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Technical and Agronomical Assessment of the Use of Desalinated Seawater for Coastal Irrigation in an Insular Context

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Abstract: The growing need for alternative water resources for irrigation has led to advanced technological developments, which are addressing some of the challenges that our planet is facing regarding the water supply. The Canary Islands Archipelago (Spain) is a singular territory with several years of desalination experience while using desalinated seawater (DSW) for agricultural purposes. The current paper will address the conducted research of one of the case studies done into the Horizon 2020 project MAGIC, with the aim of analyzing the use of DSW for crop production in the Southeast of Gran Canaria Island. A methodology of surveying farmers in the area has been put in practice, as well as an assessment of potential soil degradation risks that are related to DSW irrigation (with fifteen years of DSW data). Additionally, local good practices to improve the DSW quality for irrigation are discussed. This study demonstrates an excellent endorsement of the surveyed farmers in the studied area regarding the use of DSW for irrigation: the strategy of combining this type of water with other water resources, such as groundwater and/or reclaimed water is very frequent and it can guarantee water and food security in the island's territory.

Keywords: desalinated seawater; irrigation; arid island; agricultural survey; soil degradation risks; desalted water post-treatment

1. Introduction

Freshwater supply has been altered worldwide due to human-induced changes, like habitat degradation, anthropogenic subsidence, climate-related risks, and the increasing disproportionate water consumption [1–3]; causing water scarcity and salinization in some regions and flooding in others [4–6]. Besides, the agricultural activity prompts natural water overexploitation and pollution [7].

The growing need for Alternative Water Resources (ARW) (water desalination and reclaimed water) has led to technological developments, which address some of the aforementioned challenges that our planet is facing regarding worldwide water supply. Global desalination capacity is higher than 80 million m^3 per day of freshwater from saline water sources (brackish (BW) or seawater (SW)) and the reverse osmosis (RO) technology leads the installed capacity [8]. The use of SW and its transformation into potable or irrigation water has made population settlement and the development of arid geographic areas possible in the past decades [9]. Freshwater can be considered to be an infinite resource if obtained from desalination in arid areas near the coast. However, there are several limiting factors in the case of agricultural purposes, as the high energy cost of desalination (up to 3.5 kWh/m^3) [7], the high final price (from 0.53 to 0.72 €/m^3) in comparison with conventional resources [10], or the brine discharge impacts in the coastal ecosystem.

The use of desalinated water (DSW) has been growing worldwide. Currently, Europe accounts for 10% of the world's desalination capacity—the Middle East is the global leader, with 70% of capacity [11]. Water providers in Southern Europe, like in Spain—as well as in Italy, Greece and Malta—are progressively turning to desalination to address freshwater needs in dry periods [12]. Regions with water scarcity in Europe are increasingly exploring the technology of desalination for irrigation purposes in their effort to match the increasing demands of water with available resources [13].

In this regard, the Canary Islands Archipelago (Spain) is a singular territory with more than fifty years of desalination experience and the 1% of the worldwide desalination capacity installed [14]. Eight habited islands located in the Atlantic Ocean at a latitude of 28 ° N, where the use of DSW for irrigation has achieved the exploitation of geographical arid areas in recent decades, in addition to having become, particularly in the west islands (Gran Canaria, Lanzarote, and Fuerteventura islands), world references in desalination for irrigation, coupled with the combined use of renewable energies [15].

The current paper will address the conducted research of one of the case studies done into the Horizon 2020 project MAGIC—Moving Towards Adaptive Governance in Complexity: Informing Nexus Security [16]. Following the participatory strategy promoted by the European Water Framework Directive, which lead to the appearance of new questions on how to define problems, how to know if something is a problem, and for whom; the case studies proposed in the MAGIC project assessed adaptive governance in the context of broadening narratives regarding the Water-Energy-Food (WEF) Nexus [17]. The use of AWR for irrigation in one key agricultural area of the Southeast (SE) of Gran Canaria Island—called Comarca del Sureste—was analyzed and is presented in this paper. The aim was to provide empirical insights on how these non-conventional waters perform in practice and the real WEF nexus interrelations that take place in this context. The location of the SE makes up three municipalities (Ingenio, Agüimes, and Santa Lucía), with 800 ha of agricultural area below 200 m above sea level with several desalination plants, as well as a reclaimed water irrigation network.

2. Materials and Methods

The case study is focused on the SE of Gran Canaria Island (Figure 1). The island presents the following hydraulic balance (from 2015): 78.3 hm^3/year of DSW or desalted brackish water (DBW) (RO technology), 54.4 hm^3/year of groundwater (GW), 12.7 hm^3/year of reclaimed water (with RO and electrodialysis desalination tertiary technologies), and 11 hm^3/year of surface water. The total demand (from 2015) is approximately 156.3 hm^3/year and it is mainly supplied with DSW (50%) and GW (35%), while a much smaller contribution is derived from reclaimed water (8%) and surface water (7%). The agricultural and livestock sector of the island accounts for the highest water consumption, with a volume of 66.70 hm^3/year from the total demand from 2015 [18]. There is increasing demand for DSW in the agricultural sector close to the sea [19]. This water demand is covered from SW desalination mainly, which can then be used alone or mixed with different freshwater resources (GW, DBW, and surface water). Already since the last century, the BW desalination exploitation has caused marine intrusion due to the over-exploitation of the coastal GW. For this reason, the practice of using DBW is displaying a setback.

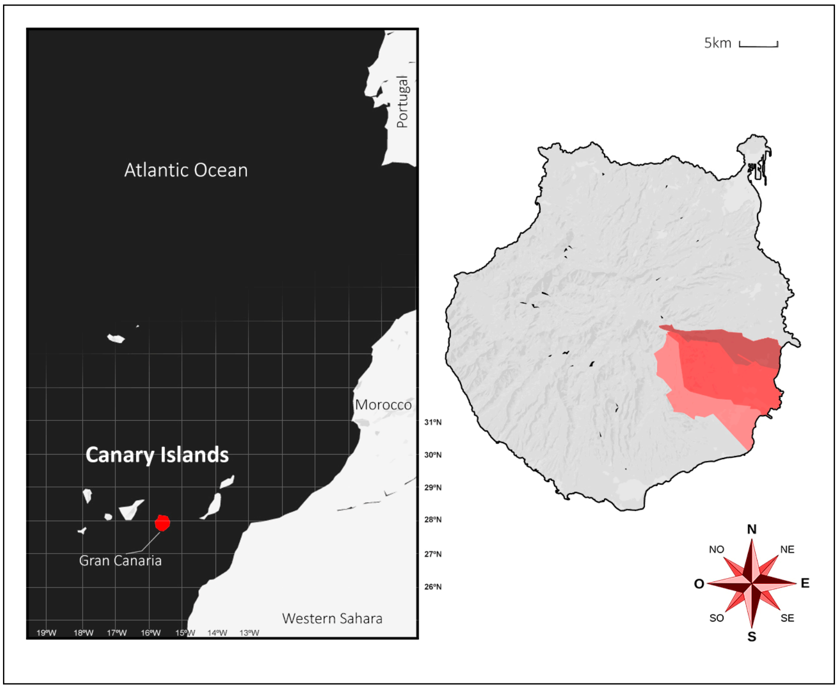

Figure 1. Location of the study area in the Canary Islands (Spain) (Southeast Region of the Gran Canaria Island in red shades). Source: Own elaboration.

The documentation process for this study was carried out in different steps. Firstly, the plot of the crops' map of the SE region of Gran Canaria was done thanks to the use of the IDECanarias' Crops Map viewer tool, which allows for identifying the farms and the crop typology (strata) in the study area (Figure 2). The SE region was chosen, as it is a key area with the greatest agricultural activity on the island. The figure includes the existing reclaimed water network (below 200 m above sea level) (blue line), which delineates the study area downstream.

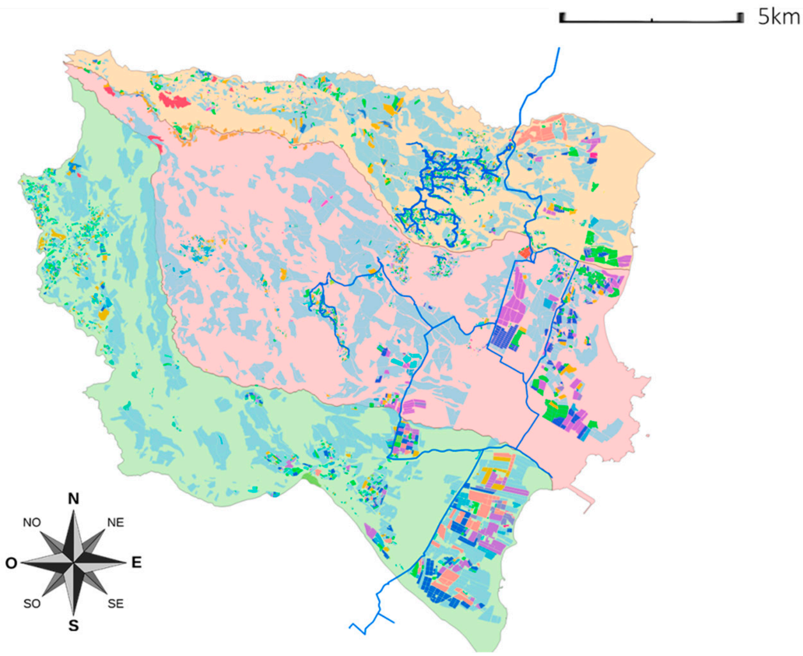

Figure 2. Map of crops' determination in the Southeast of Gran Canaria island including the reclaimed water network (blue line) in the area. Source: IDECanarias (https://visor.grafcan.es/visorweb/ on the 15 June 2018). Own elaboration.

Based on this, stratification was carried out with the different types of crops available.

Below the reclaimed water network level, the crops' typology was established in specific strata (Figure 3). Each crop area was identified with a colour and surface. Tomato (in red) has historically been the most predominant crop in this region. The plantation of banana (in yellow) is also prevalent. Table 1 shows the crop strata that were analyzed in the study area and the crops' representation.

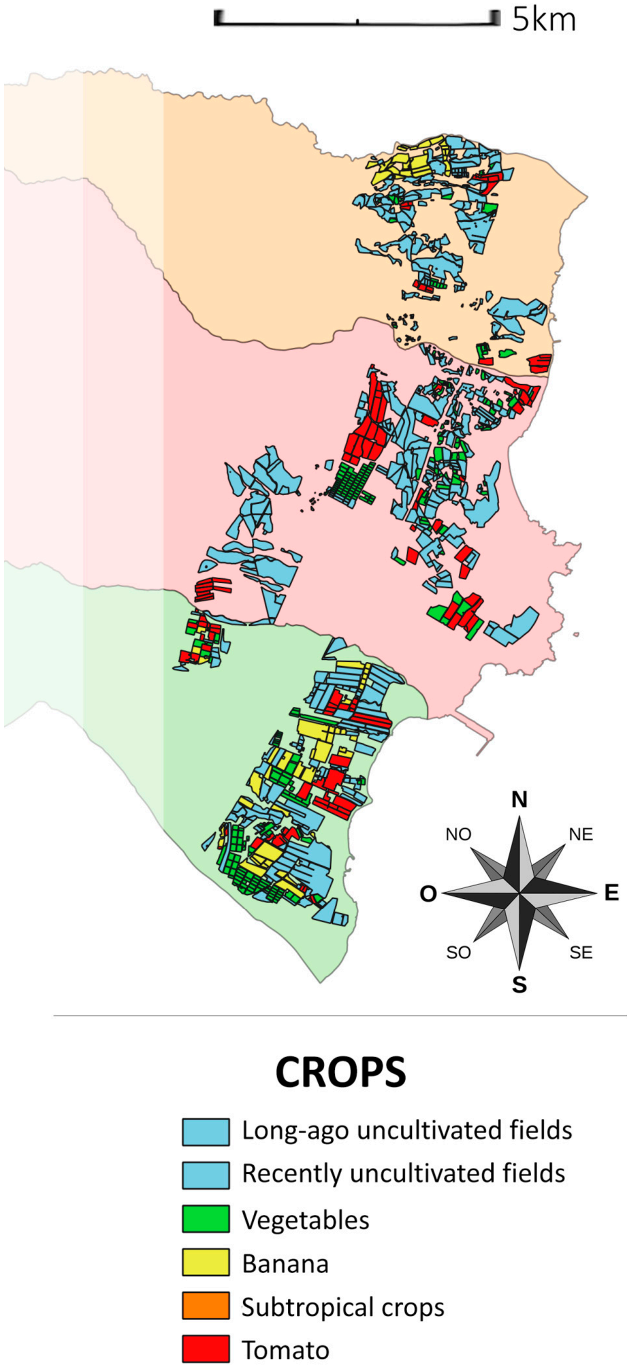

Figure 3. Crop strata in the Southeast of Gran Canaria below the reclaimed water network level for this study. Source: IDECanarias (https://visor.grafcan.es/visorweb/ on the 15 June 2018). Own elaboration.

Table 1. Crop strata and its definition.

Crop Strata	Definition
Cereals and legumes	Corn, beans
Subtropical crops	Mango, papaya or avocado
Mediterranean crops	Citrus fruits
Vegetables	Grouped according to their edible parts: leaf vegetables, root vegetables, fruit vegetables, flower vegetables, tubers, and legumes
Family orchard	Crop production intended for food self-sufficiency
Ornamental	Plants cultivated for decorative purposes
Banana	Main cultivated and exported crop in the island
Tomato	Main cultivated and exported crop in the island

Secondly, an agricultural survey methodology was prepared to collect WEF nexus data from the whole 802 farms in the 728.77 ha agricultural area. The under-represented crops were not considered. The sample size was determined with the same parameters that were used in the study that was conducted by Hernández and de la Rosa [20]. This methodological reference was a local study on the efficiency of irrigation that used the agricultural survey as a basis tool to collect data from primary sources to estimate water consumption. The approach was probabilistic and it was performed through simple random sampling. Subsequently, the representative size was calculated with the following formula:

$$\mathrm{n} = \frac{\mathrm{N} \cdot \mathrm{Z} \cdot \alpha^2 \cdot \sigma^2}{\mathrm{d}^2 \cdot (\mathrm{N}-1) + \mathrm{Z} \cdot \alpha^2 \cdot \sigma^2} \tag{1}$$

where,

- d, the precision was the breadth of the level of confidence. In this case, the average of the surface of the farms by crop (strata).
- α, the percentage of security opted with a security level of 90% with a coefficient Z of 1.65.
- σ^2, the variance was the average surface area of farms by type of crop (strata).
- N, the population in this study was the total number of plots found in the three municipalities of the SE region of Gran Canaria (Ingenio, Agüimes, and Santa Lucía), taking the reclaimed water irrigation network as the upper limit (see Figure 2).

In total, the result of the sample size (n), was of 31 farms (from N = 802, the total farm population). Table 2 shows the total area analyzed per crops and the number of representative surveys and area to do following the methodology explained. It shows that the crop strata of Vegetables, Tomato, and Banana represent 89% of the total study area. Thirty-one surveys were carried out to various types of agricultural holdings, being distributed among the study area, which covered 291.5 ha (40% of the total area).

Table 2. The study area crops' strata and number of surveys following the proposed methodology.

Strata	Area per Crops (ha) (and %)	No. of Farms	No. of Surveys	Area Survey/Area per Crops (%)
Cereals and legumes	10.71 (1.47%)	46	1	9%
Subtropical crops	43.08 (5.91%)	57	2	13%
Mediterranean crops	6.25 (0.86%)	19	1	8%
Vegetables	241.00 (33.07%)	342	14	32%
Family orchard	13.25 (1.82%)	112	1	4%
Ornamental	6.47 (0.89%)	19	2	53%
Banana	159.72 (21.92%)	89	6	72%
Tomato	248.29 (34.07%)	118	4	35%
Total study area	728.77 (100%)	802	31	40%

Source: own elaboration from the IDECanarias' Crops map and survey methodology.

The type of proposed survey followed the guidelines that were established in the GSARS tool [21]. The survey consisted of coded questions and it was divided into the following thematic blocks: the physical environment (with farm data), the type of crops and agricultural production, water and energy consumption, human activity (sociodemographic profile), and agronomic model (local/export/self-supply). Naturally, the technical and agronomic aspects were the main input. However, special emphasis was given to the perception of the farmers, as farming implies an appropriate relation between categories of human activity and categories of land use [22]. That is the reason why the survey combined both qualitative and quantitative questions.

It was decided to execute the agricultural surveys on site, to achieve a greater truthfulness of the answers, as the conditions of the agricultural holdings were then directly observed. The fieldwork was performed with the Computer-Aided Personal Interview (CAPI) technique that avoided transcription errors and permitted direct access to maps and geolocation. Qualified personnel in the agricultural sector and in conducting surveys were utilized to carry out the collection of data in the field. The ODK (Open Data Kit) Collect application—an open-source software application for collecting, managing, and using data—was used to collect the data from the 31 surveyed farms. The agricultural holdings in the SE of Gran Canaria were then characterized with the results from the surveys.

Following the MAGIC project target, the final purpose of collecting field data was to create a space for Quantitative Story-Telling [16]. It was possible to answer the research question that had the intention to know the extent at which the use of DSW and/or reclaimed water innovations solve the problem of irrigation at a local/regional level with water scarcity based on the collected quantitative and qualitative information. The study allowed for the team to extract different narratives behind AWR, to find out whether water problems are being sorted out or if they are actually worsened with strategies like desalination or industrial/urban treated wastewater reuse. The MAGIC aimed precisely aimed at integrating qualitative and quantitative styles of analysis and contrasting the narratives with a reasoning of the socio-ecosystems.

Finally, a DSW water assessment and the presumed good practices that could improve the quality of this kind of agricultural water were investigated. At this point, it is relevant to explain the behavior of the DSW used for irrigation. As shown in Figure 4, the roots (rhizodermis area—right corner of the figure below), through the radical or absorbent hairs, carry out the absorption of water and mineral salts. The water penetrates through forward osmosis, since, inside the roots, there is a higher concentration of salts than in the outside environment. This process makes it possible for water and mineral salts to advance into the roots by passing through the rhizodermis, the layer of cells that form the epidermis of the root; and, reaching the conductive vessels of the xylem that are distributed throughout the plant. This osmosis process is the one that occurs in the RO membranes (left side of the figure below), but in a reverse way. In this case, a SW with a high concentration of salts is driven, so that it loses part of the salts through a RO membrane. Naturally, the majority of ions' concentration (as Na^+ or Cl^-) and other toxics (as Boron (B)) that are present in the SW interact with the rest of compounds of the soil and others added by chemical and organic amendments, after being irrigated (see bottom part of the graphical description).

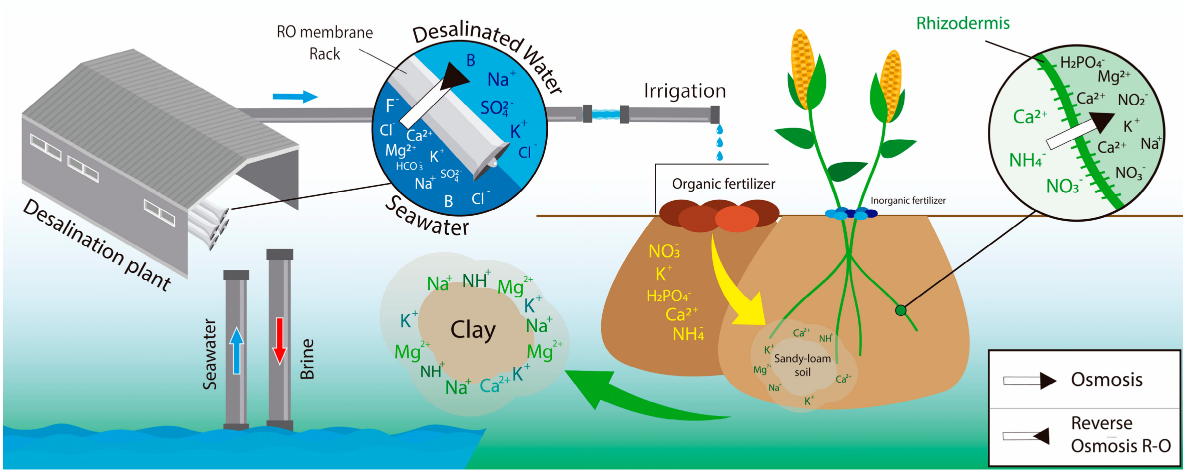

Figure 4. Graphical description of the key elements' absorption supplied for a desalinated seawater. Source: Own elaboration.

The DSW water assessment was done while using data that were supplied by desalination plant managers in the area under confidential location, which were integrated and analyzed. The data corresponded to two samples per year over a 15-year period (2003–2019). Additionally, input SW for the desalination plant sampled twice during the study period (2007 and 2019) was evaluated. The following parameters for the water samples were considered: electrical conductivity (EC), pH, cations (Ca^{2+}, Mg^{2+}, Na^+, K^+), anions (HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-), and B. The Sodium Absorption Ratio (SAR) was calculated while using the cation values (Ca^{2+}, Mg^{2+}, Na^+), the alkalinity from bicarbonate levels and the Langelier index using pH, the EC, Mg^{2+}, HCO_3^-, Cl^-, and SO_4^{2-} values, and a temperature of 21 °C. All of the analyses were performed in accordance with Standard Methods for the Examination of Water and Wastewater [23]. The results were used to assess the irrigation water quality and its potential effects on soil quality.

3. Results and Discussion

3.1. Agricultural Survey and Narratives

Collecting the personal definitions and experiences from stakeholders of a particular region and contrasting the narratives can make it possible to understand why and/or how the natural resources are (over) used in that location. Cabello V., et al. (2019) and Valinia, et al. (2012) have shown that the perceptions from local stakeholders of what is a "desired state" of natural resources (water in this case) might differ greatly from the actual ecological dimension [17,24]. Defining the sustainable level of water use very much depends on social and cultural values and, therefore, an in-depth participatory evaluation with interested and relevant stakeholders is crucial [25].

For this reason, the agricultural survey was conducted in the SE of Gran Canaria, with the aim of distinguishing the relevant environmental and socio-economic components, the technical elements of the water used for irrigating the crops in each of the analyzed agricultural holdings, and to contrast the perception that the farmers had with the use of AWR in general, particularly with DSW.

In relation to the survey's section "type of water used", the results are shown in Figures 5–7. The following graph (Figure 5) illustrates the typology of water resources used in the agricultural holdings of the representative sample. It shows that the surveyed area is mainly irrigated with DSW (31% of the farms), following of reclaimed water (25%) DBW (20%). The rest is GW and surface water.

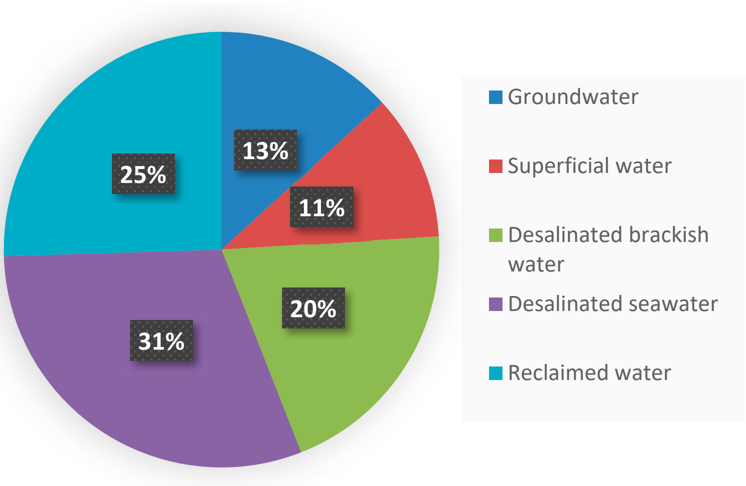

Figure 5. Typology of water resources used in the farms in the study area (% farms).

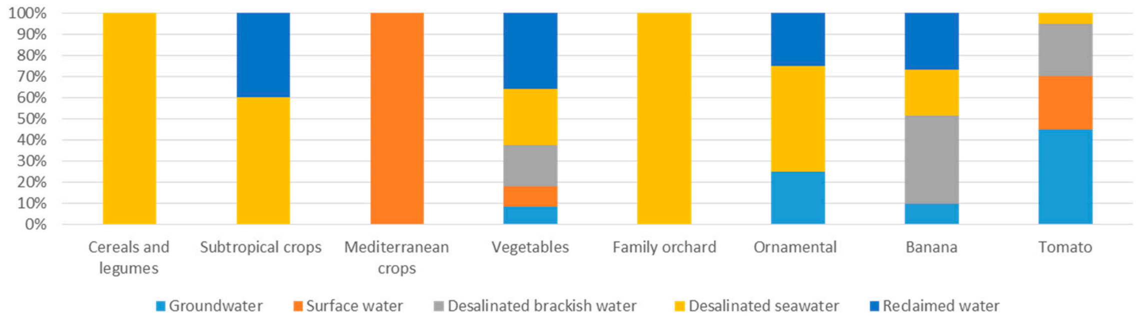

Figure 6. Typology of water resources used per crops in farms of the study area (% per farms).

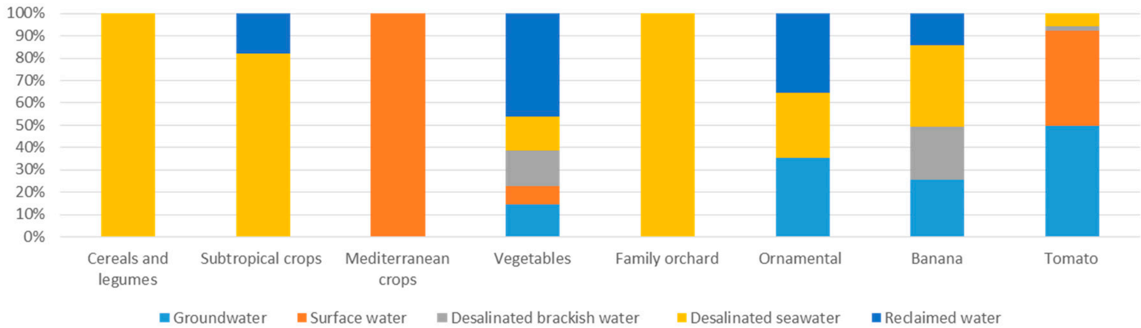

Figure 7. Typology of water resources used per crops in farms of the study area (% per hectare).

The majority of the surveyed farmers in the studied area have extensive experience in the use of DSW. They usually blend DSW with other types of water. When asked why, some farmers explained that DSW contains several parameters that may be harmful to the soil structure and/or to certain crops. Therefore, the mixtures are completed to improve the final water quality (this practice is thoroughly explained in Section 3.4). The most common blending is made with DBW and GW. The proportion of reclaimed water is less frequent, but its use is gradually increasing.

The analysis of the water typology in correlation to the crop strata (Figure 6 per farms; Figure 7 per hectare) indicates the great diversity of water resources that are used by type of crop and farm. The evaluation of the water usage of Tomato, Banana, and Vegetables' crop strata is a matter of considerable importance. Tomato and Banana, the main export crops, use the five types of water resources that are available in the study area (as well as the Vegetables). However, Banana cultivations do not use surface water. In these two types of export crops, the use of DSW is low, because those agricultural holdings tend to have their own resources of natural origin or BW desalination. According to the survey results, 23% of farms only use DSW, while 26% use DBW combined with other resources. Only 10% of the farms that combine resources do not use DSW. The strategy of combining DSW with other resources is very frequent due to the scarcity of water resources in this region during the summer. In this sense, irrigation with DSW in the study area guarantees water and food security [26], demonstrating that it can become one of the main strategies for increasing food sovereignty in the island territories.

When scrupulously observed, the contribution of DSW in the crop strata of this subtropical region is more significant from the point of view of irrigated hectares than from the number of farms in operation. This is not the same for Ornamental and Vegetables, as it is shown in the Figures 6 and 7.

In relation to the survey's section "water consumption", the results are shown below. The unitary consumption of the crops was determined in m^3 ha^{-1} $year^{-1}$ (Figure 8). The demand for water in the study area was estimated based on the type of water used per crop and the surface. From the results, it can be seen that the most predominant water consumption in the area corresponds to the DSW type.

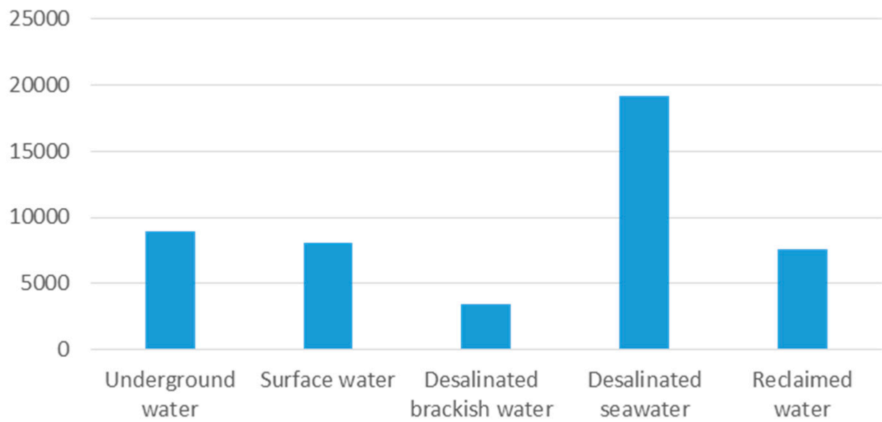

Figure 8. Consumption (m^3 ha^{-1} $year^{-1}$) per water typology in the studied area.

In relation to the survey's section "soil risks and amendments", the farmers are aware that DSW presents restrictions on the use. The practice of applying organic fertilization in crops (organic amendment) is very common in the SE of Gran Canaria, owing to the problems of low organic matter content in the soil and the characteristic sandy loam soils found in the area. Organic fertilization improves the structure and mineralization of the soil. From the results of the agricultural surveys, it is perceived that about 60% of the farms use manure and more than 20% compost (as seen in Figure 9). Of the farms that use DSW as their main resource, 50% provide manure and 29% compost. The contribution of organic fertilization in soils that were irrigated with DSW improves the ionic balance of the soil colloids and, therefore, prevents possible crusting in the soil.

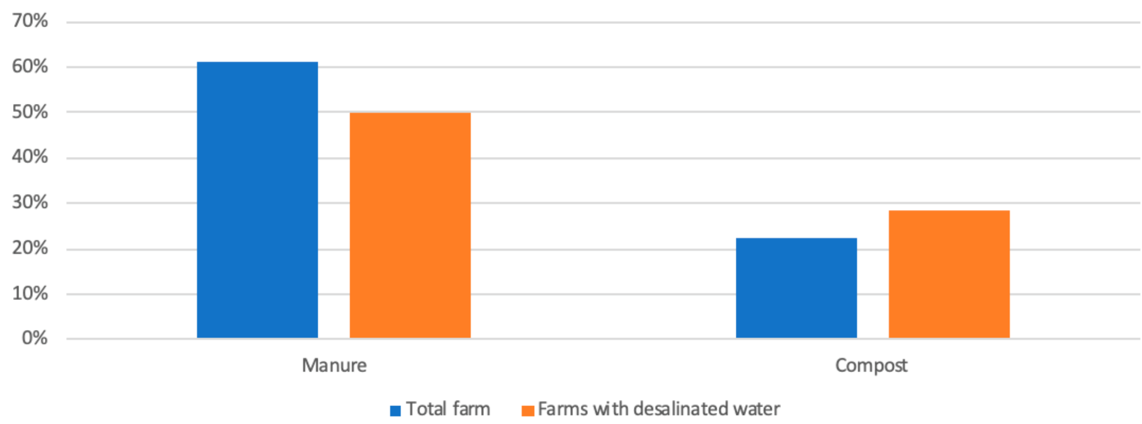

Figure 9. Manure and compost use in farms in the study area. Source: Own elaboration.

3.2. Price and Cost Production of Desalinated Water Supply to Irrigation

According to the survey's section "water price" results, the range of price of the private DSW in the area is from 0.6 to 0.87 €/m^3 in the period of 2010–2019. It is higher in comparison to the private GW available price (0.5 and 0.6 €/m^3) or subsidized public reclaimed water cost (from 0.45 to 0.53 €/m^3) (CIAGC, 2019). The price of water is one of the main problems expressed by the surveyed farmers, in view of this diversity of types of water and prices. Basically, the general idea is that publicly owned waters influence the traditional private water market by regulating and lowering prices.

The price of DSW is obtained when separating the cost of the water production while using medium-scale RO technology in the area and the insignificant water distribution cost. The SWRO technology exploited here presents a low specific energy consumption—from 2.90 to 3.55 kWh/m^3 considering SW catchment and desalination process—thanks to the combined use of the highest efficient energy recovery devices (isobaric chambers, and positive-displace pumps), the last generation SWRO membranes and SW shallow catchments through beach wells [27].

Under these premises and while assuming 0.75 €/m^3 as the average water cost of the DSW obtained through a low or medium-scale SWRO desalination plants in this area including the distribution cost, its cost can be distributed in the following way: 35% capital amortization, 25% energy, 14% staff, 12% membranes replacement, 10% consumables and spare parts, 4% insurances, taxes, and others.

Special mention requires the high potential of wind power existing in the SE of Gran Canaria and the real combination with desalination plants. The monthly average wind speed is 7.5 m/s with predominant NE direction (average of more than 20 years that were obtained at the ITC weather station in Pozo Izquierdo—Santa Lucía). Wind energy is connected to SWRO desalination plants located in this area with the aim of reducing the DSW cost combining wind farms connected to the grid, besides the environmental benefit of reducing carbon dioxide emissions. The RO plant and DSW pumping distribution are driven in parallel by the electrical grid and are also connected to on-shore wind power farms. The variable energy cost of the DSW can be reduced in 35% as an annual average with this innovation contribution and an adequate energy load control [15].

3.3. Irrigation Water Quality and Potential Soil Quality Problems

Table 3 provides the mean values of the chemical variables analyzed in the input SW and DSW supplied in the SE of Gran Canaria, along with literature recommendations for agricultural use of DSW. Table 4 shows the recommended parameters per crops (pH, EC/SAR and B) of irrigation water by the Canary Islands' integrated production regulations.

Table 3. General characterization of the seawater catchment (SW) and desalinated seawater (DSW) used for irrigation in the Southeast of Gran Canaria during 2003–2019 period; average +/− standard deviation; n = 30.

Parameter	SW	DSW	Recommendation for DSW [a]
pH	6.7 ± 0.1	5.8 ± 0.4	<8.5
EC dS m^{-1}	47.7 ± 7.4	0.7 ± 0.2	<0.3
Ca^{2+} mg L^{-1}	644.7 ± 35.9	4.0 ± 2.7	32–48
Mg^{2+} mg L^{-1}	1503.8 ± 5.3	6.0 ± 4.1	12–18
K^{+} mg L^{-1}	358.7 ± 30.1	4.9 ± 1.3	—-
Na^{+} mg L^{-1}	10,643.3 ± 504.4	125.8 ± 38.8	<20
SAR (meq $L^{-1})^{0.5}$	52.4 ± 2.2	10.5 ± 2.0	—-
Alkalinity mg L^{-1} as $CaCO_3$	194.0 ± 7.8	13.5 ± 3.1	>80
Cl^{-} mg L^{-1}	20,211.5 ± 299.1	208.6 ± 69.4	<20
S-$SO_4{}^{2-}$ mg L^{-1}	861.3 ± 109.9	4.1 ± 2.9	>30
N-$NO_3{}^{-}$ mg L^{-1}	20.7 ± 2.7	0.8 ± 0.4	—-
B mg L^{-1}	4.8 ± 0.4	1.2 ± 0.3	0.2–0.3
Langelier saturation index (LSI)	0.5 ± 0.1	−4.1 ± 0.6	−0.5–0.5

Source: Data supplied by desalination plants manager under confidential location. [a] Values based on Yermiyahu et al. (2007) [28] and Lahav and Birnhack (2007) [29].

Table 4. Recommended water quality parameters per crops of irrigation water by the Integrated Production Regulations of the Canary Islands.

Crop	pH	EC (dS/m 25 °C)	B (mg L^{-1})	Low Relation SAR/EC (*)	Medium Relation SAR/EC (*)	High Relation SAR/EC (*)
Ornamental						
Rose	6.5–8.4	<2	<1	0–3/0.7–1.1	3–6/1.2–1.4	6–12/1.5–1.9
Subtropical crops						
Banana	6.5–8.4	<1.1	<1	0–3/0.7–1.1		
Mango	6.5–8.4	<1.5	<1	0–2/0.7–1.5		
Papaya	6.5–8.4	<3	<1	0–2/0.7–3		
Avocado	6.5–8.4	<1.6	<0.75	0–2/0.7–1.5		
Pineapple	6.5–9	<1.5	<1	0–3/0.7–1.1	3–6/1.2–1.4	
Mediterranean crops						
Citrus	6.5–8.4	<1.3	<0.5	0–3/0.7–1.3		
Vegetables						
Lettuce	n.a.	<1.25	<2	0–3/0.7–1.25		
Tomato	6.5–8.4	<1.5	<1	0–3/0.7–1.1	3–6/1.2–1.4	
Cereal and legumes						
Corn	n.a.	<1.7	<1.7	0–3/0.7–1.1	3–6/1.2–1.7	
Tubers						
Potato	6.5–8.4	<2	<1	0–3/0.7–1.1	3–6/1.2–1.4	6–12/1.5–1.9

Source: Canary Islands Regional Integrated Production Regulations of the Canary Islands related to potato, banana, tomato, avocado, mango, papaya and pineapple. (*) SAR and EC values for each relation without irrigation restrictions.

Desalination treatment removed 99.0% of dissolved salt in the seawater giving an average EC for the final DSW of 746 µS cm^{-1}, ranging from 410 to 1446 µS cm^{-1} through the study period. Approximately 50 % of the samples had an EC over 700 µS cm^{-1}, which lead to a moderate degree of restriction on use due to potential soil salinity problems [30], and all of the samples were above the limit for DSW set out in the Israeli recommendations (~300 µS cm^{-1}) in order to avoid salinity issues. The EC values were adequate for most crops with the exception of banana crop in some DSW samples (Table 4). Particularly, in extremely arid areas, such as the SE of Gran Canaria, with a high evaporative demand (ETPo~1786 mm $year^{-1}$; period 2001–2018) and very low precipitation (~94 mm $year^{-1}$; period 2008–2017), the accumulation of soluble salts in the upper zone of the profiles might be a limiting factor (i.e., osmotic effects) for production in sensitive and moderately sensitive crops if no adequate leaching fractions are applied. Therefore, Diaz, et al. (2013) [31] reported, also in a very arid insular environment, a significant increase in soil salinity, when compared to rainfall soils, after 20 years of irrigation with DSW (average EC~580 µS cm^{-1}).

The SAR values varied from 5.4 to 14.0 (meq $L^{-1})^{0.5}$ in the DSW, averaging 10.5 (meq $L^{-1})^{0.5}$ (Table 3). Those values indicated an unbalanced concentration of Ca^{2+} and Mg^{2+} with respect to Na^{+} that can cause a deterioration of soil physical properties, such as clay dispersion, lower infiltration rates, lower hydraulic conductivity, and, consequently, anoxia and a low flux of soil water to the roots [32]. SAR in irrigation water should be considered alongside EC in any evaluation of the potential effects of irrigation water on soil structure and hydraulic properties, being the combination with the most potentially adverse effects in soils a high SAR value accompanied by a low EC level [33]. In the assessed DSW, that combination would result in moderate restrictions (severe restrictions when EC < 500 μS cm^{-1}) on the use of this water due to potential mid-long term deterioration of the physical properties, mainly in the fine-textured soils that are common in the study area; and, the resulting impact on crop yield. Desalination plant managers have increased EC in the DSW product in response to the farmers' demand of water with a higher salt load that avoid soil physical degradation (personal communication), bearing in mind the interaction between SAR and the electrolyte concentration in the soil solution. Although irrigation in many farms of the study site has been developed in the last decades exclusively with this kind of water, no evident symptoms of structural degradation have been observed yet. That could be due, on the one hand, to the frequent use of chemical (calcium sulfate) and organic amendments (manure), and on the other hand, to the appreciable amounts of precipitated or native calcite that contain carbonated soils in the study area that could be dissolved by the DSW (with extremely negative SLI~−4.1, indicating its dissolving power), providing soluble calcium to offset the sodium effects [30].

Specific ion effects might occur due to Na^{+}, Cl^{-} and/or B that accumulate in the plant causing specific damage or visual injury, and in some cases (i.e., high concentrations of sodium) can also cause nutritional imbalances in the plants [34]. Specific ion toxicity can become the dominant growth suppressing effect mainly in tree and vine crops, overall under hot and dry conditions, such as those in the study site [35]. Desalination treatment effectively reduced the amount of Na^{+}, Cl^{-} and B by 98.8, 99.0, and 75%, respectively (Table 3), however remaining levels can result in being problematic for sensitive crops. Sodium and chlorides ranged from 65 to 237 mg L^{-1} (mean ~126 mg L^{-1}) and from 120 to 410 mg L^{-1} (mean ~209 mg L^{-1}), respectively. In both cases, those levels greatly exceed the 20 mg L^{-1} established, as recommended limit for DSW use in irrigation [28]. Attending to the general guidelines for interpretation of water quality for irrigation, the Na^{+} and Cl^{-} concentration would imply a moderate degree of restrictions on use [30]. However, the tolerance of tree crops to Na^{+} and Cl^{-} greatly depend on varieties and rootstocks [34]. For example, grapes can tolerate more than 700 mg L^{-1} of Cl^{-}, while sensitive berries and avocado rootstocks can only tolerate up to 120 mg L^{-1} [35]. With regard to Na^{+}, avocado, citrus, and stone-fruit trees, all of them being important crops in the study area, has shown injuries at concentrations as low as 115 mg L^{-1} [35].

The boron levels in the DSW varied from 0.7 to 2.3 mg L^{-1} (mean ~1.2 mg L^{-1}), with approximately 87% of the samples exceeding 1 mg B L^{-1}. This relatively high B content, above the recommended limit for irrigation water in the regional legislation (<1.0 mg L^{-1} for all crops), and well above the upper limits for DSW set out in the Israeli recommendations (0.2–0.3 mg L^{-1}), is a consequence of its high content in the input seawater (~4.8 mg L^{-1}; Table 3), which is not effectively reduced by RO during desalination. As a large portion of B in seawater takes the form of boric acid (H_3BO_3), with no ionic charge, makes it can pass through the RO membranes and a lower percentage of B is therefore eliminated [36]. Yermiyahu, et al. (2007) [28] reported that, without additional treatment, B in Mediterranean seawater after RO reach 2 mg L^{-1}, which is toxic for numerous crops. Irrigation with DSW has been found to significantly increase soil B content, even with lower water B levels than those that are found here (i.e., 0.5–1.1 mg B L^{-1}; Díaz, et al., 2013) [31], and it has triggered B toxicity problems and led to diminished yields in several sensitive crops [28]. Nevertheless, the sensitivity of the plant and soil and irrigation management largely influence the yield impact. For example, for citrus spp., a sensitive crop abundant in the study area. Grattan, et al. (2015) [37] established that an irrigation water B concentration of 0.3–0.5 mg L^{-1} is secure for long-term irrigation providing soils are well drained, an average rainfall of 250 mm occurs annually, adequate supplies of water are available, and good irrigation management practices are used, such that average seasonal leaching fractions of 20% are readily achieved. If soil, climate, and/or irrigation conditions do not meet those requirements (i.e., poorly drained soils, extremely dry conditions), B concentration limit might not provide appropriate long-term protection. Some local studies have not reported phytotoxicity in banana crops related to B exposition after 30 years of irrigation with DSW [19].

The desalination process by RO removes not only potential harmful salts from seawater, but also cations and anions that represent essential nutrients for plant growth and, also, in some cases (i.e., Ca^{2+}), with a key role in plant development due to its interactions with growth limiting factors, such as plant disease agents [28,29]. In the present study, desalination removed 99.4, 99.6, 98.6, 99.5, and 96.0% of the seawater Ca^{2+}, Mg^{2+}, K^{+}, SO_4^{2-}, and NO_3^{-} contents, respectively, leading to extremely low concentrations of those elements in the DSW for irrigation (Table 3). For instance, the average values for Ca^{2+} and Mg^{2+} in DSW were eight and two times, respectively lower than the minimum levels recommended in DSW in order to avoid soil nutrient imbalances and offset the effect of Na^{+}. Similarly, SO_4^{2-} averaged 4.1 mg L^{-1}, which falls well short of 30 mg L^{-1} as the recommended minimum level in DSW for irrigation purpose [29]. Therefore, several plant nutritional problems (i.e., Ca^{2+}, Mg^{2+}, and S deficiency) that are associated with the intensive use of DSW for irrigation have been reported in different crops [38]. Conversely, long-term irrigation with DSW did not cause nutrient imbalances in an arid environment with calcareous soils of the Canarian archipelago, and even had a positive effect on available phosphorus levels [31]. Those results could be due to the addition of chemical and organic amendments, and the dissolution power of DSW that could dissolve part of the soil calcite.

The low pH and alkalinity found in the DSW appear as one of the main problems that present this water quality, as other authors have already pointed out [29]. The pH of the DSW ranged from 5.2 to 7.0 (mean ~5.8), with 80% of the samples having pH under 6. Although pH is unlikely to cause problems for soils or crops, it could lead to metal corrosion in pipelines, sprinklers, and control equipment, and cause red water episodes due to iron addition from water pipes [29,39]. The quality criteria for DSW agricultural use recommend that pH should be as high as possible up to 8.5, to favour the chemical and biological stability of the water [28,29]. Alkalinity in DSW ranged from 6.0 to 15.0 mg L^{-1}, values much lower than 80 mg L^{-1} $CaCO_3$, the minimum recommended level in DSW for irrigation, and also below the minimum of 25 mg L^{-1} $CaCO_3$ established in the European Directive [40]. An appropriate DSW alkalinity is required to increase buffering capacity and stabilise pH when acidic or basic fertilizers are added, and/or when DSW is mixed with other types of water, particularly GW with low pH [29,41]. Moreover, high DSW alkalinity reduce corrosion in the distribution systems preventing the discharge of metallic ions into the water, and contribute to stabilising the biological processes (e.g., nitrification) in treatment plants that treat wastewater originating from DSW [40].

3.4. Potential Good Practices to Improve the Desalinated Water Quality for Irrigation

The main water quality problems showed led to promoting several good practices to improve the production and handle of DSW in this area. It is a normal procedure to blend the DSW with waters with lower EC and higher pH, as DBW or reclaimed waters, with the aim of balancing the presence of specific ions and increase the pH and alkalinity. Due to the regional water scarcity, it is not a common practice to blend natural water with other water resources. The reclaimed water in this area presents the lowest EC. The standard blending rate is that of 60% (DSW) and 40% (reclaimed water). Besides, the supply of magnesium sulfate to the DSW, directly applied to the water, is a recommended practice.

Additionally, specific innovations that are related to the RO membrane rack design are being put forward. The introduction of B high rejection membranes without modifying the SW pH shows up to 95% of B rejection. Reverse osmosis hybrid membrane inter-stage design is showing a reduction of the EC below 350 μS cm^{-1}, with a slight increase of the energy consumption [42]. In this case, a membrane combination in a seven-elements pressure vessel of 4–5 five high rejection membranes in the first positions and 3–2 low energy elements in the final positions of the pressure vessels is the ideal combination for these purposes.

In the way to propose additional remineralization techniques to warrant the improvement of the DSW, different conventional DSW post-treatment processes could be implemented in this case of increasing the concentrations of Ca^{2+}, Mg^{2+}, and ${SO_4}^{2-}$; reducing the SAR value thanks to the increase of Ca^{2+} vs. Na^+; increasing the pH and alkalinity; and, adjusting the Langelier index. Some of these techniques are adequately mentioned in the literature: sulfuric acid to dissolve calcite (limestone), $CaCO_3$ with gaseous CO_2, Dolomite dissolution or the combination of it with $CaCO_3$, blending with a portion of water not-post-treated [41].

Beyond conventional water post-treatments, some strategies are being established before the application of irrigation water. Some examples are: (1) To increase the levels of calcium in the soil by providing lime or agricultural plaster for organic crops; (2) The use of calcium nitrate and magnesium sulfate for crops with integrated/production certification or conventional system; and, (3) Provide manure and compost to increase the organic matter and ions balance.

4. Conclusions

The use of desalinated seawater (DSW) has been growing, not only in the arid region, but also worldwide. In terms of irrigation, there is an existing gap between water availability and demand, which requires the exploitation of non-conventional water resources to cover the high irrigation demands. Nevertheless, several limiting factors emanate for the whole acceptance of the use of DSW for irrigation, such as the high energy cost of desalination, the high price, the brine discharge impacts in the coastal ecosystem, or the risk that it poses for the soil and crops.

A key agricultural area sited in the Southeast (SE) of Gran Canaria Island has been analyzed to provide qualitative and quantitative information on how DSW, under technical and agronomic criteria, performs in practice.

A agricultural survey has contributed to know the relevant environmental and socio-economic components of the farms in the study area, to describe the key technical practices that are handled due to the use of DSW for irrigation, to identify the crops stratum in the area, and, finally, to contrast the positive perception that the farmers have with the use of AWR in general, particularly with DSW. The surveyed area is mainly irrigated with DSW (31%), following of reclaimed water (25%) and DBW (20%). GW and surface water are being used in a minor scale. They usually blend DSW with DBW and GW. The proportion of reclaimed water is less frequent, but its use is gradually increasing. The DSW price is one of the main problems that the surveyed farmers expressed.

The DSW supply for irrigation in the study area presented EC values slightly higher than the range that was reported by others for DSW used in agriculture in arid territories; an unbalanced and low concentration of Ca^{2+} and Mg^{2+} with respect to Na^+; moderate risks in relation of the SAR and EC combination; and, a negative Langelier index, as well as a low pH and alkalinity. Finally, concerning the specific ions, the DSW supply showed high concentrations of B, Na^+, and Cl^-, which would imply a moderate degree of restrictions on use.

Based on the water quality assessment and, in order to ensure the agrosystems' sustainability in the study area, the farmers improved the DSW quality while using several techniques joined with appropriate soil management practices. Beyond conventional techniques, a typical procedure is to blend the DSW (60%) with waters with lower EC and higher pH, as DBW or reclaimed waters, with the aim of balancing the presence of specific ions and mainly increasing the pH and alkalinity. Appropriate management practices are indeed required, particularly the application of calcium and organic amendments and adequate leaching fractions, to prevent progressive soil degradation.

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