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ORIGINAL ARTICLE

Urban green spaces and their relationship with groundwater quality: the case of a shallow aquifer in the south of Mexico City

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Abstract

Water supply security is a top priority for decision-makers in cities. Urban population growth increases water demand from aquifers, while urban expansion reduces water infiltration and boosts water pollution sources. Urban green spaces are a few of the remaining infiltration areas. Therefore, they are essential for water supply and urban hydric resilience. The urban dynamic directly influences shallow aquifers, but they usually are unappreciated. This work illustrates the relationship between urban green spaces and city water quality by evaluating the influence of urban green space, *Reserva Ecológica del Pedregal de San Angel* (REPSA), on a shallow aquifer in Mexico City. Five springs were sampled: two upstream of REPSA, a spring within REPSA, and two downstream. Because the study area is mainly residential but with an industrial history, water quality was tested based on microbiological pathogens, nutrients, pharmaceutical drugs, and heavy metals. Results showed an enhancement of water quality of the shallow aquifer in the sampling points downstream of REPSA for some of the pollutants. These results illustrate how urban green spaces can help to dilute pollutants present in the water of shallow aquifers, increasing water quality in cities.

Keywords Cities · Aquifers · Infiltration · Natural spaces · Ecosystem services · Groundwater

Introduction

Cities around the world are increasingly large and dense, causing land use modifications disturbing the quality and quantity of urban green spaces (UGS) (Elmqvist et al. 2013). Those modifications affect the provision of benefits that UGS spaces provide to society (Ecosystem Services—ES) such as climate regulation, reduction of air pollution, carbon capture, and biodiversity maintenance (Ayala-Azcárraga et al. 2019). Particularly, UGS deterioration also decreases ES related to water such as flood control, aquifer recharging, water supply and water quality regulation (McPhearson et al. 2014; Zhang et al. 2012).

Since must of the cities must solve water-related problems, the relevance of UGS as ES providers for urban hydrologic issues is enhanced (Nasrabadi and Abbasi Maedeh 2014; Palmer and Lewis 1998; Singh and Singh 2002; Zambrano et al. 2017). In many cities, aquifers are the primary source of water for human consumption. Therefore, population growth increases urban water demand and generates a potential overexploitation of those aquifers (Soto and Herera 2009). The change in land use promoted by urbanization processes is one of the variables that drastically affect the amount of water entering the soil (infiltration). The replacement of natural areas (green areas) with urban areas (grey areas) impacts water dynamics and promotes the presence of impervious areas, limiting water infiltration and aquifer recharge. Additionally, the reduction and fragmentation of green areas, and the expansion of grey areas, favor the runoff of water into the sewage system and promote the presence of floods (Dimitriou and Moussoulis 2011; Gregory et al. 2006; Kollet and Maxwell 2008; Zambrano et al. 2017). Lastly,

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urban expansion increases the presence of potential groundwater pollution sources (Carmon et al. 1997).

Therefore, as UGS are crucial areas for water infiltration, their protection means the safeguard of water sources necessary for sustainable urban development (Carmon et al. 1997; Mazari-Hiriart et al. 2006). Water infiltrated into UGS could act as a contaminant diluent for groundwater, particularly for shallow aquifers. These aquifers provide lower water quantities and are more vulnerable than deeper aquifers (Morris et al. 2003). There is limited knowledge about the relation of this type of aquifers with the surface. Therefore, having deeper information about the relation between shallow aquifers and UGS could contribute to facing some water supply challenges in cities. However, it is necessary to understand the relationship between urbanization, UGS, and water quality in shallow aquifers to understand if shallow aquifers could be used as alternative water sources to address water availability issues in cities.

Mexico City is an example for the understanding of UGS as ecosystem services providers related to water. In this city, around of 70% of freshwater comes from aquifers (CONAGUA 2020) and land use change due to urbanization has induced the reduction of water infiltration and the increase of pollution sources (Mazari-Hiriart et al. 2006; Zambrano et al. 2017). In the south of Mexico City, there is a relation between an urban green space, the *Reserva Ecológica del Pedregal de San Angel* (REPSA in Spanish), and a shallow aquifer located beneath this UGS. REPSA retains its original characteristics regarding its biodiversity and its soil and subsoil (Canteiro et al. 2019; Lot and Cano-Santana 2009). These characteristics favor the infiltration and percolation of rainwater towards the aquifers. This condition is because of the hydraulic conductivity in this type of system is 9×10^{-3} at 864 md^{-1} (Freeze and Cherry 1979). Therefore, all the rain in this region could infiltrate the aquifer because its capacities are greater than the amount of water that falls in the region (the average rainfall in REPSA is $2.54 \times 10–5$ m s^{-1}). Even considering the rainiest month of the year ($8.3 \times 10–5$ m s^{-1}), the rainwater is far from saturating the soil (CONAGUA 2017; Freeze and Cherry 1979; Lot et al. 2012). However, these characteristics make the shallow aquifer susceptible to contamination from the surface along its entire length. This unconfined aquifer has rapid dynamics due to its short path and recent water infiltration (Canteiro et al. 2019). Therefore, the relation between said aquifer and the surface is decisive in the water quality in the aquifer. In this sense, due to the possibilities of water infiltration that REPSA presents, without altering its quality, the water infiltrated there could contribute to improving the aquifer water quality through the effect of dilution of the contaminants. The previous considering that the shallow aquifer receives water from infiltration in the REPSA and infiltrated water throughout its extension, and a large part of that area is entirely urban, so the quality of infiltrated water could be altered.

The threat that urban development represents for groundwater quality has been extensively demonstrated (Carmon et al. 1997; Mazari and Mackay 1993; E. Soto et al. 2000). Some studies show the role of the UGS in regulating the amount of water in the city (floods and recharge of aquifers) (Calderón-Contreras and Quiroz-Rosas 2017; Gregory et al. 2006; Zambrano et al. 2017, 2019). However, the direct relation of a UGS with the improvement of groundwater quality is unknown, and this information is relevant for the planning and management of water in cities such as Mexico City. Therefore, the objective of this investigation is to evaluate the benefits of the UGS in the infiltration process to shallow aquifers based on a potential dilution effect of water infiltrated in REPSA in the groundwater quality.

Methodology

Study area

Mexico City, as several cities worldwide (Nasrabadi and Abbasi Maedeh 2014; Singh and Singh 2002), is categorized as a city with high vulnerability associated with low water availability due to an overexploitation of the aquifer and an improper management of water supply (Ávila García 2008). For example, in Mexico City and its metropolitan area, nearly 20 million people live daily, with a total water demand of 77 m^3/s (Mazari-Hiriart et al. 2014). This demand is mainly supplied (70%) by extracting water from the aquifer called the *Zona Metropolitana de la Ciudad de México* (the primary aquifer in this investigation) (CONAGUA 2020), which is located at a depth of between 70 and 500 m (Morales-Casique et al. 2014). Moreover, according to *Comisión Nacional del Agua* (CONAGUA), this aquifer is under intensive exploitation since there is a deficit of 507,230,340 m^3 per year of water extracted at the expense of non-renewable storage of the aquifer (CONAGUA 2020).

The south of Mexico City is an important area related to water dynamics in the city due to its geologic characteristics. The subsoil of this area is the result of the lava spill due to the eruption of the Xitle volcano 1670 years ago (Lot et al. 2012), and it was originally known as the Pedregal of San Angel (The Pedregal). The Pedregal had an original extension of 80 km^2, but due to urban expansion, the Pedregal was reduced and fragmented, and currently covers an area of 2.37 km^2 that corresponds with REPSA (Zambrano et al. 2016a, b).

In addition, in a previous study based on the analysis of geological sections, it is estimated that the extension of the shallow aquifer would represent the dimensions of El Pedregal (80 km^2) and that this aquifer is hydraulically separated from the primary aquifer throughout its entire extension (Canteiro et al. 2019). The main recharge of the shallow aquifer occurs mostly outside of the urban land, in the Xitle volcano area at an elevation of 2800 m.a.s.l., and the flow direction of the aquifer is from southwest to northeast, following the general topographic behavior of the valley and sharing the same direction with the primary aquifer (Canteiro et al. 2019).

The influence of a UGS on water dynamics encompasses its territory and the environment. Therefore, the study area includes REPSA and the 5 km around it. In this area, five springs were identified and selected within the basalt limit generated by the spill of the Xitle volcano (Fig. 1), and therefore it is assumed that their water belongs to the shallow aquifer (Table 1). Their selection was based on their location, the topographic characteristics of the city and considering the direction of water flow in the shallow aquifer estimated in a previous investigation (Canteiro et al. 2019).

Table 1 Location of the five springs sampled

Site	Coordinates		
	x	*y*	*z*
S1	481,003.365857	2,132,374.235820	231
S2	480,847.809306	2,133,771.367710	228
S3	481,782.999964	2,135,937.999890	207*
S4	483,932.999979	2,137,664.999920	225
S5	482,629.999973	2,138,359.999890	225

*the value of the "*z*" coordinate of the S3 spring was estimated from the value of the surface in that area, subtracting 20 m because it is a spring resulting from an excavation of an old stone quarry (Lot 2007)

Two springs (S1 and S2) were selected upstream of REPSA (southwest respect REPSA), two springs (S4 and S5) downstream of REPSA (northeast respect REPSA) and a spring within REPSA (S3) (Fig. 1).

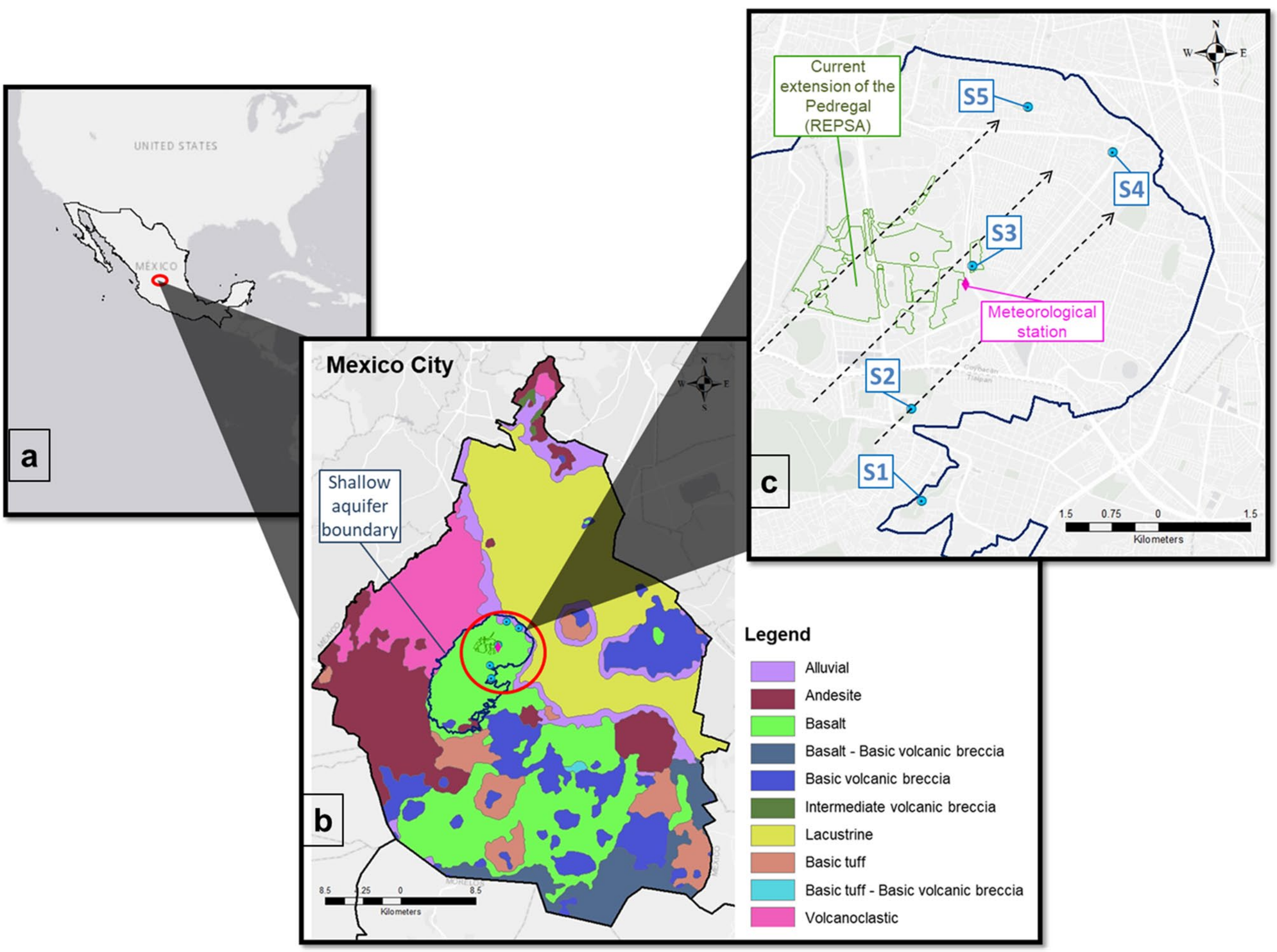

Fig. 1 "**a**" shows the Mexico City location in the country. "**b**" shows the geological characteristics of the city and the shallow aquifer extension. "**c**" shows the sampled points with blue dots and the Pedregal current extension (REPSA) in green. Also, the image "**c**" shows the location of the meteorological station in pink and the water flow direction is illustrated with black arrows

Method

The five selected springs were sampled twice a year, based on the seasonality of Mexico City. This city is located in a mountainous basin of 2240 m above sea level, named the Valley of Mexico. Its climate is tropical mountain with slight annual temperature variation and with seasonality divided into dry season (November–April) and rainy season (May–October) (Cui and De Foy 2012). The first sampling was carried out at the beginning of May 2017 to obtain water samples after the entire dry season. Complementary, to obtain water samples after the entire rainy season, sampling was carried out at the beginning of November 2017 (CONAGUA 2017). The comparison of the results allowed the analysis of seasonality differences in water quality of the shallow aquifer. Moreover, the sampling allowed a comparison between the water quality upstream and downstream of REPSA (Fig. 1). A table illustrating the level of precipitation in Mexico City in 2017, when the samplings were carried out, is presented in Table 2.

Water quality was measured through the following parameters: Temperature, pH, Eh, DO, CE, STD, sulfates (US-EPA 1986), total Aluminum (US-EPA 2000), total Mercury (US-EPA 1998), Lead (US-EPA 2000), Arsenic (US-EPA 2000), BTEX (Benzene, Ethylbenzene, Xylene and Toluene) (US-EPA 2006), total and fecal coliforms (Secretaría de Economía, 2015), Salmonella, total Nitrogen, nitrates and nitrites (O'Dell 1996a), orthophosphates (O'Dell 1996b) and pharmaceutical drugs (Mazari-Kriart et al. 1999; Sorensen et al. 2015). These parameters were selected based on available literature on urban groundwater pollution and considering the possible sources of groundwater pollution in the area (Lee et al. 2015; Nasrabadi and Abbasi Maedeh 2014; Soto et al. 2000).

Subsequently, the samples were sent to the Interteck + ABC Analytic Laboratory to perform analyzes of sulfates, total Aluminum, total Mercury, Lead, Arsenic, BTEX (Benzene, Ethylbenzene, Xylene, and Toluene), total coliforms, fecal coliforms, salmonella, total Nitrogen, nitrates, nitrites, and orthophosphates. Samples were also sent to the Environmental Engineering Laboratory of the Institute of Engineering of the UNAM where pharmaceutical drug analyzes were performed (Clofibric acid, Ibuprofen, Salicylic acid, 2,4-dichlorophenoxyacetic acid, Gemfibrozil, Naproxen, Ketoprofen, Diclofenac, and Carbamazepine) (Lee et al. 2015; Mazari-Kriart et al. 1999; Sorensen et al. 2015; Soto et al. 2000).

In addition, the Electrical Conductivity (EC) of the water was measured in the spring S3 through a CTD-Diver by Schlumberger Water Services that was placed since January 2017 for one year to have a complete cycle, and the data were collected through the software Diver-Office 2017. Precipitation data were obtained from a meteorological station in the National Center for Disaster Prevention (CENAPRED in Spanish) because this is the nearest station from the sampling point S3. Data of EC and precipitation were analyzed to know the response of the aquifer to precipitation events. This information made it possible to know the time between the precipitation event and the spring water emerging in the REPSA.

Results

The range of temperature of the five springs was from 12.86 °C to 19.70 °C, and the values of Electrical Conductivity (EC) were from 116.00 µS/cm to 869.88 µS/cm. The site S4 was the spring with the highest temperature and EC with 19.70 ºC and 0.87 mS/cm, respectively. The pH values were from 6.18 to 8.34; the sites downstream of REPSA have lower values than the sites upstream. In the intra-site relation between dry and rainy sampling, the values kept the same trend and only in the site S4 we can observe a difference between dry and rainy season regarding to pH values (Table 3). In addition, in the case of organic pollution, our outcomes show that 60% of the samples were positive to coliforms, while Salmonella bacteria were not present in any of the samples.

The Total Nitrogen (TN) concentration had values that were increasing in the same direction that the water flow of the aquifer. This increasing was up to site S3 where was the maximum value, and after this, the TN values decrease (Fig. 2a). Regarding the concentrations of nitrites found in the two sites upstream of REPSA (S1 and S2) and the site within REPSA (S3), there were no differences between the sampling in the dry season and the rainy season, nor between the sites. However, the two sites downstream the REPSA (S4 and S5) had concentrations that differed from the other sites and between seasons on the same site (Fig. 2b). These two sites were the sites with the highest concentration of nitrites in the rainy season with values of 0.01 mg/l and 0.009 mg/l respectively (Fig. 2b). Regarding the concentrations of nitrates found in the five sampling sites, it is possible to observe that the concentrations are similar in both seasons and that they tend to be higher upstream of REPSA (Fig. 2c).

Ortho-phosphates were observed in higher concentrations downstream of REPSA, and no differences were found between the results in dry and rainy seasons in any of the samples. Only one of the five sites (S4) located downstream of REPSA had a higher concentration than the other four sites (Fig. 2d). This elevated concentration could be due to wastewater urban infiltration or discharges on the aquifer.

Table 2 Precipitation in Mexico City in 2017

Month	1	2	3	4	5	6	7	8	9	10	11	12
Precipitation (mm)	0	0	18.1	12.9	48.9	86.2	101.7	101.3	86.8	31.4	0.6	0

Regarding the four heavy metals analyzed, the presence of Aluminum was found in low concentrations in all sites. This presence can be related to the characteristics of the basalt of volcanic origin that promotes a colloidal behavior of Aluminum, since inorganic particles are small enough to aggregate and remain in the water column for long time scales, such as days (Viaroli et al. 2016). Besides, the site S4 was the only one with the presence of Arsenic and only in the rainy season with a concentration of 14 µg/l. Lead did not present concentrations above the detection limit (DL) at any sampling site (DL: 0.13 µg/l). Mercury was found on the S2 site, in the dry season, with a concentration 1.624 µg/l (Table 4).

In the case of hydrocarbon pollution, even if the analyzed areas were reported to be sensible to this kind of pollution due to the presence of fuel tanks in the area (E. Soto et al. 2000), our sampling does not present any concentration above the detection limit of: Benzene (LD: 0.041 µg/l), Ethylbenzene (LD: 0.032 µg/l), MYP-Xylene (LD: 0.071 µg/l), o-Xylene (LD: 0.039 µg/l) Toluene (LD: 0.047 µg/l).

Table 3 Values of temperature, pH and electrical conductivity measured in each sampling site

Site	Temperature (°C)		pH		Electrical conductivity (µS/cm)	
	Rainy season	Dry season	Rainy season	Dry season	Rainy season	Dry season
S1	12.85	12.86	7.29	8.34	127.00	116.00
S2	14.17	14.12	8.25	7.91	235.20	183.20
S3	16.90	18.33	7.59	7.83	424.70	456.00
S4	19.70	19.11	7.58	6.18	869.88	707.80
S5	18.83	19.56	7.25	6.59	458.14	497.50

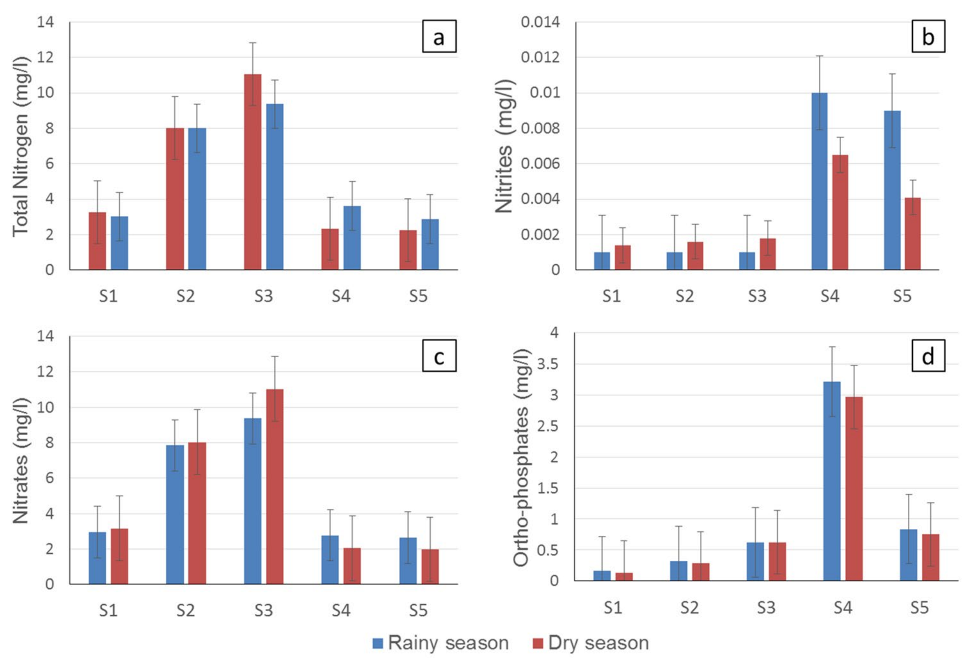

Fig. 2 Concentrations of nutrients in the five sampling sites. "**a**" shows the concentration of Total Nitrogen, "**b**" shows the concentration of Nitrites, "**c**" shows the concentration of Nitrates and "**d**" shows the concentration of Ortho-phosphates

Table 4 Concentrations of heavy metals in the five sampling sites

Site	Total aluminum (µg/l)		Total arsenic (µg/l)		Total mercury (µg/l)	
	Rainy season	Dry season	Rainy season	Dry season	Rainy season	Dry season
S1	0	11.70	0	0	0	0
S2	93.60	11.20	0	0	0	1.62
S3	10.70	10.20	0	0	0	0
S4	0	10.60	14.00	0	0	0
S5	11.60	131.90	0	0	0	0

Besides, no pharmaceutical drugs were found at the furthest sampling point upstream of REPSA (S1), whereas in the remotest point downstream of REPSA (S5), the presence of four different types of drugs was found (Ibuprofen, Salicylic acid, Naproxen, and Diclofenac). This gradient in the presence of these substances could be related to the contribution of pollutants from the urban area to the aquifer (Table 5).

The relation between the precipitation events and the Electrical Conductivity (EC) of the aquifer, analyzed in the spring S3, shows that to perceive a change in EC values, it is necessary a rain with an intensity higher than 7.8 mm. Besides, the response of the aquifer is within the first hour after a rain event higher than 7.8 mm (Fig. 3).

Discussion

Shallow urban aquifers are systems with a close relation to the surface. On the one hand, this characteristic makes them more vulnerable to contamination than deeper aquifers in urban areas (Morris et al. 2003). On the other hand, this strong relation with the surface also makes shallow aquifers capable of being promptly benefiting from Ecosystem Services related to water when they are located under Urban Green Spaces. For instance, by infiltrating rainwater in a shorter amount of time than deeper aquifers. This relation is highlighted by the analysis results

Table 5 Concentration of drugs found in water in the springs in both seasons (dry and rainy). DL is the detection limit of the method

Site	Ibuprofen (ng/l)		Salicylic acid (ng/l)		Naproxen (ng/l)		Diclofenac (ng/l)	
	Rainy season	Dry season	Rainy season	Dry season	Rainy season	Dry season	Rainy season	Dry season
S1	< DL	< DL	< DL	< DL	< DL	< DL	< DL	< DL
S2	4 ± 1	< DL	4 ± 1	< DL	< DL	< DL	< DL	< DL
S3	< DL	< DL	8 ± 2	< DL	< DL	< DL	< DL	< DL
S4	< DL	< 5 ± 1	< DL	< 7 ± 1	< DL	4 ± 1	< DL	< DL
S5	4 ± 1	< DL	6 ± 1	3 ± 1	3 ± 1	< DL	4 ± 1	< DL
DL: 0,25 ng/l								

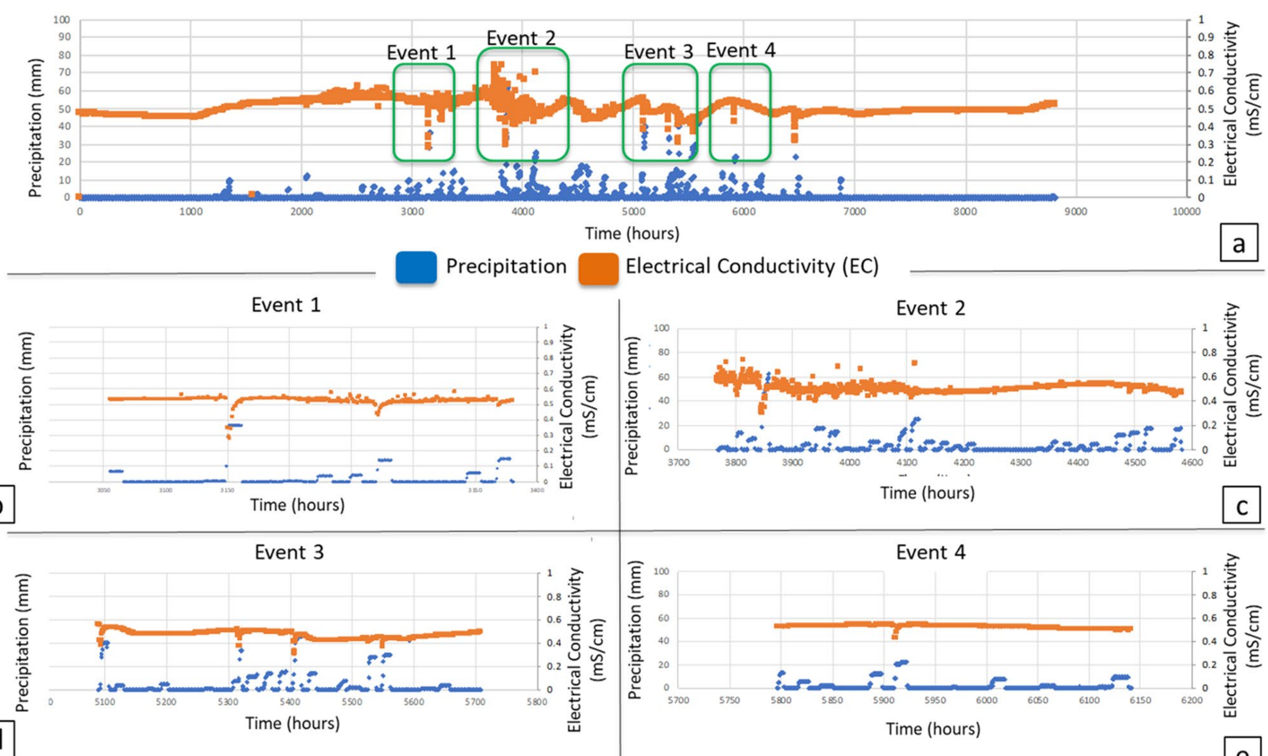

Fig. 3 Relation between precipitation and the Electrical Conductivity in the shallow aquifer. "**a**" shows the complete cycle of the 1 year, "**b–e**" show precipitation events analyzing the dynamics of the aquifer in terms of time and intensity of the precipitation

related to the behavior of the Electrical Conductivity of water in the S3 spring and its relation with the amount of precipitation in the area. In this sample site, located within the REPSA, it was possible to observe that the rainwater reached the shallow aquifer in a period of hours.

It is estimated that the presence of REPSA over the shallow aquifer contributes around 2,000,000.00 m^3 of water per year (Zambrano et al. 2016a). In addition, due to the state of conservation of the REPSA and its geological and ecological characteristics, it is possible to assume that this amount of infiltrated water would not alter its quality before reaching the shallow aquifer. Therefore, the water infiltrated in the REPSA could positively impact the water quality of the shallow aquifer through a dilution effect of the contaminants present in the aquifer. For example, the values associated with pollutants, such as total nitrogen and nitrates concentration, are higher in the aquifer areas which are inside the urban land and upstream the REPSA (according to the water flow). In contrast, the aquifer areas downstream of the REPSA have lower concentration values of these pollutants.

Another example is the concentration of Mercury found in site S2 (upstream of the REPSA). The presence of this metal could be related to a paper factory that existed in that area between 1825 and 1991, which used Mercury compounds as preservatives (Martinez et al. 2015; Parnreiter 2002; Ramírez et al. 2004). Mercury was possibly deposited in the soil and by leaching, downward percolation, runoff, and horizontal transport reached the groundwater, causing aquifer pollution (Hatcher and Filippelli 2011). However, in the spring, located on the REPSA and the ones downstream of the REPSA, this metal was not found. Both examples could be associated with a dilution effect of the water infiltrated in the REPSA on groundwater quality.

These assumptions are based on the limited knowledge currently available about the characteristics of the studied shallow aquifer, who was recently discovered and described in the literature (Canteiro et al. 2019). Therefore, it is necessary to deepen the understanding of the dynamics of the aquifer and its relationship with the surface with other layers of groundwater. In this sense, we must consider that the shallow aquifer not only receives water from REPSA, but that most of its recharge occurs in the south of the city on conservation land, that after the shallow aquifer enters the urban area, it also receives different types of contributions both from the surface and from the water distribution system. The latter acquires importance since in Mexico City it is reported that up to 42% of the water is lost due to leaks in the system (Silva and Martínez Omaña 2023). Both this amount of water from the distribution system, as well as other possible sources of clean water that feed the aquifer, can contribute together with REPSA to the dilution of contaminants present in the shallow aquifer.

Urban areas above the aquifers can also have a negative impact on groundwater. If it is strong enough, this negative impact can counter the positive impact of the UGS or other sources of clean water. For example, in this study, values of temperature, EC, and orthophosphates, all of them related to urban pollution, are high in the urban area and remain high with a growing path downstream REPSA (Table 3 and Fig. 3). This is also the case of pharmaceutical drugs analyzed in this research, which remain present upstream and downstream REPSA. These results indicate that, for some contaminants, the negative impact of the urban area on the shallow aquifer is higher than the positive influence of REPSA and other possible sources of clean water. Pharmaceutical drugs are particularly relevant due to its impact on human health. Although the concentration values found for these drugs were low (World Health Organization 2012) and they are not regulated by the Mexican Norm regarding drinking water (NOM-127-SSA1-1994) (Secretaría de Salud 1994), they can be considered a threat to public health (Rivera-Jaimes et al. 2018). Despite their low levels, prolonged exposure to medical drugs, even in low concentrations, can represent a risk to human health because of the potential -and sometimes unknown- effects derived from the combination of different drugs (Osuoha et al. 2023; Rodriguez-Narvaez et al. 2017; Taheran et al. 2018). Besides, these kinds of pollutants are linked with chronic toxicity, and they bioaccumulate in macroinvertebrates, aquatic organisms, and humans.

Conclusion

We found that UGS have an important role in water infiltration to the aquifer, helping to dilute pollutants. Urban shallow aquifers are systems sensitive to the impacts from the surface because of their close relation. Depending on the characteristics of the land use above the aquifer, these impacts could be positive or negative. We found a relation between the presence of UGS over urban shallow aquifers with the improvement of groundwater quality through the infiltration of water which generates a dilution effect of the pollutants present in the aquifer, even in the case of heavy metals as Mercury. However, urbanization has a negative influence on groundwater quality through the contribution of some contaminants that might not be counteracted by the positive effects of UGS infiltrated water.

In Mexico City, REPSA is a UGS that provides the ecosystem service of contributing to the regulation of the water quality of the shallow aquifer below it. Said contribution occurs through the infiltration of clean water to the shallow aquifer, which promotes the dilution of some contaminants. However, this effect is not able to counteract all the contaminants present in the aquifer. The geological and ecological properties of the REPSA, its state of conservation and the characteristics of its management are fundamental to obtain the ecosystem services of regulation of the quantity and quality of water from the shallow aquifer. Therefore, it is essential to carry out complementary studies to determine the scope of the positive impacts provided by REPSA and other possible sources and impacts on the water quality of the shallow aquifer. For example, it is essential to know the amount of water that can be infiltrated into the REPSA to better understand the possible dilution effect proposed in this work and to further understand how UGS can be beneficial for regulating water quantity and quality of shallow urban aquifers.

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Author Contributions MC, OA-AyLZ conceived of the presented idea. MC developed the theory and performed the computations. EB and MC took the water samples. EB carried out some analyses of the samples taken. MC and LZ carried out the verified analytical methods. LZ supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

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Data availability The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflicts of interest The authors declare no conflict of interest.

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