Aquifer recharge with treated municipal wastewater, long term experience at San Luis Rio Colorado, Sonora

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Abstract

This paper presents 10 years of experience in recharging reclaimed waters, via infiltration basins in order to reverse overdraft in a previously overexploited aquifer. First, the feasibility of artificial recharge was evaluated using an infiltration experiment to estimate the percolation rates and the capacity for reclaimed water treatment by passing groundwater and treated wastewater through the soil vadose zone to the aquifer in a pilot pond. Ongoing physicochemical and bacteriological monitoring of reclaimed and recharged water to the aquifer was then conducted to assure that native groundwater was not contaminated. After transit throughout 20-m-thick vadose zone, the concentration of chloride, manganese and iron increased due to evaporation and dissolution processes, and total removal of coliforms was observed. We found that low water levels in ponds prevented the transport of fine particles to deep layers of the soil vadose zone and maintained a concentration of total suspended solids (TSS), less than 30 mg/l, thus reducing the volume of particles clogging the soil. The pilot test and maintenance practices described in this work have been followed in the development of managed aquifer recharge projects in other semiarid regions.

Keywords: managed aquifer recharge, treated municipal wastewater, Colorado river, arid lands

Introduction

Mexico, like many other countries in the world, employs groundwater as a source of urban water supply (Wada et al. 2010). The overexploitation of aquifers has become a serious problem in Mexico, with the number of overexploited aquifers growing from 32 in 1975 to 106 in 2013 (SEMARNAT 2014). The over-allocation of groundwater resources is not specific to México, however, and occurs in many regions where rainfall is scarce and aquifer development is extensive, as groundwater is often the cheapest, most accessible, and most reliable freshwater resource (Custodio 2002). This is the case for cities located in the semiarid regions of northwest Mexico, where no other water source is used for urban supply, and the exploration of more sustainable water resource management practice is necessary.

San Luis Río Colorado (SLRC) city is located on the northwest border of the Sonoran Desert at 32°27´N, 114°46´W, with an average altitude of 40 meters above sea level. The study area is bordered to the north by the valleys of Yuma in the US state of Arizona, to the west by the Valley of Mexicali in Baja California, México, and to the east and south by the desert of Altar, Sonora, that extends to the Gulf of California (Fig. 1). The mean annual precipitation is 55 mm and mean annual direct evaporation is 1500 mm.

The unconfined granular aquifer is on the Colorado River fluvial-delta system over very well-developed sedimentary fluvial deposits that vary from 600 to 2000 m in thickness (Olmsted et al. 1973). The sediment texture consists of gravels, sands, silts and clays, and despite a very irregular distribution, unconsolidated sands are predominant in most of the lithological column (CONAGUA 2008). The hydraulic conductivity varies between 7.7×10^{-5} and 4.0×10^{-3} m/s, and the depth to groundwater is 22 m on average (CONAGUA 2008). The SLRC aquifer is located on the Yuma Mesa subarea of the Colorado River fluvial-delta system. This portion of the Delta is above the river valleys (flood plains) and has not been subjected to geologically recent (Holocene) flooding by the rivers (Olmsted et al. 1973). These sediment characteristics and the variations in permeability give rise to anisotropic materials, both vertically and horizontally. Regional groundwater flow occurs in a NNE to SSW direction from the upper Colorado River delta area to the Gulf of California (CONAGUA 2008). Pumping wells located in the Yuma Valley area, on the Mexican side of the US-MEXICO border in the San Luis Río Colorado Valley area, and in the SLRC city deplete the local aquifer levels, which in turn affects the regional groundwater flow pattern, with increased pressure on the groundwater resource (Kennedy et al. 2016). Geohydrological studies of the SLRC aquifer showed overexploitation of 7.5 hm^3 annually (1 $hm^3 = 1\times10^6$ m^3), considering that the average annual recharge of 236.8 hm^3 corresponds to the sum of all volumes entering the aquifer, of which 155.2 hm^3 corresponds to the natural recharge from the Colorado River, and the remaining 81.6 m^3 to the induced recharge from the return flows of irrigation areas, while a volume of 244.3 hm^3 is allocated for consumption and natural use (CONAGUA 2010).

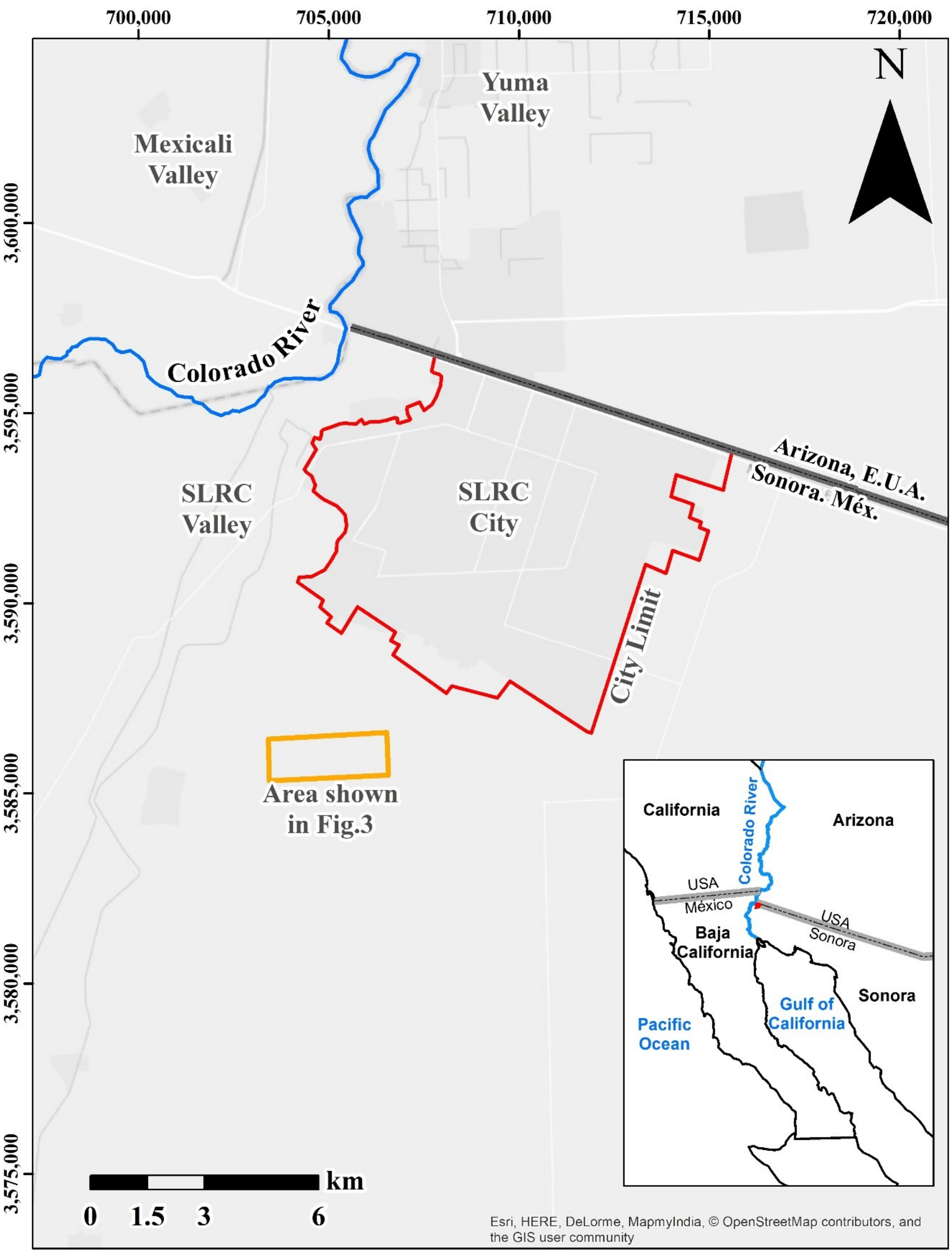

Fig.1 Location of study area.

The population of SLRC city as of 2015 was 193,000, with an annual growth rate of 1.9% (INEGI 2016). The city has actual sewage coverage of 86%, and prior to the construction of the wastewater treatment facility (WWTF), raw wastewaters was dumped into the dry bed of the Colorado River, approximately 10 km from the city. The WWTF is operated by the municipal water supply service "Organismo Operador Municipal de Agua Potable, Alcantarillado y Saneamiento" (OOMAPAS), and receives an average of 400-430 l/s. It consists of three treatment modules comprising four ponds: an anaerobic pond, a facultative pond and two maturation ponds. The treatment train enables the plant to comply with the official Mexican federal standard NOM-001-ECOL-1996, which sets the maximum concentrations of contaminants in treated wastewater directly discharged into federal water bodies (SEMARNAT 1997). According to this guideline, treated waters can be used for agricultural irrigation of crops that area non-edible when raw or uncooked. For this project, three main options were considered for sustainable reuse of municipal wastewater: (1) reuse of the water for irrigation of the SLRC agricultural valley, (2) discharge of recovered water on the dry bed of the Colorado River for riparian restoration, and (3) infiltration of the recovered water into the aquifer to reduce overexploitation. The first option was discarded after an economic analysis of water prices and water allocation. The price of groundwater for growers was around 1.38 Mexican pesos per cubic meter, whereas the operating costs alone for recovered water were 2.25 Mexican pesos per cubic meter. The cost of water treatment plus water delivery at irrigation sites approximately 15 km from WWTF could not be covered by the growers. On the other hand, conveyance of the treated water from the WWTF to the Colorado River's main channel required a large initial investment, because of the water transferred approximately 10 km to the main river channel. With these considerations in mind, the infiltration of water to recharge the aquifer seemed to be the most suitable and sustainable option, as groundwater levels around Mexican border in San Luis Rio Colorado city are generally lower than Yuma valley, due to groundwater extraction by US and Mexican wells at the 242 Wellfield (Dickinson et al. 2006). This water conservation project was supported by the North America Development Bank under the Border Environment Infrastructure Fund (BEIF) for administration of grant resources provided by the US Environmental Protection Agency (EPA) for implementation of high-priority municipal drinking water and wastewater infrastructure projects in the US-Mexico border region.

The practice of artificial aquifer recharge using recovered water –know as managed aquifer recharge (MAR)- has been carried out in United States for more than 50 years (Drewes 2009). On Burdekin Delta in Queensland, Australia, infiltration basins were established in the mid-1960s (Dillon 2009). In Spain, the first antecedents of artificial recharge date to the Arabian era and include the Alpujarros checkpoints and the Levantine levees system (Fernández-Escalante et al. 2005). In Mexico, unintentional aquifer recharge with untreated and treated wastewater has occurred since sewerage systems were stablished. However, intentional recharge with recycled water to protect and enhance groundwater resources is a recent development. Managed aquifer recharge using reclaimed water was used first in Mexico in 2007, even before the official Mexican regulations, NOM-014-CONAGUA-2003, were published (SEMARNAT 2008). These standars were prepared and reviewed by the National Water Commission (CONAGUA), which is the Mexican regulatory agency governing water resource management according to Mexico's National Water Law.

The objective of this paper is demonstrate how managed aquifer recharge with reclaimed water has helped to preserve water resources for more than 10 years in a semiarid region with a very high usage pressure. Much of experience gained is no limited to semiarid regions, and can be applied for the sustainable management of constrained water resources in other areas where aquifers are depleted by overexploitation.

Material and methods

In order to infiltrate reclaimed water into the aquifer, it was first necessary to characterize the physicochemical and bacteriological characteristics of the reclaimed water and native groundwater to ensure that the native groundwater was not contaminated. Pilot recharge experiments were then carried out to evaluate the hydrogeological properties of the unsaturated zone and aquifer as well as the purification capacity of the unsaturated zone during the travel to the aquifer. The pond was designed to receive the volume of water recovered under high and low levels of evaporation during the summer and winter, respectively. Finally, a maintenance program was established for sustainable long-term operations according to the season

Pilot recharge experiments

The WWTF and the experimental site are located 5.2 km south of the city of San Luis Rio Colorado, Sonora. The first step for the infiltration of reclaimed water in to the aquifer was to assess the feasibility of soil infiltration, by studying the properties of the subsoil hydraulic conductivity, porosity, and purification capacity of the soil, the unsaturated zone depth and the hydrogeology, including the aquifer transmissivity and storage. The aquifer hydraulic parameters were obtained by performing short-term pumping tests, both in the depletion and recovery stages. The sandy strata of the unsaturated zone as was reported by Sol et al. (2008) to consist of 82-85% sand, 10-11% silt, and 6-10% clay.

The pilot recharge experiment consisted in constructing an infiltration pond with block walls, keeping the soil unchanged within the pond. The 28-m^2 pond was 5.6 x 5.0 x 1.0 m in size and was located 100 m from WWTF. Four observation wells of 8, 15, 20, and 100 m were installed at distances of 0.35, 0.9, 3.2, and 3 m from the edge of the pond, down-groundwater gradient. The 20-m-deep observation well is at the groundwater table (Fig. 2). The pilot infiltration experiment was completed in two steps. The first step consisted in filling the pond with native well water from the local aquifer (clear water) to a volume of 10 and 300 m^3, while the second step involved the use of treated wastewater from military quarters located close to the study area. The first step was carried out to evaluate the infiltration process. The water moisture front was registered in the observation wells along its transit through the unsaturated zone and before its arrival to the groundwater level. It should be noted that the bottom of the pond consisted of natural soil composed of fine sand, similar to the location where the infiltration basins were constructed.

The infiltration capacity was estimated by measuring the water level and the infiltration time of the water in the pond at 1-min intervals. In order to evaluate the evolution of water quality, during transit from the pond to the aquifer, water samples were taken from the pond and from different depths (8, 15, 20, and 100 m) in the observation wells and in the aquifer. The water samples were collected at observation wells with small diameters (3 inches) at 1.5-m screening intervals, and 0.3 m of casing tube with a cap known as the ‘‘tailpipe’’at the bottom to recover the water at the depth (Fig. 2). A well of 100 m in length was screened from 44 to 100 m.

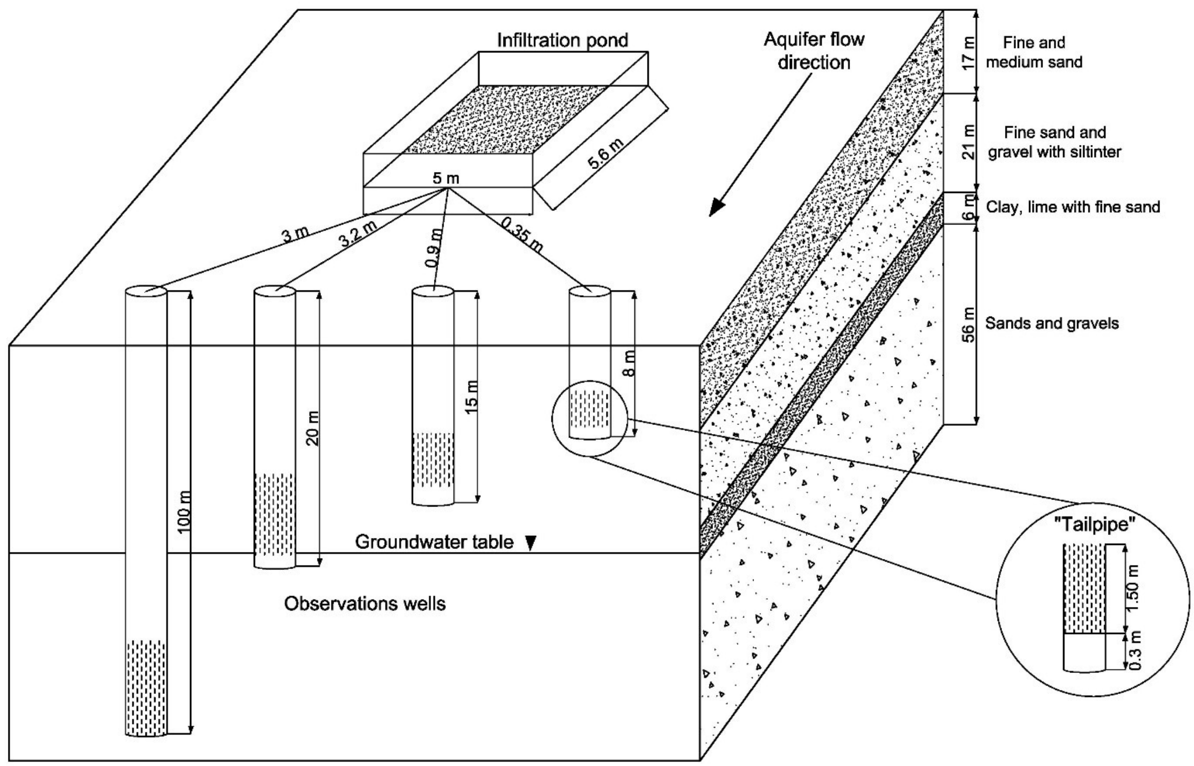

Fig. 2 Pilot test pond and wells design. Not to scale.

Design of infiltration ponds

The reclaimed water infiltration system consists of a delivery channel, eight infiltration ponds for treatment modules 1 and 2, and four additional infiltration ponds for module 3, for a total of 12 infiltration ponds. The infiltration ponds measure 120 x 120 x 1.0 m. The size, location and number of infiltration ponds was estimated considering the infiltration rate and the volume of influent to the WWTF, infiltration ponds 9 to 12 are used primarily during extraordinary events such as treatment facility or during cold rainy days in winter. The inside walls of the ponds are protected with a plastic membrane to prevent erosion. Figure 3 shows the sequential numbering of filling of the infiltration ponds for modules 1, 2 and 3. The inflow of the ponds is from a central distribution channel and controlled by lock-gates.

Operation and maintenance of infiltration ponds

The infiltration ponds are operated with an average volumetric load of 100 and 60 l/s during the summer and winter seasons, respectively. In summer, the ponds are filled to a depth of 0.32 m, because the high evaporation rates induced by temperatures around 50^{o}C cause the ponds to dry faster (3 days), which enables earlier maintenance. In addition, the concentration of suspended solids decreases in summer, which gives the ponds the capacity for higher hydraulic load. In contrast, during winter, the ponds are filled only to a depth of 0.1 m, as the very low evaporation (temperatures <15^{o}C) causes the ponds to remain wet longer (7 days), thereby delaying their maintenance. The content of suspended solids also rises in winter. The ponds are used in pairs and alternated (i.e. 1, 4, 5 and 8 are wetted simultaneously, and 2, 3, 6 and 7) to prevent the infiltration delay caused by increased moisture in the subsoil. Once the pond has been taken out of operation and the bed has dried, maintenance is carried out (Fig. 4).

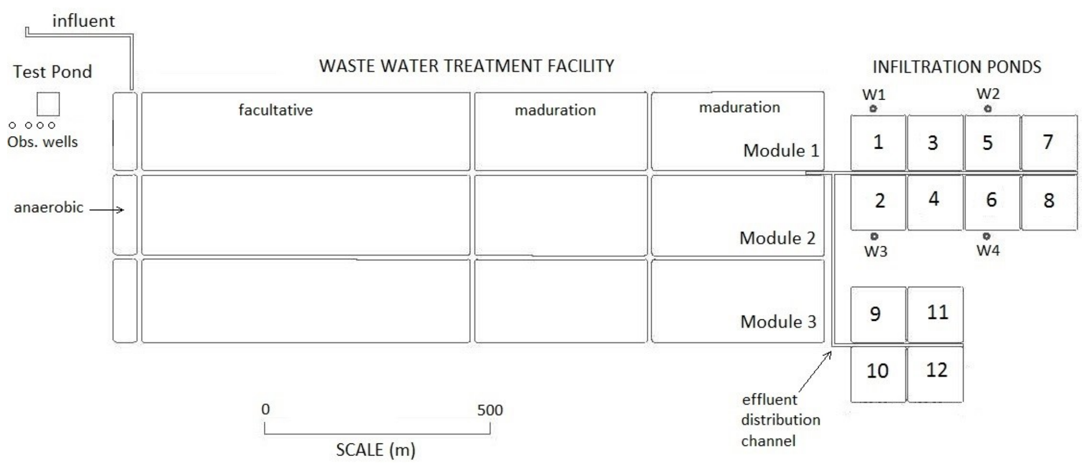

Fig. 3 Waste water treatment facility, infiltration ponds and test pond location. See Fig. 1 for location of WWTF

Initially, the crust formed by organic matter and solids on the bottom of the pond were mixed, because a decrease on the infiltration rate was observed. Maintenance labor involves the removal of the 0.1 ±0.05 m of crust formed by algae on the entire surface of the basin bottom. The material removed is used as compost substrate mixed with other soil materials and disposed in the green areas of the WWTF. The maintenance technique is very important to conserve the percolation rate, because soil surface clogging significantly impedes infiltration. This reduction in infiltration capacity results from the obstruction of pores that comprise the upper strata of the soil (Bouwer 2002; Dillon et al. 2010). The clogging on infiltration systems has been studied in the context of groundwater recharge (Ye et al. 2010), recovery wells (Rinck-Pfeiffer et al. 2000), constructed vertical-flow wetlands (Langergraber et al. 2003) and stormwater gravel infiltration systems (Siriwardene et al. 2007).

Fig. 4 Maintenance of infiltration ponds

[Figure 5](#) shows the compaction of the upper layer of the infiltration basin. It is also important to aerate the soil, because septic conditions can reduce water quality, according to studies carried out in filtration systems in sandy strata (Fair et al. 1966).

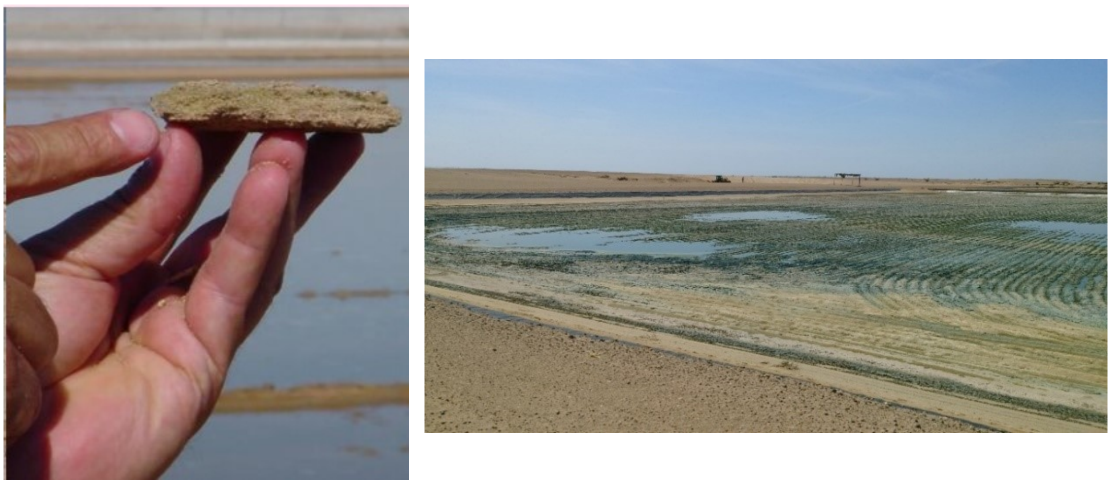

Fig. 5 Clogging of infiltration ponds soil. *Left*: a piece of soil crust compacted by dead algae accumulation and clotting. *Right:* basin shows reduced infiltration and loss of surface smoothness

Monitoring of the efficiency of the recharge system is carried out by physicochemical analysis of the water obtained from four drilled observation wells at depths of 15 and 25 m. Figure 3 shows that monitoring wells are located around the infiltration lagoons, and the casing is made of PVC pipe 8" in diameter, W1=15 m; W2 = 25 m; W3 = 25 m; W4 = 15 m depth.

Sampling is performed twice a month to obtain a monthly average concentration of parameters listed in NOM-001 to whether the water meets these quality parameters upon reaching the aquifer. However, in order to obtain information on a weekly basis, in situ monitoring of the wells is carried out to determine groundwater level, electrical conductivity, pH and redox potential. These physicochemical data are recorded in a database for use in review of the infiltration process.

Figure 6 shows two samples of water, one from the effluent of the WWTF prior to the infiltration water facility and the other from only the aquifer at a depth of 25 m in observation well W2.

Fig. 6 Samples taken from WWTF effluent (*left*) and from the aquifer at a depth of 25 m adjacent to the basin, in 2016 (*right*).

Results and discussion

Native groundwater

The physicochemical composition of native groundwater was obtained from the average composition of 18 wells supplying drinking water for SLRC city during 2006 (Table 1). The formation of the Yuma Mesa by fluvial, aeolian and marine sediments and the presence of volcanic rocks in the upper area of the delta, i.e. Chocolate Mountains, affords an average native groundwater composition with high levels of total dissolved solids (TDS), manganese and iron at 975, 0.12 and 0.08 mg/l, respectively. The concentration of chloride is higher than that of sulfate, and it is the main anion constituent, as was reported by Olmsted et al. (1973).

Pilot plant

The pilot test revealed the hydraulic characteristics of both the unsaturated zone and the aquifer. In the case of clear water, the infiltration rate ranged from 9.7 at the beginning to 4.8 at the end, with an average of 6.9 m/day during the las part of the recession curve after 12 h of infiltration. A short-term pumping test on an observation well at a depth of 100 m indicated representative values of aquifer transmissivity in this area ranging from 6.9 x 0^{-3} to 3.2 x 10^{-1} m^2/s, with an average value of 7.4 x 0^{-2} m^2/s, and a specific yield of 25% was obtained from a comparison of lithological well cuttings and sediment texture analysis with data reported in the literature (Olmsted et al. 1973).

Table 1 Parameter concentrations of native groundwater, treated water from pilot pond, and water from depths of 15, 20 and 100 m during pilot test.

Parameter	Units	Native GW	Pond	Observation well depth (m)		
				15	20	100
Total Coliforms	MPN/100 ml	0	10,500,000	250	51	0
Aluminum	mg/l	0.02	0.02	0.04	0.12	0.03
Arsenic	mg/l	0	0	0	0	0
Cadmium	mg/l	0	0	0	0	0
Chloride	mg/l	273	339	252	412	252
Chromium	mg/l	0	0	0	0	0
Copper	mg/l	0	0.03	0.32	0.06	0.02
Fluoride	mg/l	0.27	0.82	0.65	1.57	0.19
Hardness	mg/l	402	22.5	41	256	301
Iron	mg/l	0.08	0.12	0.19	0.26	0.03
Lead	mg/l	0	0	0	0	0
Manganese	mg/l	0.12	0.11	0.17	0.57	0.02
Mercury	mg/l	0	0	0	0	0
Nitrate	mg/l	0.62	0.58	4.03	1.4	0.28
Sodium	mg/l	189	156.5	134	193.7	119.3
Sulfate	mg/l	179	450	280	452	280
TDS	mg/l	975	1521	1117	1717	968
Zinc	mg/l	0.01	0.04	0.09	0.09	0.04

This is in the upper range of values reported by Bouwer (2002) of 1 and 5 m/day for fine medium sands, respectively. Figure 7 shows water elevation fluctuations resulting because of clear water refills and discharges of the test pond observing the slight reduction of infiltration rate after several hours.

The tests carried out with treated wastewater showed that the infiltration coefficient decreased because of the solids that collected at the bottom of the pond. The reduction at 24 h was 50% of the initial rate, as it decreased to 2.4 m/day, at 48 hours this decreased to 0.5 m/day, and at 4 days a further decrease to 0.12 m/day was observed (Fig. 8). The pilot test showed here for clear water and treated wastewater were carried out for 12 h and 5 days, respectively, and both represent a sample from pilot testing (Reyes-López et al. 2005).

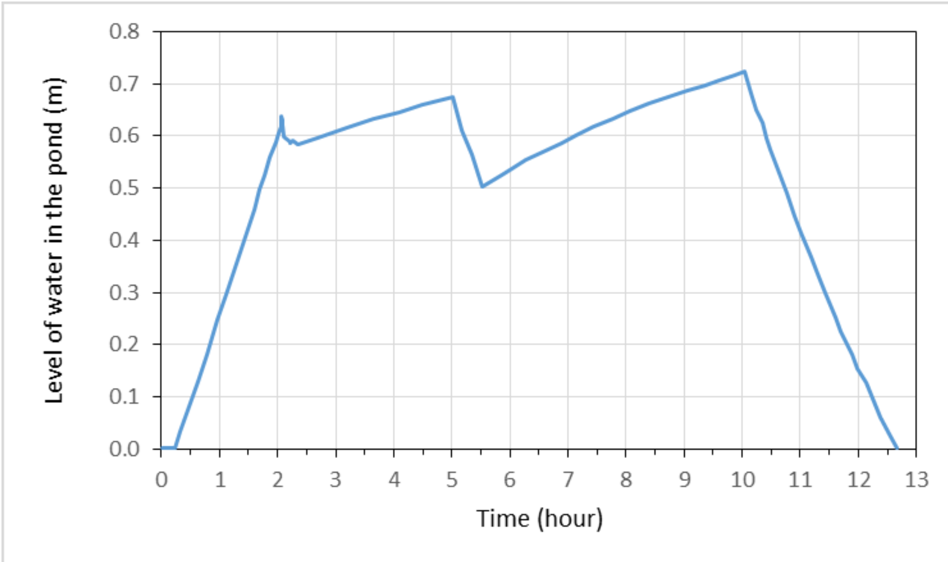

Fig. 7 Infiltration rate during the pilot test using clear water on the basin

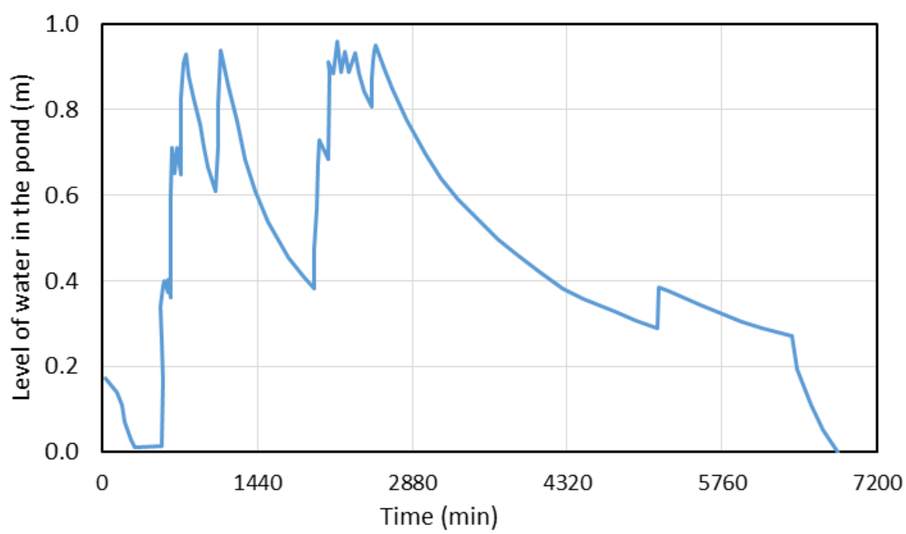

Fig. 8 Infiltration rate during pilot test with treated wastewater on the basin

Samples taken during clear-water recharge were analyzed using quality measurements according to Mexican Standard NOM-127-SSA1-1994 (SSA 1996), and the recharged treated wastewater was analyzed under NOM-001 criteria. The first standard establishes the maximum contaminant levels for water designated for human consumption, and the second establishes the maximum levels for wastewater discharge into Mexican surface water bodies. NOM-014 for recharging of treated wastewater was not considered, because at that time it had not been published. The concentrations described in NOM-014 depend on the distance between extraction wells and infiltration ponds: if there is an extraction well for human consumption less than 1 km from an infiltration facility the NOM-127 criteria for infiltrated water quality must be considered.

In order to analyze the concentration of treated water in the pond and in observation wells, the average concentration of water across all tests was obtained (Table 1). During the pilot test, the infiltrated treated wastewater showed a considerable decrease in the microbiological parameter, with a reduction up to 200,000 times the original concentration after 20 m of transit through the vadose zone.

An increment on chlorides, sulfates, TDS, iron and manganese was observed at 20 m depth. The increase in chlorides and sulfates is explained by saline strata washing along the water course to the aquifer. The increase in iron and manganese concentrations is due to the presence of strata rich in clay loam sands in the aquifer, as was later explained by Ramírez-Hernández et al. (2013).

Efficiencies of infiltration lagoons

The current infiltration rate of the ponds is around 8.2 hm^3 per year, taking into account direct evaporation of around 1500 mm per year in the WWTF and in the infiltration lagoons. This recharge volume represents more than the total aquifer overexploitation of 7.5 hm^3. Table 2 shows the maximum concentrations included in NOM-127, the average concentration from biweekly analysis of the WWTF effluent during 2016, and the concentrations in 2013 and 2016 from observation well W2, at a depth of 25 m.

This clogging process is associated only with effluent TSS concentration higher (97.5 mg/l) than the NOM-001 (75 mg/l) limit, and not included in NOM-127, but at depths below 25 m, it is drastically reduced, to 25 mg/l. Ye et al. (2010) recommend a TSS concentration of less than 10 mg/l of in a surface recharge system in order to prevent physical clogging, whereas Bouwer (2002) suggest a TSS concentration ≤30 mg/l for potable use of groundwater from aquifers recharged with sewage effluent in California. Although the treated sewage effluent discharged to infiltration ponds exceeded the NOM-127 standard for total coliforms (6.66 MPN/100 l) after passage through the unsaturated zone, TSS was well within the standard, as were all other measured parameters covered by the NOM-127 standards, except chloride, sodium, TDS, and manganese which are manly derived from native groundwater used for municipal water supply service and saline strata washing along the water course to the aquifer, which also occurred during the pilot test. After 10 years of operation, the amount of contaminants removed is almost unchanged; however, a considerable decrease in infiltration rate has been detected, which according to our studies is a result of the degree of clogging at the bottom of the basin. During the first 4 years of operation, plowing of the first 0.20-0.30 m of pond soil was undertaken to reduce the drying time by loosening and turning over the top of soil; nevertheless the infiltration rate decreased very rapidly. The optimal maintenance procedure for restoring the initial infiltration rate involves superficial scraping to a depth no greater than 0.15 m. Recent laboratory clogging studies demonstrate that the clogging rate is faster for suspended solids with small diameters is faster than those with large diameters (Wang et al. 2012).

Table 2 Values obtained from water in the infiltration pond and after crossing 25 m of unsaturated soil and aquifer for 2013 and 2016.

Parameter	NOM-127	Aver. Conc. 2016 Effluent (n=24)	2013 *W2* (25 m)	2016
pH	6.5-8.5	8.36	7.72	7.89
Total coliforms, MPN/100 l	absent	6.66	ND	ND
Aluminum, mg/l	0.2		0.108	0.196
Arsenic, mg/l	0.01	0		ND
Cadmium, mg/l	0.075	0	0.0006	ND
Chloride, mg/l	250		331.3	360.1
Chromium, mg/l	0.05	0	0.0063	ND
Copper, mg/l	2.0	0.155	0.0189	ND
Cyanide, mg/l	NI	0.247		0.0021
Fluoride, mg/l	1.5		0.31	0.1248
Hardness (mg/l $CaCO_3$)	500		481.9	
Iron, mg/l	0.3		0.342	0.223
Lead, mg/l	0.01		ND	ND
Manganese, mg/l	0.15		ND	0.464
Nickel, mg/l	NI	0		0.0059
Nitrate, mg/l	10		0.0336	
Sodium, mg/l	200			340
Sulfate, mg/l	400		130.3	196.4
Total dissolved solids TDS, mg/l	1000		1214	1379
Total suspended solids (TSS),	NI	97.5		25
Zinc, mg/l	5.0	0.040	0.115	0.029

NI not included, *ND* not detected

The phenomenon of clogging by organic materials such as those deposited in these lagoons is currently being studied, and preliminary results show that the pores in the first soil profile (0-0.05 m) are filled by organic matter by similar size by means of a sedimentation process on the soil surface, while the underlying profile (0.5-0.15 m) is filled by finer particles that are entrained during the infiltration process. The occurrence of fine sediments of organic origin is not observed below a soil depth of 0.30 m, so it is assumed that the rate of infiltration is not substantially modified below this depth. The restoration of the infiltration rate after ripping 0.15 m of soil can be attributed to the fact that the water level of recharge basin is never is higher than 0.32 m, and the hydraulic head is insufficient for seepage of particles to the deepest soil strata, as has been described by Ye et al. (2010). Scraping intervals are a function of infiltration rate reduction, and in our experience, ponds need to be scraped after two to three wet-drying periods, but this is ultimately dependent of the TSS concentration and soil texture.

Conclusions

The artificial recharge of aquifers with reclaimed water allows for the reuse and conservation of water. Sustainable water use is a challenge for cities on semiarid land where there is increasing demand for water resources. Infiltration ponds at the SLRC play a very important role in the elimination of local aquifer overexploitation, recharging an annual volume of around 8.2 hm^3, which is 3% higher than that for all other recharge sources, according to CONAGUA (2010) balance.

The chemical composition and vadose zone sediment texture, composition and sedimentation processes of reclaimed water and native groundwater were characterized before the recharge basins were constructed in order to avoid the risk of native groundwater contamination. However, it was also necessary to maintain frequent water quality monitoring during operation in order to identify possible variations in the concentration of certain constituents that could be dissolved during infiltration through the vadose strata, leading to changes native groundwater composition. The treatment plant, in combination with the treatment capacity of the vadose zone, has enabled operation of the artificial recharge system for more than 10 years, with acceptable results under Mexican standard NOM-001.

The pilot test enabled the estimation of the hydraulic properties of the soil, the vadose zone and the aquifer, as well as the improvement in water quality through the vadose zone. The clear water test showed an infiltration rate of 6.9 m/day, while the test with reclaimed water showed a 50% reduction in the rate after 24 h to 2.4 m/day, and a further reduction to 0.12 m/day after 4 days, because of clogging.

Clogging occurs primarily in the uppermost soil strata (0.15 m) and the reduction of the infiltration rate reduces the water volume capacity of the lagoon system. Recommended procedures for improving the infiltration rate in the ponds are already described in the literature, and will ensure the long-term functionality of the ponds. The first of these is to maintain a TSS concentration below 30 mg/l to reduce the amount of particles entering soil strata ponds. Second, restricting the water levels of ponds to no more than 30 cm results in lower initial infiltration rates, but significantly reduces the transport of particles into the soil and prevents a progressive decline in the recharge rate due to clogging of subsurface layers. Third, drying of ponds has proceeded with wet-dry periods of 3-4 days during summer and 6-7 days during winter. Finally, at intervals of 15 days (of after every 2-3 drying periods) the ponds are scraped to improve the hydraulic conductivity of the upper soil layer, and ploughing the soil is not recommended. The combined effect of these measures has seen a decline in annual average infiltration rate from 0.12 m/day 2007 in 0.07 m/day in 2016, and the rate of decline has been strongly reduced in recent years by adhering to these practices. Clogging processes are expected to be influenced by the recycled water particulate composition, soil, and water. The methodology described in this work can be adapted for the evaluation of recharge processes, infiltration systems design, and monitoring of system behavior in other regions of the world.

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