low conductivity or its thickness is small.

In addition, results suggest that the main aquifer is recharged at an altitude of 3200 m.a.s.l., which corresponds to the foothills of the *Sierra del Ajusco*, while the shallow aquifer is recharged at the elevation of 2800 m.a.s.l, which is in the high areas of the Xitle volcano. Although the soil and subsoil of the original extension of Pedregal provide a high infiltration zone, the majority of this region is occupied by urban area (63%). Therefore, the main recharge of the shallow aquifer occurs in the area close to Xitle volcanic cone. However, an important part of this infiltration may come also from the preserved green spaces.

The water tables of both aquifers in the geological sections provide an important tool for understanding aquifer dynamics and interactions. Through the geological section analysis, some characteristics of the shallow aquifer were identified, like the shallow aquifer thickness that has an average of approximately 10 m.

The isotopic and hydrochemical results suggest that both aquifers have the same origin, possibly from rainwater infiltration in the southern part of the valley, and that both receive the same mineral inputs. Additionally, places of the wells for water extraction (i.e., A, B and C) are close to the local meteorological line, suggesting they are principally originated from rainwater and they are not heavily affected by the evaporation process. Those places were springs are located are more distant from the local meteorological line, suggesting they may be more affected by the evaporation process (Craig, 1961). This high evaporation can explain the results from D and E, which are farther than the rest of the sampled springs. The level of evaporation suggests that the water from the extraction wells circulates in a deeper component than the water in springs that circulates near the surface. This is consistent with spring evaporation (E, F and G) that is shown in the Piper diagram.

The water chemical composition of both aquifers is similar, since water interacts with rocks from volcanic origin. Processes such as water-rock interaction could dominate behavior in wells and springs. Therefore, results suggest that wells are more influenced than springs by the water-rock interaction process. The ionic content is relatively low and similar in both aquifers. Because springs D and E (in the northeastern and southwestern regions respectively) have the lowest hydrochemical value, it is likely that water was recently infiltrated and had a short course through the subsoil (Chebotarev, 1955; Domenico, 1972; Freeze and Cherry, 1979).

The water flow of the shallow aquifer is contained in the basalt associated with the Xitle lava spills (Delgado et al., 1998; Siebe, 2000). The circulation of groundwater occurs through interconnected fractures, vacuoles and lava-flow tunnels. This generates highly variable groundwater flows most of them at high speeds compared to other groundwater dynamics. In the main aquifer the water circulation occurs in two types of rock with high hydraulic conductivity from the Quaternary age: dacite and andesite (Arce et al., 2015; Morales-Casique et al., 2015).

The same direction of groundwater flow (from southwest to northeast) indicates that the water in the strata of both aquifers moves gravitationally from the recharge zones in high topographic areas to the lower areas of the valley. These lower regions are located outside of the limit of the shallow aquifer, but it is probable that the isolating conglomerate and clay layers are highly reduced here, and both aquifers may be hydraulically connected. This assumption appears to be confirmed because the basalt strata from the Xitle ends in this region leaving only the basalt strata from the Ajusco, which was under the Xitle strata in higher areas. To support this, there is no record of springs or other type of water discharges from the shallow aquifer to the surface in the border area were Xitle strata ends. However, this potential hydraulic connection should be evaluated in future studies.

The extension of the shallow aquifer seems to correspond to the original extension of the Pedregal (80 km^2), and therefore enhances the potential influence of surface activates on the shallow aquifer. The land use in this area is divided into two categories, urban and green spaces, which respectively represent 73% and 27% of the original extension of the Pedregal (Lot and Cano-Santana, 2009). Additionally, green spaces

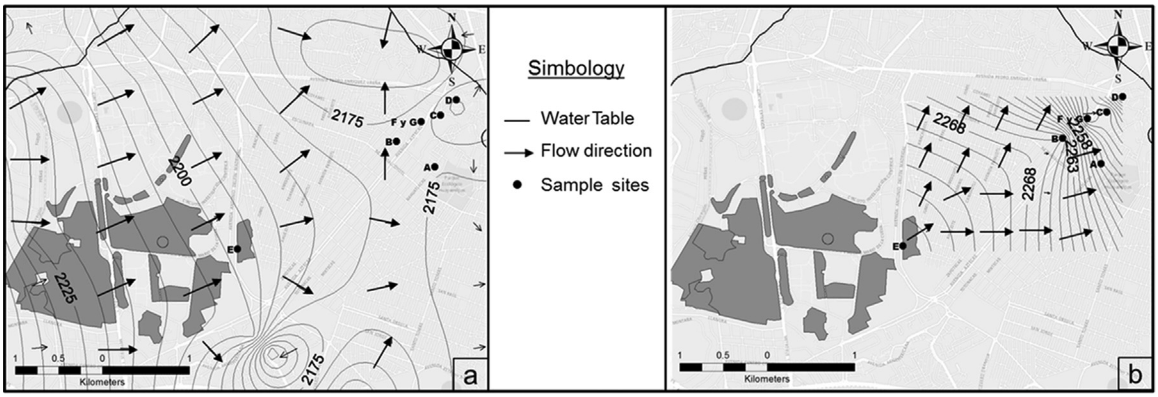

Fig. 6. Flow direction of both aquifers. “a” main aquifer, “b” shallow aquifer. The sample sites with dots.

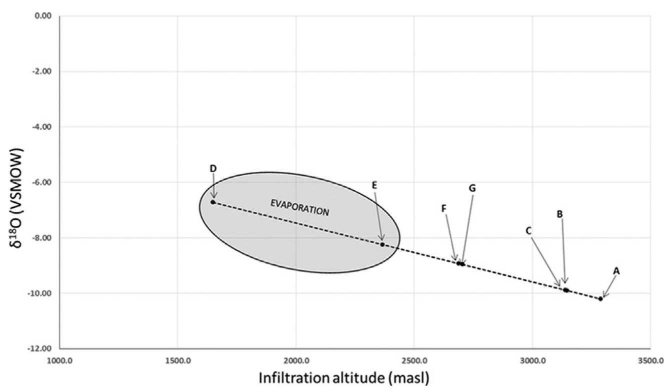

Fig. 7. Altitude above medium sea level of the estimated height of recharge of groundwater systems based in Cortés and Durazo (2001). The sample sites with dots.

above the shallow aquifer can be divided into two categories: green spaces that have suffered human modifications (e.g., parks), and green spaces with original characteristics (e.g., urban forests) (Calderón-Contreras and Quiroz-Rosas, 2017). The first type of green spaces, built with artificial materials and including exotic vegetation, represent 7% of the volcanic influence region and 47% of the green spaces. The second type of green spaces represent 8% of the volcanic influence region and 53% of the green spaces (based on Lot and Cano-Santana, 2009). There are also private gardens that have the same characteristics as the urban parks, but their size and distribution are unknown and thus they were excluded from the analysis.

Nevertheless, because decision makers do not recognize the shallow aquifer, there has not been any planning or management strategy related to it (Kralisch et al., 2012). All the management strategies are focused on the main aquifer that it is overexploited and influenced by processes that occurred thousands of years ago, while the shallow aquifer is affected by recent events, such as urbanization south of the city. The absence of management implies short-term consequences for the city. These consequences are even more relevant since the shallow aquifer could be a complementary source of water supply if it is properly managed. In addition, due to the depth of the urban shallow aquifers and the types of rock and soil that are above them, these aquifers are highly sensitive to pollution from different kinds of sources on the surface, like industries, disposal of solid waste, sewage system, gas stations, fuel tanks, urban zone and abandoned water extraction wells (Soto et al., 2000). Therefore, the need of a proper planning and management strategy that includes land use, green spaces perseveration, is needed to prevent and reduce the pollution of both aquifers.

5. Conclusion

The results confirm the presence of a shallow component of the groundwater system in the south of Mexico City. The shallow aquifer is unconfined and hydraulically independent from the main aquifer, but it is possible they have a connection close to the border of the shallow aquifer. This aquifer could be considered as a complementary source of the water supply for the city. However, a deeper analyses of water quality and its relationship with the main aquifer is needed to understand its impact on water supply for the city. Green spaces located in zones above the shallow aquifer seem to be important for the recharge of the aquifer in urban zones, and land use management must consider this interaction.

Around the world, the importance of shallow aquifers are increasing for a sustainable hydric management. The time scale of their fluxes is short enough to react to human activities, and therefore, this allows to evaluate the effect of human actions on the water supply. On the contrary, deeper aquifers have large time scale geological processes, implying that the present activities would modify water management thousands of years in the future.

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Table 3
Trace elements of wells and springs. LOD: Limit of detection.

Site	Type of site	Al (mg/l)	As (mg/l)	Ba (mg/l)	Cd (mg/l)	Cr (mg/l)	Cu (mg/l)	Fe (mg/l)	Mn (mg/l)	Pb (mg/l)	Zn (mg/l)
A	Well	< LOD	< LOD	0.032	< LOD	< LOD	< LOD	10.060	0.002	< LOD	< LOD
B	Well	< LOD	< LOD	0.037	< LOD	< LOD	< LOD	NA	< LOD	< LOD	< LOD
C	Well	0.020	< LOD	0.045	< LOD	< LOD	0.009	2.120	0.003	< LOD	0.024
D	Spring	< LOD	< LOD	0.014	< LOD	< LOD	0.016	NA	< LOD	< LOD	0.012
E	Spring	< LOD	< LOD	0.024	< LOD	< LOD	0.010	NA	< LOD	< LOD	< LOD
F	Spring	0.032	< LOD	0.022	< LOD	< LOD	0.023	0.087	0.004	< LOD	0.030
G	Spring	0.026	< LOD	0.027	< LOD	< LOD	0.022	0.068	0.007	< LOD	0.008

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Appendix 1. List of the water extraction wells used to do the geological sections

Coyoacan Municipality				
ID	Well name	Coordinates		
		x	y	z
1	AUXILIAR XOTEPINGO 3 - A	483462.90	2134632.80	2258.20
2	LA CIENEGA	482675.41	2137817.85	2252.59
3	METRO C.U.	481711.74	2136494.21	2271.56
4	PEDREGAL DE CARRASCO	482103.09	2134828.63	2284.41
5	PEDREGAL DE SAN FRANCISCO	482721.19	2138261.74	2253.41
6	PEDREGAL DE SANTO DOMINGO	482113.00	2136070.00	2287.00
7	PERIFERICO 3	485033.09	2134582.44	2241.10
8	PERIFERICO DIRECTO # 18	489229.00	2136506.00	2254.00
9	PERIFERICO DIRECTO # 19	488842.00	2136963.00	2238.00
10	PERIFERICO DIRECTO # 21	479702.91	2134315.98	2326.00
11	PERIFERICO DIRECTO # 24	482104.73	2135355.80	2302.00
12	PERIFERICO DIRECTO # 25	482888.62	2137328.47	2264.00
13	SANTA URSULA COAPA	483913.91	2134494.33	2252.22
14	PERIFERICO DIRECTO N° 17	482120.00	2134094.31	2260.47
Tlalpan Municipality				
ID	Well name	Coordinates		
		x	y	z
15	BELIZARIO DOMINGUEZ	481310.51	2133122.66	2287.99
16	FUENTES BROTANTES No. 1	481285.01	2132363.97	2316.55
17	JARDINES DE LA MONTAÑA 1	479035.24	2133959.74	2376.00
18	JARDINES DE LA MONTAÑA 2	478453.00	2133987.00	2264.00
19	PADIERNA PICACHO	476859.00	2134206.00	2439.00
20	SAN FERNANDO TLALPAN	481499.32	2133539.36	2282.00
21	VILLA OLIMPICA No. 2	480485.47	2134005.18	2292.24
22	XOCHITL	480772.03	2132665.91	2320.03

Appendix 2. Isotopic results from springs and wells

Site	Type of site	d18O	d2H
A	Well	− 10.20	− 72.9
B	Well	− 9.90	− 69.5
C	Well	− 9.88	− 70.5
D	Spring	− 6.71	− 50.4
E	Spring	− 8.24	− 61.4
F	Spring	− 8.96	− 61.7
G	Spring	− 8.92	− 64.5

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