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Drinking water provision and quality at the Sahrawi refugee camps in Tindouf (Algeria) from 2006 to 2016

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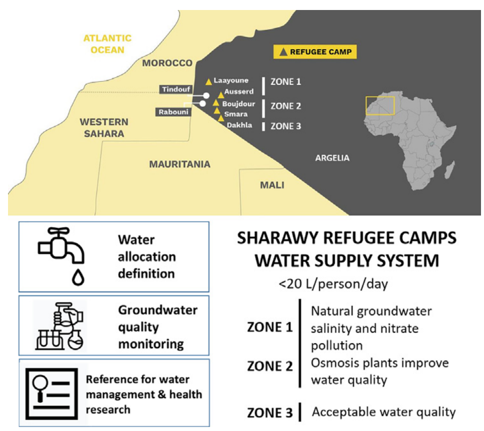
HIGHLIGHTS

- Sahrawi refugee camps water supply is an example of groundwater management in extreme conditions.
- The average water allocation supplied in the camps is below 20 L/person/day.
- A complete set with published and new data evidences the quality of raw groundwater.
- Natural groundwater salinity requires the use of reverse osmosis plants.
- This work entails a reference framework for future water management and health research.

GRAPHICAL ABSTRACT



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ABSTRACT

Drinking water provision has been a constant challenge in the Sahrawi refugee camps, located in the desert near Tindouf (Algeria). The drinking water supply system is itself divided in three zones which pump groundwater from different deep aquifers. It is equipped with reverse osmosis plants and chlorination systems for treating water. The allocation of water supplied to the Saharawi refugees for human consumption in 2016 has been estimated at between 14 and 17 L/person/day on average. This supplied water volume is below recommended standards, and also below the strategic objective of the Sahrawi government (20 L/person/day). Yet the local groundwater resources are huge in comparison with estimated consumption, and hence there is great potential for increasing the supplied volume through effecting improvements in the supply system. The physico-chemical quality of the raw and supplied water between 2006 and 2016 has been assessed according to Algerian standards for human consumption. The raw water of two zones of the supply system presents a very high conductivity and high concentrations of chloride, nitrate, fluoride, sulfate, sodium, calcium, potassium and iodide concentrations of natural origin, which may entail health risks. The treatment of water in a reverse osmosis plant greatly improves its quality and osmosed water met the standards. However, the supply of osmosed and raw water needs to be combined in Zone 1, to avoid an excessive reduction in water volume, and the supplied raw water poses a risk to the health of the refugees. The present study provides an example of a drinking water supply system under extreme drought conditions and in the political and social conditions of a refugee camp. Furthermore, it establishes a reference for supplied water allocation and quality in the Sahrawi refugee camps.

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1. Introduction

The settlement of the population in the Sahrawi refugee camps had its origins in the so-called conflict of Western Sahara, a former Spanish colony and currently a province recognized as a non-autonomous territory in resolution 1542 of the General Assembly of the United Nations (UN, 1960). The departure of Spain as the colonizing power of Western Sahara in 1976, after the Tripartite Agreement of Madrid signed by Morocco, Mauritania and Spain, led to the occupation of the Saharan territory by Mauritania and Morocco (UN, 2002). An armed conflict arose between Mauritania, Morocco and the Sahrawi population, leading to a massive influx of refugees in Algeria. Mauritania withdrew from the conflict and the territories in 1979. After several more engagements between 1989 and 1991, a ceased-fire agreement was reached between the Polisario Front, a Sahrawi rebel national liberation movement, and the Moroccan government. Today 80% of the Western Sahara territory remains under Moroccan control. Meanwhile, about 165,000 refugees, according to local authorities and the estimates of the Algerian government, are still displaced and are living in the refugee camps near Tindouf (Algeria) (Fig. 1). This humanitarian crisis is the only one that attained the highest score in ECHO's list of forgotten crises in 2014 (ECHO, 2015).

The Sahrawi refugee camps (SRCs) are governed by the Frente Polisario, and while they are administratively part of the Sahrawi Arab Democratic Republic (SADR) they are effectively under their own constitution and laws. At the present time they are composed of an institutional center (Rabouni), this comprising the ministries and central administration, and five *wilayas* (districts): Awserd, Boujador, Dakhla, Laayoune and Smara. The *wilayas* are divided administratively into 29 *dairas* (municipalities). Although the management of the SCR is the responsibility of the Sahrawi government through its administrative structures, international assistance has been essential in keeping the Sahrawi population alive and guaranteeing its basic needs for more than 40 years of exile. The coordination of such aid falls within the auspices of the United Nations High Commissioner for Refugees (UNHCR).

Water–Sanitation–Hygiene (WASH) remains vital for the 2030 Agenda for Sustainable Development, including SDG 6, which focuses on ensuring the availability and sustainable management of water and sanitation for all. In African countries, the fulfilling of SDG 6 is at different states of accomplishment (Nhamo et al., 2019). In order to achieve equitable access to WASH services, the most vulnerable and disadvantaged segments of the population have to be considered, but important knowledge gaps still remain with respect to identifying their specific barriers and needs (Ezbakhe et al., 2019). In forced displacement conditions, environmental health provisions such as adequate water supply and excreta management, are among those essential services (Behnke et al., 2020; Shackelford et al., 2020).

Drinking water provision has been a challenge from the early days of the refugee situation in the Algerian *Hammada*, a desert of barren, hard, rocky plateaus with very little sand. Initially, in 1975, the water supply adopted involved an emergency approach, in that a rapid return to Western Sahara was envisaged for the population. This consisted of manually dug wells with an uptake of shallow groundwater, located in the vicinity of homes, plus superficial ponds dug in Laayoune and Dakhla. Water quality was originally good, although contamination was the main risk, and water quantity was seriously limited. In 1994, heavy rains caused significant floods that led to an epidemic of cholera in Laayoune due to the lack of a sanitation system. This forced the closure of family wells, and a change in the approach to water management (Vivar et al., 2016). Deep wells were drilled and pumped water was distributed by tanker trucks to the camps. Moreover, the start-up of chlorination systems and bacteriological monitoring was initiated. This supply system improved the safety of drinking water but decrease the water allocation to 7 L/person/day, which is significantly below the standard of 15 L/person/day of drinking water for emergencies established by the WHO (2011a).

In the late 1990s the refugee population increased, while a political solution to the conflict still seemed very far off. The Sahrawi authorities and the UNHCR decided to take steps to improve the water system, always bearing in mind that any type of infrastructure must be portable, in order to be transported to Western Sahara once the conflict was resolved. A Water Supply Master Plan was drawn up in 2001, funded by ECHO and with the technical support of the Spanish NGO Solidaridad International Andalucía, and the Andalusian public water management enterprise Aguas del Huesna Consortium (SIA, 2001). That plan included the drilling of deep boreholes (~100 m deep), the installation of osmosis plants, and the gradual replacement of water trucking with a pipeline network. A second plan, the Water and Sanitation Strategy 2011–2016, was developed in 2010 by water sector stakeholders at the refugee camps: beneficiaries, the Ministry of Water and Environment, several funders, and NGOs. Within the framework of these plans, a group of numerous international institutions (UNHCR, Spanish regional governments, universities, NGOs, etc.) have been jointly working to improve the drinking water supply system. The first water supply network was built in Dakhla in 2002. It includes 95 water points (taps). Awserd and Smara water supply networks followed in 2003 and 2004, respectively. Hydrogeology and Water Quality Units were created in

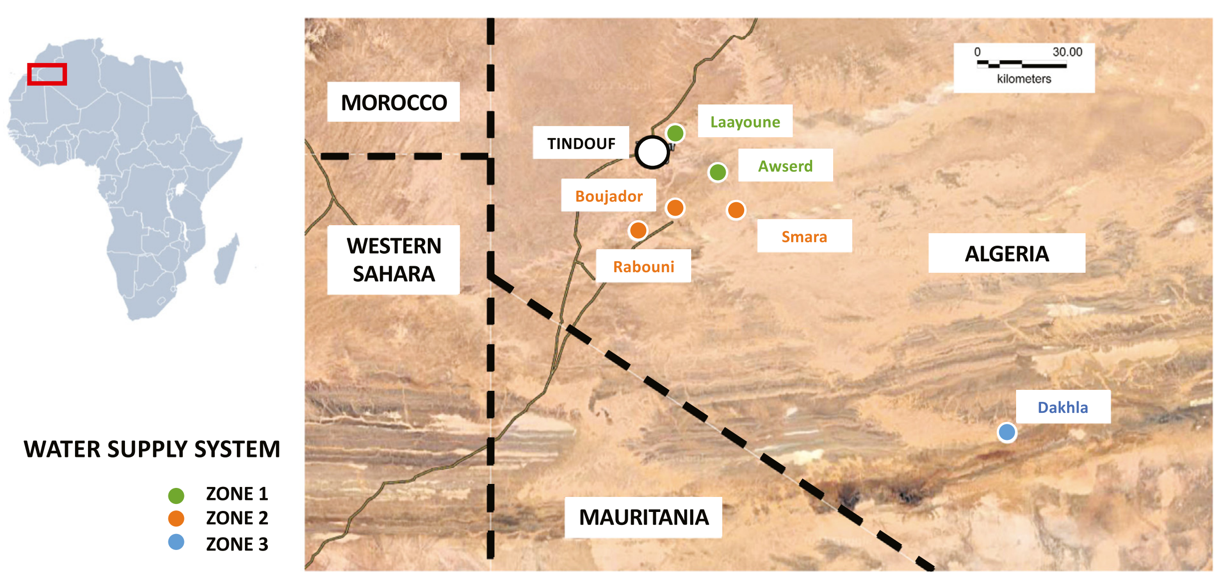

Fig. 1. Location of the Sahrawi refugee camps in the surroundings of the Algerian city of Tindouf. The division of the *wilayas* into three zones for the drinking water supply is indicated.

2004 within the Water and Environment Ministry, aiming at suitable management of the groundwater resources and the monitoring of physico-chemical and microbiological water quality, respectively. Water supply system complexity and extreme conditions made it necessary to produce a Water Safety Plan in 2014, this with the aim of guaranteeing the appropriate allocation and quality of water (García et al., 2018). The plan establishes control mechanisms to minimize risk impacts, which are compiled in action protocols for infrastructures and water quality monitoring. Such protocols have begun to be applied since the end of 2014.

This article assesses the quantity of drinking water supplied to the population, the evolution of the physico-chemical and microbiological quality of the raw water and the drinking water in the SRCs between 2006 and 2016 and the role of the desalination plants in the water supply system. The present work aims the long-term evolution of groundwater and supplied water quality to determine if the water resources management strategy carried out in camps affects to the raw water physico-chemical properties. The study is based on previously available information and on new data of drinking water allocation and quality presented here. Lastly, this work also stablishes baseline reference status of the drinking water provision and quality for subsequent works to be developed at the area.

2. Description of the study area

The refugee camps are located in the *Hammada* of Tindouf (Algeria) at an altitude of 350–400 m, except for Dakhla *wilaya* which is located in an oasis at 200 km to the south and at an altitude of 300 m. The topography is very smooth, formed by wide plains of rocky desert crossed by ephemeral streams, called *wadis*, which also flow into ephemeral lagoons, called *sebkhas*.

The world climate classification by Strahler and Strahler (1989) includes the study area as a desertic climate. It is characterized by warm temperatures and scarce and very irregular precipitation. Temperatures exceed 50 °C in summer and drop rapidly after midday. Torrential precipitations lasting a few days occur once every few years. Average annual precipitation is less than 100 mm (Docampo and Molinero, 2006).

Geologically, the study area is located in the Paleozoic Basin of Tindouf, which was developed as a marginal cratonic basin in the Precambrian-Devonian, accumulating a maximum thickness of mainly detrictic sediments of about 7 km (Traut et al., 1991). The geological structure of the Tindouf Basin is an asymmetrical syncline, and the southern area, where the refugee camps are located, is practically horizontal. The episodes of Palezoic sedimentation ended at the end of the Carboniferous (Traut et al., 1991). Since then, the Tindouf basin has mainly been in an erosive state, although there are small records of Mesozoic and Tertiary sedimentary episodes. The thickness of post-Paleozoic sediments can reach 300 m (Ratschillar, 1970), but is generally smaller than 170 m (Traut et al., 1991). Mesozoic sediments are a succession of conglomerates and sandstones interspersed with reddish clays. Neogenous sediments are found on the top of these, formed by conglomerates and sandstones interspersed with sandy limestones.

Docampo (2006) carried out a hydrogeological study of the area, in which at least four different aquifers were found to exist:

1) A detritic aquifer of Tertiary sandstones in the *Hammada* of Tindouf, near Laayoune. The estimated average thickness of the aquifer is 30 m. According to hydraulic tests performed, its transmissivity is 4 m^2/d and the storage coefficient is 0.06 m^3/m^3 (Docampo, 2006).
2) The carbonated aquifer of *Sebkha Abdalla* in Rabouni which consist of dolomitized limestones from the Carboniferous forming a well-developed karstic system. The average thickness of the aquifer is estimated at 20 m. According to hydraulic tests performed, its transmissivity is between 15 and 17 m^2/d and has a storage coefficient of 0.1 m^3/m^3 (Docampo, 2006; Molinero and Ron, 2016).
3) The shallow aquifer of Dakhla formed by superficial sand and sandstones. It is responsible for the existence of an ancient oasis and contains a very large volume of water. However, this aquifer is highly polluted because of the lack of a sanitation system and authorities advise against the consumption of the groundwater here.
4) The deep aquifer of Dakhla in Devonian sandstones, which is very productive. There is no available estimate of the hydrogeological parameters of this aquifer.

The exact volume of the aquifers is unknown. However, an estimate of the groundwater resources was performed for those in the *Hammada* of Tindouf and *Sebkha Abdalla*, for which hydrogeological parameters are known at a local scale, that is, considering circular areas with a radius of 30 km in which all the boreholes are located. The estimated volume of groundwater is ~5600 hm^3 for the aquifer in *Sebkha Abdalla* and ~ 5000 hm^3 for that in the *Hammada* of Tindouf (Docampo, 2006). Therefore, local reserves are huge in comparison to estimated consumption for drinking water supply and irrigation, which is less than 2 hm^3/y.

3. The drinking water supply system

The drinking water supply system of the SRCs is divided into three zones, each of them using a different groundwater source: (i) Zone 1 supplies drinking water to the *wilayas* of Laayoune and Awserd in the North, (ii) Zone 2 supplies drinking water to the *wilayas* of Smara and Boujador and the institutional center of Rabouni, and, (iii) Zone 3 supplies drinking water to the *wilaya* of Dakhla, located 120 km to the south of Rabouni.

3.1. Zone 1: Laayoune and Awserd water supply system

This part of the system pumps groundwater from the aquifer in the *Hammada* of Tindouf by means of 7 deep wells (HT12, HT13, GL01, GL02, GL03, GL06 and GL08). Flow rates pumped in each well range from 0.5 to 5 L/s, totaling some 24 L/s in 2016 (Molinero and Ron, 2016). Raw water is saline, with electrical conductivities reaching 2200 μs/cm, and measured fluoride and nitrate concentrations exceed the parametric values established by both WHO recommendations (WHO, 2011) and Algerian regulations (Algeria, 2011). Since 2014, a reverse osmosis plant has been working which demineralizes water by pumping it through semi-permeable membranes. During this osmosis, more than 30% of the water volume is rejected. The brine discharge from the osmosis is used to manufacture adobe bricks for building construction.

Available raw water volume is not sufficient for supplying treated water continuously. Therefore, each *wilaya* receives treated water for 20 days and raw water for a subsequent 20 days, in turns. Raw and osmosed water flows from regulation reservoirs to the distribution reservoir of Laayoune (Fig. 2). From there, a high pressure 25 km long pipeline transports water to the distribution reservoir at the Awserd camp. The distribution network of Awserd *wilaya* supplies water to the community water points (taps) provided with two outlets. One of these is connected to a flexible hose of about 150 m, allowing for the filling of domestic cisterns (1–2 m^3). The other outlet connects a small flexible tube for the filling of 20 L cans. In addition, the network includes recharge points for tanker trucks which supply those areas which are not connected to the network. Water distribution in Laayoune is performed wholly by means of tanker trucks.

3.2. Zone 2: Smara, Boujador and Rabouni water supply system

This part of the system pumps groundwater from the aquifer in *Sebkha Abdalla*. In 2016, the system had two wells, SA-10 and SA-11, these being between 70 and 100 m deep. Total pumped flow rate was about 20 L/s (Molinero and Ron, 2016). Raw water is even more saline than that of Zone 1, with electrical conductivities of ~4000 μs/cm, and

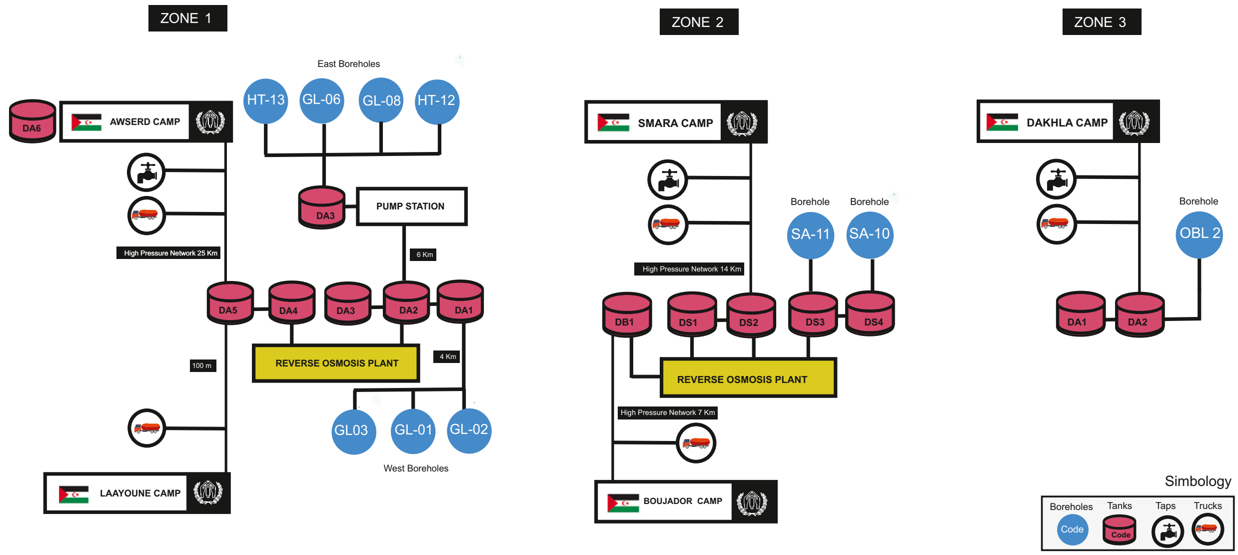

Fig. 2. Sahrawi refugee camps' drinking water supply systems in 2016 in Zone 1 (El Aiun and Awserd), Zone 2 (Smara, Rabouni and Boujador) and Zone 3 (Dakhla) including boreholes (circles), reservoirs (cylinders), reverse osmosis plants and recharge points for tanker trucks.

measured fluoride and nitrate concentrations exceeding the parametric values. Hence, since 2006 all the raw water has been treated by a reverse osmosis plant. Brine rejection is discharged directly to a small shallow pond located 1 km from the boreholes. Vegetation has grown in the area for camel grazing. Rejected water is not expected to affect to water supply boreholes quality.

Osmosed water is distributed from the reservoirs to community water points and the recharge points for tanker trucks (Fig. 2). In 2017 the system was improved, increasing the supplied water volume by building a new well and connecting an additional reverse osmosis plant.

3.3. Zone 3: Dakhla water supply system

Only one well in the deep aquifer of Dakhla supplies water to Zone 3. The water has a high level of salinity but is acceptable for human consumption according to the regulations (Algeria, 2011; WHO, 2011). Thus, after chlorination it is directly distributed, without any additional treatment, to the community water points and the recharge points for tanker trucks.

Although there are more than 450 taps in the whole water supply system, coverage of the low pressure network reaches only around the 50% of the population, the rest being supplied by water trucking.

4. Supplied water volume

The UNHCR estimates that the average supplied water volume per person and per day in 2001 in the SRCs was between 5 and 7 L. Docampo (2006) estimated the annual average supplied water volume from 2003 to 2005 from data collected through interviews with Saharawi Hydraulic Department technicians on the volumes pumped from wells and assuming a total population in the camps of 200,000 people. According to these calculations, there was a clear increase in water allocations from 5 L/day/person in 2003 to about 13 L/day/person in 2005, as a result of international cooperation projects for the construction and improvement of supply networks.

Pumped raw water and treated water volumes have been systematically monitored from 2014 in the three zones of the supply system. Flowmeters are located in the outlets of each pumping well and reverse osmosis plant. We might note here that each 65 m^3 of osmosed water requires approximately 100 m^3 of raw water for its production, that is, more than 30% is rejected during treatment.

Fig. 3 shows the monthly supplied water volume in 2016 by the complete supply system and each of its zones. The total volume of supplied water in the SRCs in 2016 was nearly 0.95 hm^3, representing an average monthly volume of 79,000 m^3. The supplied water volume

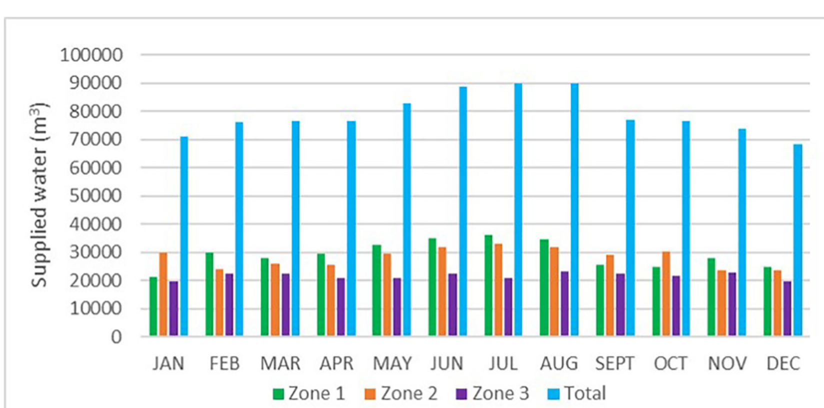

Fig. 3. Monthly supplied water volume in the Sahrawi refugee camps in 2016.

changes seasonally with monthly volumes about 40% larger in summer than those in winter.

Network losses due to leakage account for 3 to 6% of the total supplied water volume (García et al., 2018). Services, livestock and brick kilns consumption account for 6–8%, 5–10% and 5–12% of that water volume, respectively. Therefore, only between 67 and 81% of the total supplied water volume is used for human consumption.

The calculation of the supplied water volume by inhabitant requires population data. The number of Sahrawi refugees in the Tindouf camps is disputed and politically sensitive because of its relevance in the possible event of a referendum to determine Western Sahara's future status. Algerian and Saharawi authorities have historically estimated the number of refugees to be 165,000 (UNHCR, 2010). Several population estimates between 90,000 and 165,000 inhabitants were considered as a planning figure by the UNHCR and the World Food Program (WFP) up to 2006 (UNHCR, 2018). From 2007 to 2017, a constant population of 125,000 refugees, with 90,000 most vulnerable individuals, was assumed by the UNHCR and the WFP, despite the growth rate of the population. The UNHCR (2018) updated the estimated population of the Sahrawi refugees living in the camps in Tindouf to 173,600 inhabitants on December 31st, 2017. This figure is a conservative one, to be used strictly for humanitarian purposes in the camps.

The quantity of water supplied to the Saharawi refugees for human consumption was between 14 and 17 L/person/day on average in 2016, considering a population of 125,000 inhabitants, once network losses and other consumption had been discounted. There were significant differences between the quantity of water supplied to each zone of the network. The volume was greatest for the *wilaya* of Dakhla (Zone 3), exceeding 27 L/person/day, and was of 10–12 and 14–17 L/person/day for Zones 1 and 2, respectively.

All humanitarian agency guidelines stress that between 15 and 20 L/person/day of water is the minimum needed in camp situations (Cronin et al., 2008). The strategic objective of the Sahrawi government is to achieve an allocation of 20 L/person/day. According to recent population estimates, that objective was only achieved in Dakhla in 2016. This situation, below recommended standards, is similar to that of other refugee camps. Cronin et al. (2008) reported supplied water volumes of less than 15 L/person/day in Mozambique, and Bruinjn (2009) reported an average water availability of 14 L/person/day in the refugee camps of Uganda. A similar situation is reported in the Kakuma refugee camp in Kenya, with distribution of between 8 and 17 L/person/day (Shultz et al., 2009).

Molinero and Ron (2016) conducted a hydrogeological study to assess the performance and productivity of the wells of Zones 1 and 2. They concluded that the pumping rates of wells in Zone 2 (SA-10 and SA-11) could be increased from 20 to 35 L/s by changing the pumps, increasing water production by 80%. They also recommend a slight increase in the pumping rates of wells HT-12, HT-13, GL-1, GL-2 and GL-3 in Zone 1, and the cessation of water extraction from wells GL-6 and GL-8 to reduce the large amount of silt and sand that ends up in the reverse osmosis plants, affecting their performance. It is expected that, on the implementation of the recommendations of Molinero and Ron's (2016) study and the planned drilling of a new well in Zone 2 (SA-12), the volume of water supplied to the SRCs will be seen to have increased from 2017 onwards.

5. Water quality

5.1. Water quality monitoring

The control of drinking water quality in the SRCs is governed by Algerian law. Executive Decree no 9–414 of 15/12/2009 establishes the sanitary criteria for drinking water, fixing the type, frequency and methods of analysis of the water in Algerian territory. Executive Decree no. 11–125 of 22/03/2011 sets the parametric values of the quality parameters for water (Algeria, 2011). Sampling preservation and handling procedures are based on ISO 5667-3 guidelines (ISO, 2018). Conversely, working in Sahrawi refugee camp conditions involves some technical limitations: (1) The lack of certified laboratories; (2) The difficulty in supplying reagents; (3) The absence of qualified, motivated and regularly remunerated local technicians. García (2014) defined a monitoring program for the control of drinking water quality within the framework of the SADR Water Safety Plan (García et al., 2018), which establishes a compromise between Algerian regulations and existing limitations. This program has been progressively implemented since 2014 by the Sahrawi administration, and includes:

a) Typical preventive maintenance control measures affecting all installations: networks, plants, tanks, trucks and taps
b) Daily analyses of total and residual chlorine at defined sampling points throughout the whole system
c) Daily analyses of conductivity and pH at the outlet of the osmosis plant
d) Analysis of microbiological parameters of water samples taken periodically from tanks and truck recharge points performed in their own water quality laboratory
e) Annual controls to study the evolution of the physico-chemical quality of raw water and the performance of the reverse osmosis plants. Water samples should be taken in all the pumping wells of the supply system and at the outlet of the reverse osmosis plants, and sent in an appropriate form to certified laboratories abroad.

Within the framework of this systematic water quality monitoring program established in the SADR Water Safety Plan, we will present here the results of the physico-chemical analyses performed on raw water samples from all the wells of the water supply system and on treated water samples taken at the outlet of the osmosis plants in 2014 and 2016. After 2016, the Sahrawi Administration maintains the monitoring program with the support of international organizations.

Prior to 2014, water quality monitoring was not performed in a systematic way. Physico-chemical analyses were generally undertaken by foreign parties carrying out studies on the quality of drinking water (Docampo, 2006; García-Lopez, 2009) or as part of epidemiological studies (Pezzino et al., 1998; Díaz-Cadórniga et al., 2003; SMH/NCA/AUC, 2008; Henjum et al., 2010, 2011; Grewal, 2011; Barikmo et al., 2011; Aakre et al., 2015, 2018).

Docampo (2006) conducted a hydrogeological study of the area including the characterization of the physico-chemical composition of groundwater used for human consumption. Physico-chemical analyses of drinking water samples taken in 2000 from 2 wells, in 2001 from 18 wells, and in 2004 from 15 wells were performed. These wells covered all the study area, allowing thus a characterization of the quality of the groundwater of the different aquifers. However, most of these are currently not included in the drinking water supply system. The results of the analyses performed on samples taken from wells HT13, SA10 and OBL2 of the supply system in 2004 (Docampo, 2006) are considered a reference for drinking water quality in 2006 of Zones 1, 2 and 3, respectively.

In 2008, the NGO Ingeniería Sin Fronteras and the University of A Coruña carried out a field work campaign in which raw water samples were taken from wells and sent to a Spanish laboratory in order to study groundwater quality evolution. Samples included those taken from wells GL01, HT12 and HT13 of Zone 1, SA11 of Zone 2 and OBL2 of Zone 3. In 2009, the NGO Solidaridad Internacional Andalucía and the enterprise Consorcio de Aguas del Huesna conducted a new campaign in which samples were taken from wells GL01, HT12 and HT13 of Zone 1 and OBL2 of Zone 3. The results of the physico-chemical analyses have not previously been published. García-Lopez (2009) presented a hydrogeological characterization of the superficial and deep aquifers of Dakhla, including the results of physico-chemical analysis of a water sample taken at pumping well OBL2.

In terms of epidemiological studies, Díaz-Cadórniga et al. (2003) reported average measured concentrations of iodide and fluoride in drinking water of 235 μg/L and 1.65 mg/L, respectively, within a study on endemic goiter. From 1995 to 2000, they measured iodide concentrations of between 180 and 400 μg/L and fluoride concentrations between 0.7 and 1.5 mg/L. Pezzino et al. (1998) reported iodine concentrations in drinking water of 934 μg/L in Laayoune, 724 μg/L in Rabouni, and 259 μg/L in Dakhla.

A research team from Akershus University College (Norway) has published results of water analyses carried out within studies of excessive iodine intake by the Saharawi population, performed in collaboration with the Sahrawi Ministry of Health. The iodine concentration measured in 2007 on 92 samples of household drinking water ranged between 55 and 545 μg/L (Henjum et al., 2010, 2011; Henjum, 2011). Average measured iodide concentrations were 300 μg/L in Laayoune and Awserd, 87 μg/L in Smara, and 70 μg/L in Dakhla (Barikmo et al., 2011; SMH/NCA/AUC, 2008). The authors published the results of physico-chemical analyses of 12 drinking water samples, which included samples taken from 5 wells of the supply system and a sample taken from the Smara osmosis plant in 2007 (SMH/NCA/AUC, 2008). Grewal (2011) reported measured iodine concentrations in supplied drinking water of 267 μg/L for Laayoune, 236 μg/L for Awserd, 90 μg/L for Smara and 76 μg/L for Dakhla. A study conducted in 2013 analyzed 12 samples of supplied water in high iodine areas (treated water of Zones 2 and 3) plus 12 samples in very high iodine areas (partially treated water of Zone 1), obtaining average iodide concentrations equal to 80 μg/L and 254 μg/L, respectively (Aakre et al., 2015). Aakre et al. (2018) also published average water composition for those two high iodine and very high iodine areas.

A research team from the University of Jaén and IMDEA Water performed a study on drinking water access in health institutions in the camps in 2015 (Vivar et al., 2016). It includes physico-chemical analyses on water samples taken from well GL01 and at the outlet of the Laayoune reverse osmosis plant in Zone 1, at the inlet and the outlet of the Smara reverse osmosis plant in Zone 2, and from well OBL2 in Zone 3. Pichel and Vivar et al. (2016) also present a review of iodine concentration in drinking water at the supply system and household levels.

Sending water samples outside the SRCs to be analyzed in certified laboratories is complicated due to limited resources and logistical difficulties. Nevertheless, in recent years a significant number of samples have been gathered which provide reliable information on water quality. Those data have helped to track the evolution of groundwater and supplied water quality and to assess the sustainability of the supply system. Table 1 lists the sources of physico-chemical data considered in this study for the assessment of water quality of the supplied drinking water in the SRCs from 2006 to 2016. It includes for each set of data: (1) The organizations which performed the study; (2) The references, where data have been previously published; (3) The certified laboratory in which the analyses were performed; (4) The year when the sampling was performed; and (5) The sampling points within the supply system. In unpublished data sources, sampling preservation and handling procedures are based on ISO 5667-3 standards (ISO, 2018). The water quality data from 2004 (Docampo, 2006) have been included because they

Table 1
List of sources of physico-chemical data considered for the assessment of water quality of the supplied drinking water in the Sahrawi refugee camps between 2006 and 2016. It includes, for each set of data: (1) The organizations which performed the study; (2) The references, where data have previously been published; (3) The laboratory in which the analyses were performed; (4) The year in which the sampling was performed; and (5) The sampling points within the supply system.

Organizations and references	Laboratory	Year	ID	Sampling points											
				Wells Z1							Osmosis Z1	Wells Z2		Osmosis Z2	Z3
				GL01	GL02	GL03	GL06	GL08	HT12	HT13		SA10	SA11		OBL02
Universidad de Santiago de Compostela (USC) & Ingeniería Sin Fronteras (ISF) *Docampo et al. (2006)*	SAI-UDC (A Coruña, Spain)	2004	a							■		■			■
Ministero De Salud Publica de la RASD, Norwegian Church Aid & Akershus University College. *SMH/NCA/AUC, 2008*	NIRU Tygerberg (Cape Town, South Africa)	2007	b	■					■	■		■		■	■
Universidad de A Coruña (UDC) & Ingeniería Sin Fronteras (ISF) *Unpublished data*	SAI-UDC (A Coruña, Spain)	2008	c	■					■	■			■		■
Universidad Complutense de Madrid (UCM) *García-López, C. (2009)*	UCM (Madrid, Spain)	2009	d												■
Solidaridad Internacional Andalucía (SIA) & Consorcio de Aguas del Huesna (AHC) *Unpublished data*	Las Chimeneas (Seville, Spain)	2009	e	■					■	■					■
Solidaridad Internacional Andalucía (SIA) Consorcio de Aguas del Huesna (AHC) & Ingeniería Sin Fronteras (ISF) *Unpublished data*	Labygema (Seville, Spain)	2014	f	■	■	■	■	■	■	■	■	■	■	■	■
Instituto Madrileño de Estudios Avanzados (IMDEA) [(2)] *Vivar et al. (2006)*	IMDEA (Madrid, Spain)	2015	g	■							■	■	■	■	■
Solidaridad Internacional Andalucía (SIA) Consorcio de Aguas del Huesna (AHC) & Ingeniería Sin Fronteras (ISF) *Unpublished data*	Labygema (Seville, Spain)	2016	h	■	■	■		■	■	■		■	■	■	■

have been taken as a reference for the initial conditions of groundwater in the period 2006–2016. All available data which have not been included in the analyzed set of data, such as data from iodine intake studies, are within the range of those included.

5.2. Raw water quality 2006–2016

Tables 2 and 3 present the results of the physico-chemical analyses performed on samples of raw water taken from the pumping wells of the drinking water supply system between 2004 and 2016 for Zone 1 and Zone 2–3, respectively. As noted above, parameter values measured in 2004 are taken as a reference for the initial conditions of groundwater during the period 2006–2016. The values of the parameters exceeding the parametric values established in Algerian legislation (Algeria, 2011) have also been indicated. Besides the parametric compliance with the Algerian laws of the different water quality parameters, the following analysis is also focused in the evaluation of the possible sources of groundwater pollution and the temporal evolution of the water quality. Both aspects are relevant for the definition of a sustainable exploitation of groundwater strategy.

The groundwater in the study area has an average temperature of about 26 °C. According to Bogomolov's (1966) classification, it is moderately warm water. Measured pH ranges from 6.8 to 8.7, and hence the groundwater can be considered from neutral to slightly alkaline. Sections 5.2.1–5.2.5 present raw water data quality related with the electrical conductivity, major anions, major cations, trace metals and bacteriological contamination, respectively.

5.2.1. Electrical conductivity

High electrical conductivities have been measured on samples of all the pumping wells between 2006 and 2016, showing different ranges for each zone (Fig. 4). Measured conductivity in Zone 1, Laayoune and Awserd, ranges from 1890 to 2740 μs/cm. Measured conductivities in Zone 2 are significantly higher than those of Zone 1, and are above 3600 μs/cm. Conversely, the lowest conductivities are measured in Dakhla (Zone 3), with a maximum of 1650 μs/cm. Such differences are related mainly to differences in geology (carbonated, detritic or sandstone aquifers) and infiltration areas, given the relevance of high evaporation rates in desert climates on salt accumulation in recharge. However, no clear trend of increases or decreases in conductivity is observed over time in the studied period.

The WHO does not establish a parametric value of electric conductivity as harmful for human consumption (WHO, 2011). Nevertheless, it is a parameter that affects the quality of the water by modifying its taste. Algerian regulations establish a maximum value of 2800 μs/cm for drinking water (Algeria, 2011). Thus, raw water from wells of Zone 2 (SA10 and SA11) do not meet this quality requirement. However, high water conductivity is also a problem in the other two zones. Complaints from the population about the taste of water are very common, especially in relation to the taste of tea made from supplied water. The cultural importance of tea has led to a portion of the population consuming bottled water and groundwater from shallow aquifers, the latter having been officially closed by authorities due to their unhealthy conditions.

5.2.2. Major anions

The measured chloride and nitrate concentrations also show the highest concentrations in Zone 2 and the lowest in Zone 3 (Fig. 4). Chloride concentration ranges from 292 to 450 mg/L in Zone 1, from 700 to nearly 900 mg/L in Zone 2, and below 350 mg/L in Zone 3. Concentrations above 300 mg/L give water a salty taste. Algerian regulations establish a maximum concentration of 500 mg/L for drinking water (Algeria, 2011). Therefore, measured chloride concentrations in the two wells of Zone 2 exceed the parametric value.

Chloride is deposited on the desert ground surface in windblown fallout and precipitation. It then moves into the soil profile along with infiltrating precipitation. Chloride concentrations increase in soil with depth because of progressive evaporation and water extraction by plant roots (Walvoord et al., 2003). During occasional deep-wetting events, it leaches from the soil pool to the subsoil, where the sustained absence of downward water movement has enabled its accumulation for thousands of years (Phillips, 1994). The arrival of chloride in deep aquifers would require the washing of those reservoirs into the unsaturated zone and their transport to the aquifers. Therefore, an alternation would be necessary of hyper-arid periods (when chloride accumulates in the unsaturated zone) with more humid periods, this explaining the dissolution of the salts by the recharge waters and their transport to the aquifer. Since chloride is conservative, a chloride mass balance provides an estimate of the time scales over which conditions required for solute accumulation have been maintained. Estimated accumulation time from chloride inventories for desert sites range from 10,000 to 16,000 years in the southwestern of USA (Phillips, 1994; Walvoord et al., 2002), when a well-documented paleoclimate transition from cool and wet conditions to warmer and drier ones occurred (Benson et al., 1990; Morrison, 1991; Phillips et al., 1992; Allen and Anderson, 1993). In the study area, the hypothesis of a similar phenomenon is reinforced by evidence of geologically recent wet periods (Gasse, 1999; Zuppi and Sacchi, 2004; Soler et al., 1999) and by isotopic determinations which indicate that the episodes of recharge of the deep aquifers studied occurred in milder climatic conditions than the current ones (Docampo and Molinero, 2006). Although the presence of other processes, such as biochemical pathways, makes other species transport much more complex than chloride transport, the subsoil input histories, transport behavior and accumulation times, are likely to be quite similar (Walvoord et al., 2003).

The reference value for nitrate concentration in Algeria regulations (Algeria, 2011) and WHO guidelines (WHO, 2011) for drinking water is 50 mg/L. This concentration is exceeded by groundwater of the wells in Zone 1, where measured nitrate concentrations range between 71 and 110 mg/L, and in Zone 2, where they are above 120 mg/L. Measured nitrate concentrations in Zone 3 are below 10 mg/L. Excessive nitrate intake is related to methemoglobinemia (baby blue disorder), miscarriages, a increased risk of cancer (bladder cancer, ovarian cancer) and non-Hodgkin's lymphoma (Canter, 1997; Nolan and Stoner, 2000; Ward et al., 2005).

Natural pristine groundwater seldom exceeds nitrate concentrations of a few mg/L and therefore high nitrate concentration is in general an indicator of the existence of pollution episodes (Custodio and Llamas, 1983; Kendall et al., 2007; Stadler et al., 2008; Gutiérrez et al., 2018). Nitrate generally arises from the decomposition of organic matter (Böhlke, 2002), from losses in the sanitation system (Zhang et al., 2014; Shalev et al., 2016), from pastoralism (Stadler et al., 2008; Abdesselam et al., 2013), from the application of fertilizer in agricultural activities (Jalali, 2005; Ó Dochartaigh et al., 2010; Charfi et al., 2013; Gutiérrez et al., 2018) and, to a very small extent, from atmospheric deposition (Michalski et al., 2004b). Docampo and Molinero (2006) measured high nitrate concentrations correlated with the concentration of coliforms in the shallow aquifer of Dahkla, indicating that these nitrates originate from fecal contamination which reaches the aquifer. The lack of evidence of microbiological contamination in wells of Zones 1 and 2 where nitrate concentrations are higher, the depth to which aquifers are located, the existence of clayey-silty confining levels above the aquifers, and the low levels of agricultural and industrial activity, all lead to the assumption that high nitrate concentrations are of natural origin (Docampo, 2006).

The existence of high concentrations of natural nitrates in groundwater is relatively common in areas with hyper-arid climatic characteristics. High salinity and high nitrate concentrations in groundwater of sandstone aquifers were measured in Algeria by Guendouz et al. (1997), Moulla et al. (2012) and Hakimi et al. (2021), in Libya by Edmunds et al. (2003), in Tunisia by Hamed et al. (2013) and in Egypt by Zuppi and Sacchi (2004). Böhlke et al. (1997) reported significant

Table 2
Summary of the results of the phisico-chemical analyses performed between 2004 and 2016 on samples of raw water taken from the pumping wells of Zone 1 of the water supply system and treated water taken at the outlet of the reverse osmosis plant of Laayoune. Values of parameters exceeding the parametric values established in Algerian legislation have been shaded. Sources: (a) Docampo (2006); (b) SMH/NCA/AUC (2008); (d) García-Lopez (2009); (g) Vivar et al. (2016); (c,e,f,h) Unpublished data. Details of the data sources can be consulted in Table 1.

Parameter		Pumping wells of Zone 1: GL01						GL02		GL03		GL06	GL08		HT12					HT13						Reverse osmosis plant outlet (Zone 1)		
	Year	2007	2008	2009	2014	2015	2016	2014	2016	2014	2016	2014	2014	2016	2007	2008	2009	2014	2016	2004	2007	2008	2009	2014	2016	2014	2015	2016
	Source	b	c	e	f	g	h	f	h	f	h	f	f	h	b	c	e	f	h	a	b	c	e	f	h	f	g	h
pH	-	8.2	8.3	7.4	7.2	7.8	7.5	7.2	6.9	7.1	7.3	7.2	7.3	7.3	8.1	8.7	7.5	7.3	6.9	7.5	8.3	8.7	7.2	6.8	6.9	-	7.5	7.5
Conductivity	μS/cm	2190	2014	1948	1953	2130	2015	2040	2383	1890	2009	2127	2194	2174	2240	2180	2110	2006	1948	2540	2740	2220	2200	2323	2141	452	309	356
TDS	mg/l	-	-	-	1364	815	1494	1436	1795	1284	1497	1372	1512	1632	-	-	-	1558	1667	1270	-	-	-	1996	1493	-	-	80
Alkalinity	mg/l $CaCO_3$	-	-	-	283	312	298	273	297	243	301	223	225	251	-	-	-	468	293	-	-	-	-	340	253	-	42	32
HCO_3^-	mg/l	-	-	-	344	381	-	337	-	296	-	272	274	-	-	-	-	571	-	-	-	-	-	415		-	42	39
Hardness	mg/l	-	-	-	855	-	672	755	568	674	697	765	875	800	-	-	-	754	526	-	-	-	-	875	489	-	-	-
Fluoride	mg/l	1.95	2.27	2.25	2.10	1.95	2.27	2.22	2.04	1.70	1.74	1.73	1.81	1.81	1.90	2.05	2.15	2.03	1.99	2.03	2.15	1.98	2.57	2.34	2.09	0.20	0.23	0.12
Chloride	mg/l	294	292	315	343	316	317	319	419	330	333	425	425	313	306	330	370	402	356	369	396	402	450	327	346	161	49.9	48.6
Nitrite	mg/l	-	< 2.5	-	<0.3	-	<3.2	<0.3	<3.2	<0.3	<3.2	<0.3	<0.3	<3.2	-	< 2.5	-	<0.3	<3.2	<0.5	-	< 2.5	-	<0.3	<3.2	<0.34	-	<0.1
Nitrate	mg/l	70.9	78.6	72.0	73.0	73.0	-	80.0	93.0	75.0	-	110.0	107.0	102.0	70.9	80.0	75.0	77.0	79.0	87.1	90.8	94.7	87.0	93.0	95.0	26.0	39.8	15.9
Phosphate	mg/l	5.0	< 2.5	-	-	-	-	-	-	-	-	-	-	-	3.0	< 2.5	-	-	-	<0.55	2.0	< 2.5	-	-	-	-	-	-
Sulfate	mg/l	316	345	-	>160	354.4	330	>160	454	>160	354	<160	<161	512	346	382	-	>160	375	491	463	540	-	123	524	-	8.54	21.3
Sodium	mg/l	211	231	191	215	218	203	240	228	211	191	229	232	232	214	235	199	228	191	272	282	330	254	298	186	61	57	36
Ammonium	mg/l	-	0.04	<0.2	<0.8	-	-	<0.8	-	<0.8	-	<0.8	<0.8	-	-	0.03	-	-	-	0.12	-	0.03	-	<0.8	-	<0.4	0.17	-
Potassium	mg/l	-	8.80	9.10	9.21	11.3	-	9.71	-	8.84	-	12.6	12.2	-	-	9.35	9.90	9.61	-	<17	-	9.81	10.0	10.2	-	-	1.93	1.2
Magnesium	mg/l	80.9	88.0	-	127.0	84.5	106.0	124.0	93.0	87.9	87.0	80.0	109.0	103.0	83.1	92.0	-	96.4	95.0	94.1	101.0	91.0	-	122.0	53.0	-	3.0	3.4
Calcium	mg/l $CaCO_3$	130	138	-	133	140	135	105	134	135	125	173	171	-	138	149	128	143	116	102	151	159	130	149	143	-	5	9
Iodide	μg/l	261	-	-	142	-	-	136	-	135	-	184	164	-	294	-	-	139	-	-	261	-	-	216	-	-	-	-
Silicium	mg/l	19.7	20.1	-	-	-	-	-	-	-	-	-	-	-	17.4	18.1	-	-	-	18.2	17.8	22.4	-	-	-	-	-	-
Chrome	μg/l	-	2.5	-	-	2.1	-	-	-	-	-	-	-	-	-	3.7	-	-	-	2.5	-	2.2	-	-	-	<1	0.4	0.2
Manganese	μg/l	<0.30	10.50	-	2.88	2.49	-	1.53	-	1.39	-	13.10	5.83	-	<0.30	0.57	-	9.61	-	3.70	<0.30	0.36	-	<1	-	<1	0.16	0.66
Nickel	μg/l	-	0.51	-	-	1.66	-	-	-	-	-	-	-	-	-	0.45	-	-	-	2.20	-	0.44	-	-	-	<1	0.83	1.24
Cadmium	μg/l	-	0.03	-	-	2.48	-	-	-	-	-	-	-	-	-	0.04	-	-	-	<0.1	-	0.05	-	-	-	<0.02	0.08	0.02
Mercury	μg/l	-	<0.15	-	<0.02	-	-	<0.02	-	<0.02	-	<0.02	<0.02	-	-	<0.15	-	<0.02	-	<0.99	-	<0.15	-	<0.02	-	<0.02	<0.03	<0.03
Iron	μg/l	13	526	-	<200	115	-	<200	-	278	-	293	417	-	14	12	-	<200	-	27	13	22	-	<200	-	6	3	24
Arsenic	μg/l	-	-	5.00	-	5.38	4.86	-	5.01	-	4.34	-	-	5.04	-	-	4.00	-	5.04	<10	-	-	-	-	5.50	0.62	0.07	0.17
Antimony	μg/l	-	-	-	-	<0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	<0.1	<0.01	-
Aluminium	μg/l	-	14.5	-	-	-	<5	-	<5	-	<5	-	-	<5	-	4.2	-	-	<5	118.0	-	4.8	-	-	6.7	<5	38.6	-
Lead	μg/l	-	0.09	-	-	0.32	<1	-	<1	-	<1	-	-	<1	-	0.02	-	-	<1	<2.4	-	0.12	-	-	<1	<0.1	<0.10	-
Selenium	μg/l	-	-	-	-	6.69	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.14	0.73	-

Table 3
Summary of the results of the phisico-chemical analyses performed between 2004 and 2016 on samples of raw water taken from the wells of Zones 2 and 3 of the water supply system and treated water taken at the outlet of the reverse osmosis plant of Smara. Values of parameters exceeding the parametric values established in Algerian legislation have been shaded. Sources: (a) Docampo (2006); (b) SMH/NCA/AUC (2008); (d) García-Lopez (2009); (g) Vivar et al. (2016); (c,e,f,h) Unpublished data. Details of the data sources can be consulted in Table 1.

Parameter		Pumping wells of Zone 2								Reverse osmosis plant outlet (Zone 2)				Pumping wells of Zone 3							
		SA10				SA11								OBL02							
	Year	2004	2007	2014	2016	2008	2009	2014	2016	2007	2014	2015	2016	2004	2007	2008	2009	2009	2014	2015	2016
	Source	a	b	f	h	c	e	f	h	b	f	g	H	a	b	c	d	e	f	g	h
pH	-	7.3	8.0	7.1	7.1	8.1	7.90	7.2	7.3	7.5	-	7.5	7.5	7.4	7.8	-	-	8.0	6.3	7.7	7.2
Conductivity	µS/cm	3640	4080	3811	3689	3859	3740	3644	3618	460	560	255	425	1265	1650	1480	1520	1496	1414	1326	1479
TDS	mg/l	1860	-	2776	2666	-	-	2732	2664	-	-	-	105	616	-	-	-	-	1048	600	985
Alkalinity	mg/l $CaCO_3$	-	-	189	215	-	-	206	213	-	-	-	42	-	-	-	-	-	118	187	157
HCO_3^-	mg/l	-	-	230	-	-	-	251	-	-	-	-	42	-	-	-	-	-	143	228	-
Hardness	mg/l	-	-	1020	1051	-	-	1010	944	-	-	-	-	-	-	-	-	-	473	-	540
Fluoride	mg/l	1.26	1.75	1.27	1.68	2.00	2.11	1.49	1.76	0.16	0.21	0.12	0.23	0.40	0.59	0.79	-	0.59	0.51	0.60	0.50
Chloride	mg/l	700	788	890	869	844	844	820	833	75	39	49	50	200	249	257	-	262	330	263	273
Nitrite	mg/l	<0.5	-	<0.34	<3.2	< 2.5	-	<0.34	<3.2	-	<0.34	-	<0.1	<0.5	-	<3.2	-	0.1	<0.34	-	<3.2
Nitrate	mg/l	120.0	122.0	139.0	124.0	137.0	129.0	134.0	126.0	15.7	30.0	15.9	39.0	<0.5	5.1	5.1	5.1	6.0	8.2	8.9	9.5
Phosphate	mg/l	<0.55	44.0	-	-	< 2.5	-	-	-	<1	-	-	-	<0.55	<1	-	-	-	-	-	-
Sulfate	mg/l	597	563	>160	662	557	-	>160	650	49.1	-	21.3	8.54	165	265	-	-	-	>160	262	306
Sodium	mg/l	428	485	506	464	582	582	507	448	49.5	43	36.3	56	133	182	191	-	132	171	174	161
Ammonium	mg/l	0.28	-	<1.6	-		-	<1.6	-	-	<0.4	-	-	0.27	-	0.06	-	0.04	<0.4	-	-
Potassium	mg/l	24.20	-	15.50	-	15.70	-	15.70	-	-	-	1.20	1.93	<17.20	-	3.48	-	7.86	7.73	5.56	-
Magnesium	mg/l	86.4	91.6	103.0	153.0	97.0	-	94.8	95.0	7.9	-	3.4	3.0	12.7	14.6	15.0	-	12.0	30.0	15.2	47.0
Calcium	mg/l $CaCO_3$	191	237	238	236	251	-	248	221	21	-	9	5	93	136	-	-	41	139	140	137
Iodide	µg/l	-	403	193	-	-	-	188	-	37	-	-	-	-	69	-	-	-	200	-	-
Silicium	mg/l	15.3	18.2	-	-	18.5	-	-	-	1.6	-		-	6.8	7.2	-	-	21.0	-	-	-
Chrome	µg/l	2.0	-	-	-	1.6	-	-	-	-	<1	0.2	0.4	0.5	-	-	-	2.3	-	-	-
Manganese	µg/l	3.50	3.10	<1	-	0.69	-	<1	-	<0.3	<1	0.66	0.16	6.70	59.80	5.00	-	-	21.20	-	-
Nickel	µg/l	2.30	-	-	-	5.90	-	-	-	-	<1	1.24	0.83	2.00	-	-	-	0.20	-	-	-
Cadmium	µg/l	<0.1	-	-	-	0.06	-	-	-	-	<0.02	0.02	0.16	<0.1	-	0.08	-	-	-	-	-
Mercury	µg/l	21	-	<0.02	-	-	-	-	-	-	<0.02	<0.03	<0.03	<0.99	-	-	-	<0.15	<0.02	-	-
Iron	µg/l	42	97	<200	-	12	-	<200	-	<1	5	24	3	209	2	69	-	-	<200	-	-
Arsenic	µg/l	<10	-	-	5.59	-	5.00	-	5.29	-	0.35	0.17	0.07	<10	-	-	-	-	-	-	0.15
Antimony	µg/l	-	-	-	-	-	-	-	-	-	<0.1	0.01	<0.01	-	-	-	-	-	-	-	-
Aluminium	µg/l	48.0	-	-	-	29.5	48.2	-	16.2	-	<5	17.2	-	71.0	-	104.0	-	-	-	-	-
Lead	µg/l	<2.4	-	-	<1	0.77	-	-	<1	-	<0.1	1.01	<0.1	<2.4	-	1.49	-	-	-	-	<1
Selenium	µg/l	-	-	-	-	-	-	-	-	-	0.36	0.73	<0.1	-	-	-	-	-	-	-	-

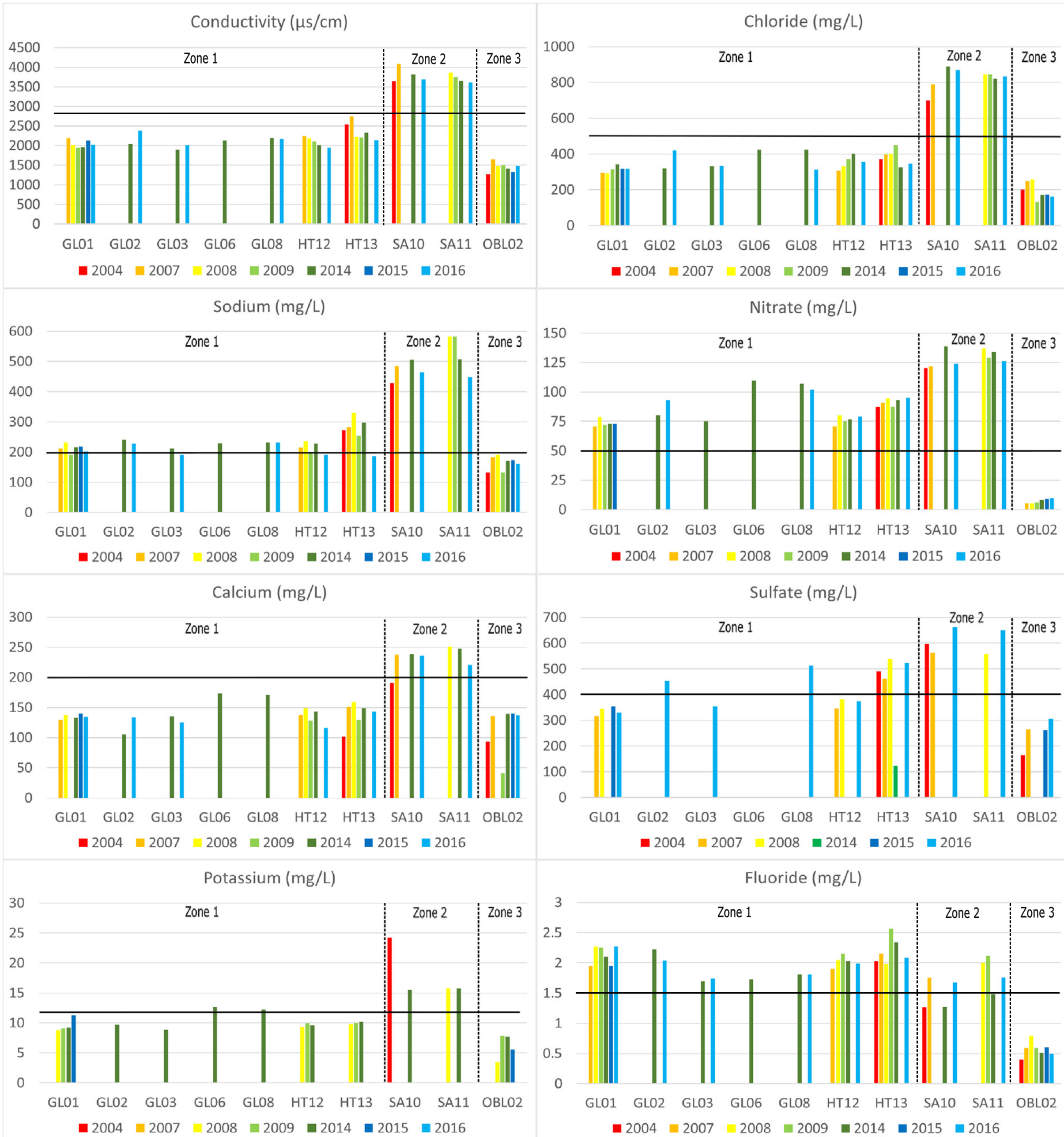

Fig. 4. Measured values of chemical parameters on water samples from the pumping wells of the drinking water supply system of the Sahrawi refugee camps from 2004 to 2016 (Table 2 and Table 3). The three zones of the system are distinguished. The parametric value of each parameter according to Algerian regulations (Algeria, 2011) is indicated in each graph by a continuous black line.

nitrate concentrations in Atacama Desert groundwater and proved their atmospheric origin. The leaching of nitrate from arid soil zones is unexpected because of the N-limited nature of desert ecosystems and the high nutrient utilization efficiency of xeric plants (West and Skuijins, 1978; Gutierrez and Whitford, 1987). Conversely, desert subsoils are persistently low in organic matter, microbial population and water content, are aerobic, and are neutral to basic pH, all of which promotes nitrate stability and inhibit denitrification (Walvoord et al., 2003). The presence of large nitrate pools in the subsoil of different deserts (Walvoord et al., 2003; Michalski et al., 2004a; Ewing et al., 2006; Graham et al., 2008; Scanlon et al., 2008; Qin et al., 2012; Stone and Edmunds, 2014) demonstrates that not all the nitrate is consumed in the soil zones or returned to the atmosphere, and therefore atmospheric nitrate accumulates in soil and subsoil. Similarly, with chloride, the alternation of hyper-arid and humid periods could explain the arrival of nitrate in the desert deep aquifers.

Sulfate content in groundwater comes in general from soil leaching, the decomposition of organic matter, and the oxidation of sulphated salts. Sulfated salts, anhydrite and gypsum, are very abundant in desert environments. A significant concentration of sulfates in groundwater causes an alteration in taste and, at very high levels, a laxative effect to unaccustomed consumers. Algerian regulations established a parametric value of sulfate concentration of 400 mg/L (Algeria, 2011). An average measured sulfate concentration in Zone 2 was 600 mg/L, and all the measurements exceed parametric value. Measured concentrations in Zone 1 were very heterogeneous and often exceed the parametric values. Finally, sulfate concentrations in Zone 3 were the lowest and clearly below established limits.

Fluoride concentration in groundwater is generally between 0.1 and 1 mg/L because of its limited solubility. Nevertheless, groundwater in arid zones presents higher concentrations since it contains a high sodium concentration which favors its dissolution (Custodio and Llamas, 1983). Fluoride in small amounts is essential to combat childhood dental problems, but excessive intake can lead to dental or even skeletal fluorosis. The parametric value in Algerian legislation (Algeria, 2011) and WHO guidelines (WHO, 2011) for drinking water is 1.5 mg/L. Measured concentrations in samples from wells of Zones 1 and 2 exceed this parametric value. Measured values in Dakhla (Zone 3) are between 0.40 and 0.79 mg/L (Fig. 4).

Iodide concentration in drinking water is a critical parameter because iodide intake in a population below or above the recommended interval is associated with the occurrence of thyroid diseases (Institute of Medecine et al., 2001). Despite the implications of iodine intake, iodine is not included in the quality standards for drinking water of the WHO (2011), Algerian regulations (2011b), or indeed those of most other countries. Only Chinese laws have classified areas in terms of water iodine concentrations, establishing a safe or suitable iodine concentration range between 10 and 150 μg/L (Ministry of Health of China, 2003, 2009). However, some data on iodide concentration in the raw water of the supply system wells are available (Table 2 and Table 3). Measured concentrations are quite heterogeneous. Average iodide concentration is about 200 μg/L and concentrations larger than 150 μg/L have been registered in the three study zones (Fig. 5). Measured concentrations in goiter epidemiological studies also show heterogeneity and measured concentrations above the 150 μg/L. Contrary to the results of the physico-chemical analysis of 2014, Barikmo et al. (2011), Grewal (2011) and Aakre et al. (2015) measured iodide concentrations in raw water of Dakhla lower than 150 μg/L.

5.2.3. Major cations

Sodium concentration in fresh water is generally between 100 and 150 mg/L, but it is easy to find much larger concentrations (Custodio and Llamas, 1983). Its origin can be found basically in the dissolution of silicates, rocks of a marine origin, and evaporitic deposits. The WHO does not consider high sodium concentrations to be harmful for human consumption (WHO, 2011), but they affect water taste. Algerian legislation establishes a parametric value for sodium concentration equal to 200 mg/L (Algeria, 2011). Measured sodium concentrations in Zone 2, between 428 and 582 mg/L, are the largest and clearly exceed the parametric value (Fig. 4). Measured sodium concentration slightly exceed the parametric value in samples from Zone 1 and are below this limit in samples from Zone 3.

The origin of calcium concentration is mainly from the dissolution of limestone, dolomite and gypsum. Calcium concentration in fresh water is generally between 10 and 250 mg/L. Measured calcium concentration is lower than 250 mg/L (Fig. 4) and only exceeds the parametric value in Algerian legislation of 200 mg/L (Algeria, 2011) in Zone 2.

Magnesium has properties similar to those of calcium, but its salts are more soluble and, as a consequence, it has lower concentrations in groundwater. The normal concentration of magnesium in groundwater does not usually exceed 40 mg/L, although in carbonated aquifers it can exceed 100 mg/L and in areas with saline infiltration it can reach 1000 mg/L. Measured magnesium concentrations are between 50 and 127 mg/L in Zones 1 and 2, and lower than 50 mg/L in Zone 3. The different regulations do not contemplate any upper value as harmful in water for human consumption.

The potassium concentration of groundwater is usually no higher than 10 mg/L, except in very saline waters. Its origin is mainly from the alteration of feldspars and evaporites. The potassium concentration measured in Zone 1 is between 8.8 and 12.6 mg/L, and only in wells GL06 and GL08 does it exceed the limit established by Algerian legislation of 12 mg/L (Algeria, 2011). Measured potassium concentrations are higher than 15.5 mg/L in Zone 2. On the contrary, they are below 10 mg/L in Zone 3 (Fig. 4). Excessive potassium intake may pose a risk for people with kidney or heart dysfunction, or diabetes.

5.2.4. Trace metals

Analyzed trace metals only show concentrations over the parametric value established in Algerian legislation (Algeria, 2011) sporadically. High mercury concentrations were measured on a sample from SA-10 well (Zone 2). This data seems not to be representative when considering the rest of the data from that well and those of the surrounding area. Conversely, high concentrations of iron, above 200 μg/L, have been measured in a few samples from wells in Zone 1. These do not appear to be erroneous. Such high iron concentrations might be due to the existence of organic matter, such as oil leakage from the pump system, which consumes the water-dissolved oxygen, favoring the reduction of Fe^{3+} to Fe^{2+} and increasing its solubility locally.

5.2.5. Bacteriological contamination

Water samples taken from pumping wells HT-12 and HT-13 (Zone 1), SA-9 and SA-10 (Zone 2) and OBL-1 (Zone 3) in 2004 were analyzed in the laboratories of the University of A Coruña (Spain) (Docampo, 2006). Only slight microbiological contamination (fecal coliforms) was detected in well OBL-1 in Dakhla (Zone 3). From 2008, the laboratories of the Sahrawi Water and Environment Ministry were able to carry out microbiological analyses to determine the concentration of total coliforms, *E. coli*, fecal streptococci, and *Clostridium perfringens*. These kinds of analyses have been performed periodically on raw water samples to monitor the microbiological quality of the groundwater. No

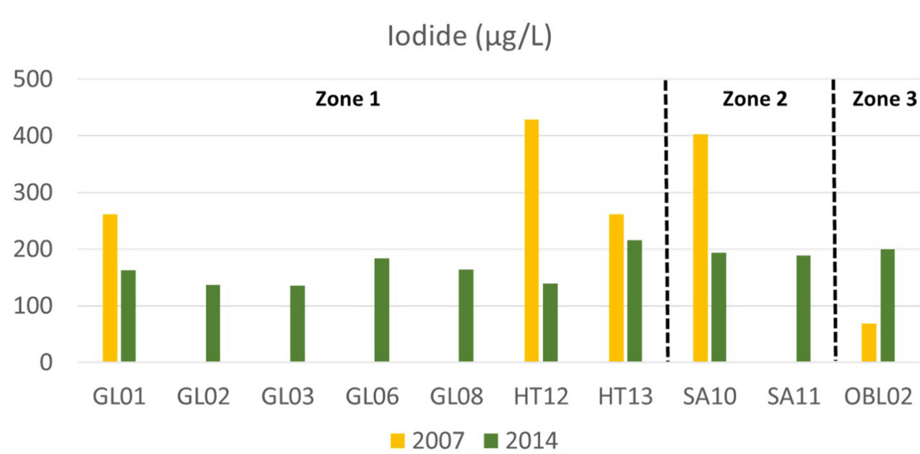

Fig. 5. Measured values of iodide concentration on water samples from the pumping wells of the drinking water supply system of the Sahrawi refugee camps in 2007 to 2014 (Table 2 and Table 3). The three zones of the system are distinguished. Note that iodine is not included in the quality standards for drinking water of the WHO (2011), Algeria (2011b), or most other nations.

bacteriological pollution has been found in general. Vivar et al. (2016) also found no bacteriological contamination on raw water samples taken in 2015 from well GL-01 (Zone 1) and from the inlet to the Smara reverse osmosis plant (Zone 2).

The good microbiological quality of the groundwater has been preserved due to the great depth at which the aquifers are located, and the lack of industry and intensive agriculture and livestock in the area. In any case, all the pumped water is treated by chlorination.

5.3. Treated water quality 2006–2016

5.3.1. Reverse osmosis plants

As stated in Section 5.2, in Zone 1 and Zone 2 high groundwater concentrations of chloride, nitrate, fluoride or sodium, are a consequence of natural hydrogeological processes in the desert and not related to aquifer exploitation. Thus, desalination plants are playing a prominent role in the water supply system of these areas in the SRC, as they are the only solution to provide potable water for the Sahrawian refugees.

Between 2004 and 2007 two reverse osmosis plants were designed and set-up in Smara (Zone 2). The results of the physico-chemical analyses conducted in 2007 by SMH/NCA/AUC (2008) reflect the improvements achieved in water quality (Table 3). While Laayoune continued to present high conductivities, fluorides, sulfate, nitrates and sodium (Table 2), the Smara water supply saw a drastic reduction in these components: conductivity from 4080 to 460 μs/cm, chloride from 788 to 75 mg/L, fluoride from 1.75 to 0.16 mg/L, sulfate from 569 to 49 mg/L, nitrite from 122 to 16 mg/L, iodide from 403 to 37 μg/L, sodium from 485 to 50 mg/L, and calcium from 237 to 21 mg/L. Another reverse osmosis plant was installed in Laayoune (Zone 1) and has been working since 2014. The comparison of the results of the physico-chemical analysis of raw water and osmosed water carried out in 2014, 2015 and 2016 shows how these reverse osmosis plants dramatically improve water quality (Table 2 and Table 3).

Fig. 6 presents the box-whisker plots of conductivity and the nitrate, fluoride and sodium concentrations measured in all the samples reviewed in this study for raw and treated water from Zones 1 and 2 of the supply system in 2014, 2015 and 2016. It illustrates the improvements in water quality for those parameters and how they are below their parametric values after treatment. The efficiency of the treatment, defined as the average reduction of the parameter value divided by its initial value, is between 80 and 90% for conductivity and is about 90% for fluoride concentration. Its efficiency for nitrate concentration reduction is of 70% in Zone 1, and 80% in Zone 2. Finally, the efficiency for sodium concentration is of 75% in Zone 1 and 90% in Zone 2. The reported averaged efficiency are below of the expected theoretical values for a desalination plant due to blending of treated water with plant by-pass and sand abrasion of the membranes which affect to their performance.

The osmosed water supplied in Zones 1 and 2 of the drinking water supply system is in accordance with the Algerian standards for human consumption (Algeria, 2011). The raw water supplied in Zone 3, although with a slightly salty taste, also meets the Algerian standards without being treated. However, the water supplied by the system in Zone 1, without being osmosed, does not meet these standards and thus poses a risk for the health of the Sahrawi refugees.

5.3.2. Chlorination systems

The chlorination systems consist of chlorine injection by means of five dosing pumps with flow regulation, located at different points in the supply networks. Three of these pumps are located at the outlet of the three reverse osmosis plants. Therefore, all the distributed osmosed water is also chlorinated. Another chlorination system is located in Zone 1, where osmosed and raw water are distributed alternatively, to treat the raw water. Finally, the fifth chlorination system is located in Zone 3, where there is no reverse osmosis plant, at the outlet of the only pumping well.

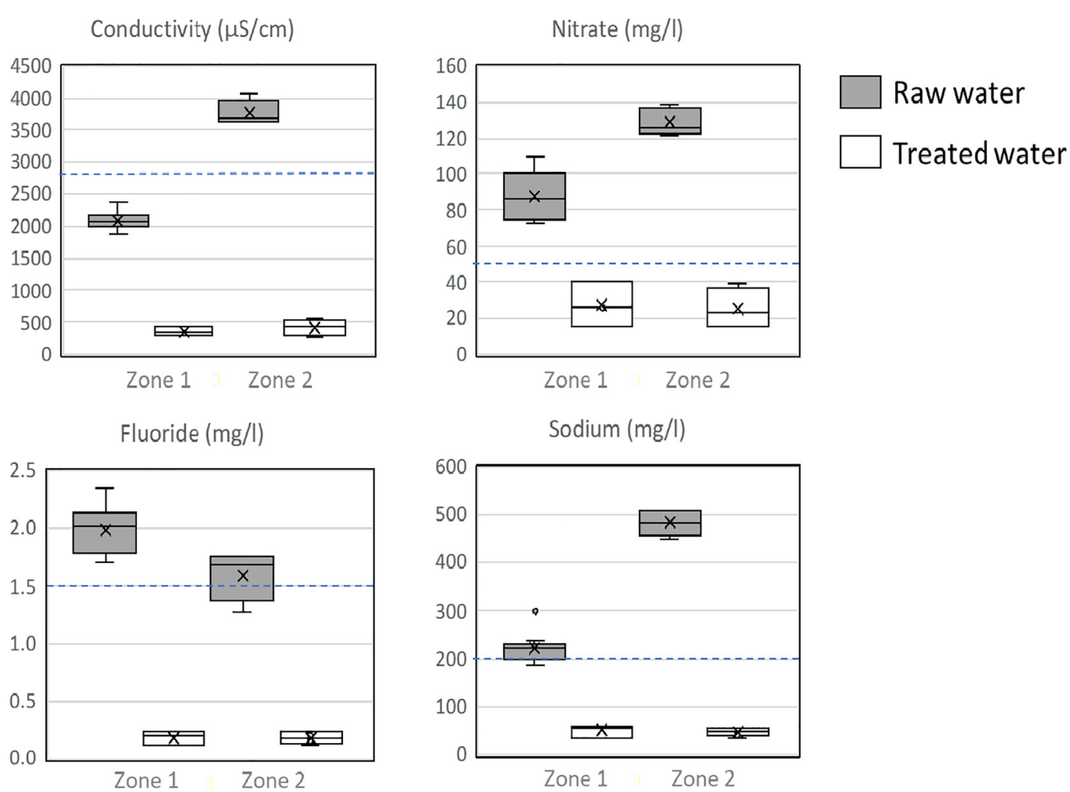

Fig. 6. Box-whisker plots of conductivity and nitrate, fluoride and sodium concentrations measured on samples of raw and treated water from Zones 1 and 2 of the supply system in 2014, 2015 and 2016. The dashed line indicates the parametric value for drinking water according to Algerian regulations (Algerie, 2011).

The complexity of the management of Zone 1 of the supply system, whose configuration had to be periodically changed to use raw or treated water, was increased by the installation of the chlorination system for raw water. The equipment was also being periodically configured to inject different chlorine doses depending on the water destination, because of the significantly different permanence times of water in the network. The complexity of this operation led to errors in chloride dosage in the past. As a consequence, it was decided that the chlorination system was to be used only for treating raw water which was being distributed to Awserd, this having a fixed configuration. The raw water distributed to Laayoune would be directly chlorinated in the distribution tanker trucks.

The injected chlorine dose depends on chlorine demand, related to physic-chemical and microbiological water quality, and on the desired concentration of residual chlorine at the end of the network. Where treated water is supplied through a distribution network to family tanks, a residual chlorine concentration between 0.2 and 0.6 mg/L at the end of the network is effective and sufficient if the population follows the established protocols of daily filling of clean family tanks for drinking water. Where the water distribution is performed by means of tanker trucks, higher chlorine doses are added to water according to the time the water is being stored, and the residual chlorine concentration should be between 0.2 and 0.8 mg/L. The residual chlorine is monitored daily in the storage tanks after chlorination and at selected points of the network located far from the chlorination system. Furthermore, microbiological analyses have been performed periodically at selected points throughout the network to ensure appropriate effectiveness of the treatment and good microbiological quality of the supplied water.

Nevertheless, the residual chlorine concentration may become insufficient if drinking water is stored for long periods of time in what are often inadequate and dirty family tanks, at the end of which the residual chlorine may have been consumed with the consequent health risks. To challenge the general idea that contamination in family tanks is widespread due to the bad conditions of these, the Saharawi Ministry of Water and Environment conducted studies on the permanence of chlorine in the tanks and microbiological contamination in 2015 (Hamdi et al., 2015). The presence of chlorine was monitored over 2 days in 41 family tanks distributed in the *wilaya* of Smara, using chlorine analysis kits. It was estimated that chlorine remained an average of between 2 and 9 days depending on the material and the conditions of the tank (i.e.: close or open, exposure to the sun, distance to pollution sources) and in no case was consumed on the first day. Microbiological analyses at the Sahrawi Ministry laboratory were performed on samples taken in duplicate from 40 Smara metal family tanks (Zone 2), 40 Ausserd metal family tanks, and 40 Boujador polyethylene family tanks (Zone 1). Evidence of fecal coliforms were found in between 5 and 8 tanks of each campaign and, of those, in only one tank of each campaign was contamination by *E. coli* confirmed. From these results, less than 3% of family tanks are estimated to be infected by *E. coli*.

6. Conclusions

Drinking water supply has been a challenge in the SRCs located in the desert near Tindouf (Algeria), where between 150,000 and 200,000 refugees are displaced today as consequence of the Western Sahara conflict. The drinking water supply system has been significantly improving since 2001, including the drilling of deep boreholes, the installation of reverse osmosis plants and chlorination systems, the gradual replacement of water trucking with a pipeline network, and the increased ability of Sahrawi technicians to undertake network operation and maintenance and water resources management.

The current drinking water supply system in the SRCs is divided into three zones. The Zone 1 supply system pumps groundwater from a detritic aquifer in Tindouf and supplies drinking water to the *wilayas* of Laayoune and Awserd. It has a reverse osmosis plant. Due to water wastage during osmosis, the pumped water volume is not enough for supplying treated water continuously. So, only part of the raw water is osmosed and each *wilaya* receives raw or treated water in turns of 20 days. All the water is chlorinated. The Zone 2 supply system pumps groundwater from a deep carbonated aquifer and supplies drinking water to the *wilayas* of Smara and Boujador and to the institutional center of Rabouni. All the raw water has been treated by a reverse osmosis plant since 2006 and is chlorinated. Finally, the Zone 3 supply system pumps groundwater from the deep sandstone aquifer of Dakhla and directly distributes it, after chlorination.

The quantity of water supplied to the Saharawi refugees was between 14 and 17 L/person/day on average in 2016, considering a population of 125,000 inhabitants and discounting network losses and other consumption. There are significant differences between the quantity of water supplied to each zone of the network. The supplied water volume in Zones 1 and 2 (10–12 and 14–17 L/person/day, respectively) is below all the recommended standards (between 15 and 20 L/person/day) and also the strategic objective of Sahrawi government (20 L/person/day). The supply volume was expected to increase from 2017 onwards due to planned improvements in the pumping systems and the drilling of a new well. Estimates of groundwater resources have indicated that local reserves are huge in comparison to estimated consumption for drinking water supply and irrigation, and no evidence of aquifer overexploitation has been found.

The physicochemical quality of raw and supplied water between 2006 and 2016 has been assessed according to Algerian standards (Algeria, 2011). The raw water of Zone 1 has very high conductivity. Measured concentrations of nitrate, fluoride, sulfate, sodium and potassium exceed parametric values for drinking water in Algeria. Iodide concentrations are also very high and, although there is no parametric value for this element, it may entail health risks. The raw water of Zone 2 has an even higher conductivity than that of Zone 2, exceeding the parametric value for this parameter. Measured concentrations of chloride, nitrate, fluoride, sulfate, sodium, calcium and potassium also exceed parametric values. Iodide concentration is also very high. By contrast, the raw water of Zone 3, although having a high salinity, met all the requirements for human consumption.

The anthropogenic pollution has been rejected as possible cause of the high concentration of salts measured in raw water due to the lack of significant industry, livestock or agriculture in the area and the absence of evidences of bacteriological contamination in the area of highest nitrate concentrations. The stability of the water drawdown at the boreholes and the measured raw water composition along 10 years discards the hypothesis of that high salinity as consequence of the overexploitation of the aquifer. Finally, that high concentrations have been found to be of natural origin, consequence of the alternation of hyper-arid and humid periods in nowadays actual deserts, as documented for other similar areas. This implies that it is not possible to obtain better quality water as a source of water supply in the Zones 1 and 2 by improving water management and forces water treatment by reverse osmosis. Alike in the Gaza Strip (Baalousha, 2005; Abuzzer et al., 2020), at SRC the desalination seems to be the only viable alternative for water resources.

The reverse osmosis plants have dramatically improved physic-chemical water quality. The osmosed water supplied in Zones 1 and 2 is in accordance with the Algerian standards for human consumption, as does the supplied raw water in Zone 3. However, the water supplied by the system in Zone 1 without being osmosed does not meet these standards, and poses a health risk for the Sahrawi refugees.

The chlorination of all the supplied water guarantees its microbiological quality if the population follows the established protocols of daily filling of clean family tanks. However, it may become insufficient if drinking water is stored in inadequate or dirty family tanks for a long time.

The present study establishes a baseline for the future work to be carried out by international humanitarian and cooperation agencies and institutions involved in the management and improvement of this drinking water supply system, and for the monitoring of groundwater resources. The application of the SADR Water Safety Plan by Sahrawi administration will allow to assure water allocation and water quality for the refugees. Continuous human and materials resources has to be committed in order to further strengthen the water supply system monitoring program, improving the household water supplied volume by increasing the pumping systems and desalinization plants capacity.

CRediT authorship contribution statement

Roberto García

Investigation, Interpretation of result, Resources, Revising the manuscript critically for important intellectual content

Acacia Naves

Conceptualization, Investigation, Interpretation of result, Writing-Original draft preparation

Jose Anta

Conceptualization, Interpretation of result, Writing-Reviewing and Editing, Supervision

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Investigation, Revising the manuscript critically for important intellectual content

Jorge Molinero

Investigation, Resources, Revising the manuscript critically for important intellectual content

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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