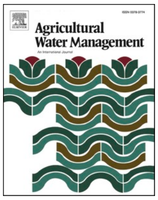
Agricultural Water Management 299 (2024) 108877

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat



Irrigation of young grapefruits with desalinated seawater: Agronomic and economic outcomes

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ARTICLE INFO

Handling Editor - R. Thompson

Keywords:
Water management
Citrus production
Soil sodicity
Phytotoxicity
Water scarcity

ABSTRACT

Given the current scarcity of freshwater resources, it is imperative to explore new agricultural management options to sustainably enhance food production. Desalinated seawater (DSW) presents a promising solution for irrigation in water-stressed regions. However, its application in perennial crops has been poorly assessed, potentially posing challenges to existing cultivation practices due to higher associated costs, salinity, and the presence of potentially harmful elements, notably boron (B). To address these uncertainties, a three-year experiment was conducted to evaluate the short-term effects of irrigation with DSW on a ‘Rio Red’ grapefruit orchard. Four irrigation treatments were assessed: DSW, freshwater (FW), a 1:1 mixture of DSW and FW (MW), and DSW with reduced B concentration (DSW–B). At present, the young age of the trees (3.5 years) and their grafting onto a five-year-old rootstock at the beginning of the experiment likely facilitated rapid foliar mass development and prevented the accumulation of phytotoxic elements up to critical levels. However, local DSW consistently exceeded recommended citrus thresholds for B (0.5 mg L^{-1}), sodium (Na^+; 115 mg L^{-1}), and chloride (Cl^-; 250 mg L^{-1}) in irrigation water, resulting in significant concentrations of B (2.1 mg kg^{-1}), Na^+ (504 mg L^{-1}) and Cl^- (476 mg L^{-1}) in soil. Moreover, these levels led to concentrations in leaves close to defined thresholds in the case of Na^+ (0.25 g 100 g^{-1}), and exceeded them in the case of B (>250 mg kg^{-1}). Although fruit quality remained unaffected, variability in yield among trees and the cost disparity between water resources, resulted in slight fluctuations in the income-outcome balance during initial cultivation years. Our findings offer insights into the irrigation of sensitive crops with DSW, aimed at mitigating potential soil and plant harm from early accumulation of phytotoxic elements. Further research is warranted to explore the impact of both single and sustained DSW usage for irrigation purposes.

1. Introduction

In the last few decades, water shortages have become a major concern for farmers, mainly in arid and semi-arid regions such as Mediterranean countries (Bar-Tal et al., 2017; Martínez-Alvarez et al., 2023). A good example of a region affected by severe water scarcity is the Segura River basin district (SRB), in south-eastern Spain. It is the third most water stressed European basin after Cyprus and Greece, with

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Abbreviations: B, Boron; Ca^{2+}, Calcium; Cl^-, Chloride; DSW, Desalinated Seawater; DSW–B, Desalinated Seawater with reduced Boron; DW, Dry Weight; EC, Electrical Conductivity; ECI, External Colour Index; ED, Equatorial Diameter; FW, Fresh Water; K^+, Potassium; Mg^{2+}, Magnesium; MI, Maturity Index; MW, Mixed Water; N, Nitrogen; Na^+, sodium; NH_4^+, Ammonium; NO_3^-, Nitrate; NVZ, Nitrate Vulnerable Zone; P^{3+}, Phosphorus; PO_4^{3-}, Phosphate; PT, Peel Thickness; PTI, Peel Thickness Index; SAR, Sodium Adsorption Ratio; SI, Side Index; ShI, Shape Index; SO_4^{2-}, Sulfate; SRB, Segura River Basin; TA, Titratable Acidity; TSS, Total Soluble Solids.

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https://doi.org/10.1016/j.agwat.2024.108877
Received 20 November 2023; Received in revised form 8 May 2024; Accepted 11 May 2024

a water exploitation index close to 30% (European Environmental Agency, 2022). The basin covers an irrigation area of 261,626 ha and supports an annual structural water deficit above 281 hm^3; *i.e.* 1074 m^3 ha^{-1} (CHS, 2022). Such a deficit is not only eventually threatening regional agriculture but also water security and the economic growth of Spain (Martínez-Alvarez et al., 2017; Arahuetes et al., 2018). For the SRB to continue being one of the regions with the largest fruit and vegetable production and exportation rates worldwide (Pellicer-Martínez and Martínez-Paz, 2018; MAPA, 2021), the exploration of new alternative sources of water is required in order to sustain its agricultural productive system (Martínez-Mate et al., 2017; Pellicer-Martínez and Martínez-Paz, 2018).

Non-conventional water resources, such as brackish water, reclaimed water, and desalinated seawater (DSW), have become promising aids for irrigation in water-starved regions (Awaad et al., 2020; Redondo-Orts and López-Ortiz, 2020). The availability of these resources can help to both reduce the overuse of surface water and groundwater as well as to build confidence among farmers who can keep their businesses operating, if appropriate agronomic practices are implemented. Since 2005, seawater desalination has been politically fostered to sustain socioeconomic development and food production in Spanish coastal water-stressed areas (Martínez-Alvarez et al., 2017; Arahuetes et al., 2018). However, for its complementary use in agriculture irrigation certain pros and cons must be considered (Martínez-Mate et al., 2017; Martínez-Alvarez et al., 2023).

On the positive side, DSW represents a plentiful, inexhaustible, and steady coastal water source, which enables climatological and hydrological constraints to be overcome (March et al., 2014; Martínez-Alvarez et al., 2019). It could also contribute to guaranteeing long-term food security and socio-economic stability in coastal regions where water supplies are scarce or unreliable (Martínez-Alvarez et al., 2016; Aznar-Sánchez et al., 2017). Concerning the agronomic aspects, its low salinity may boost crop productivity when it is used to replace marginal low-quality waters (Kaner et al., 2017), leading to a reduction in total irrigation requirements (Russo and Kurtzman, 2019). In this context, Martínez-Alvarez et al. (2023) recently conducted a multidisciplinary assessment of the agricultural supply of DSW in south-eastern Spain. They indicated that DSW can potentially decrease total irrigation requirements (m^3 ha^{-1}) by up to 6.5% and 8.6% for vegetables and citrus crops, respectively, when it is used as the only resource for irrigation, thereby leading to an increase in crop production value (€ ha^{-1}) of around 17.0% and 21.3% in each case.

On the contrary, the main drawbacks are (i) the high energy consumption for DSW production and allocation (4−5 kW·h m^{-3}) (March et al., 2014; Martínez-Alvarez et al., 2017), which results in higher supply costs than for other water sources; and (ii) its singular chemical composition, with a very low concentration of essential nutrients such as calcium (Ca^{2+}), magnesium (Mg^{2+}) and sulfate (SO_4^{2-}) therefore requires fertilization programs to be adapted in order to prevent adverse effects on crop productivity and on the environment (Ben-Gal et al., 2009; Martínez-Granados et al., 2022). Different studies have also highlighted the potential risk of soil sodicity associated with irrigation using DSW, owing to high Na^+ concentrations which may damage the soil physical properties (Maestre-Valero et al., 2020; Vera et al., 2023). In addition to Na^+, DSW usually presents high concentrations B and Cl^-, which may imply phytotoxicity risks and harmful effects for crop productivity (Martínez-Alvarez et al., 2019), especially in sensitive woody crops (Hilal et al., 2011). B toxicity threshold in irrigation water for citrus has been set at 0.5 mg L^{-1} (Maas, 1990; Nable, 1997), while vegetable crops are moderately tolerant (1.0 – 4.0 mg L^{-1}), which could be partially explained by their seasonal nature (Maas, 1990). In this context, the nutrient supply to the crops may be affected, as it requires specific management of irrigation water and fertilizers depending on the type of water available (Ben-Gal et al., 2009).

Desalinated reclaimed and well water have also been previously assessed for irrigation on vegetable crops (Sánchez et al., 2015; Silber et al., 2015; Hakkwan et al., 2020; García-Valverde et al., 2023), and woody crops in the short-term (Pérez-Pérez et al., 2015; Vivaldi et al., 2019, 2021) and medium to long-term (Romero-Trigueros et al., 2014, 2020; Nicolás et al., 2016). However, the agro-physiological concerns of irrigation with DSW are less well known. In this sense, research has mainly focused on fertigation issues and yield rates changes (Ben-Gal et al., 2009; Karami et al., 2015; Rahimi et al., 2021) rather than other physiological and agronomic impacts for which very little information is available. As of the present, there are few research that have initiated short-term studies concerning the effects of DSW on woody crops. For instance, Maestre-Valero et al. (2020) reported non-significant effects on phytotoxicity responses when young mandarin trees were irrigated with DSW. This circumstance was mainly explained by the young age of the trees; three years old at the beginning of the trial. It is particularly notable that Vera et al. (2023) demonstrated relevant effects when irrigating lemon and apricot trees with DSW for three consecutive years. Both species showed an accumulation of B in leaves that exceeded the phytotoxicity threshold. On the contrary, DSW irrigation also increased the water-soluble nitrogen content and the urease protein activity, which may have special relevance in impoverished soil areas. Furthermore, those authors' results suggested that DSW irrigation increases soil microbial biomass but also harms the physiological status of the most sensitive crops, *i.e.*, citrus crops. Nevertheless, recent research (Navarro et al., 2022, 2023) have demonstrated, under walk-in controlled environment room, that there must be some mechanisms depending on the rootstock that allow citrus plants to withstand different DSW irrigation effects. This may be related with the age of the plant, the concentration of total dissolved solids and the irrigation water temperature. Therefore, the wide range of factors that appear to affect the response of plants to DSW irrigation may hinder comparisons and the establishment of sound conclusions.

The aim of this study was to evaluate the main agronomic and economic implications of irrigating a grapefruit tree orchard with DSW for the first time. The effects on tree water relations, leaf mineral concentrations, soil salinity and sodicity, and fruit yield were evaluated for three consecutive seasons. Additionally, an economic assessment was performed, focusing mainly on the type of irrigation water and the fertilizer consumption. These results are the first stage of a long-term study and may provide important guidance for DSW use and management in water scarce semiarid areas, where low-quality waters are commonly used for irrigation. Moreover, this study provides valuable insights into the early response of citrus cultivation to continuous irrigation with DSW, thereby aiding farmers in managing their crops, particularly during the initial cultivation years.

2. Materials and methods

2.1. Experimental site and crop selection

The experimental work was carried out at an open-air commercial farm located in Torre Pacheco, Murcia, Spain (37º47'30'' N; 1º03'85'' W; 30 m above sea level), between June 2019 and December 2022. The area is characterized by a Mediterranean semi-arid climate with overall warm, dry summers and mild winters. The average annual reference evapotranspiration (ET_0) and rainfall are 1200 mm and 400 mm, respectively. The orchard comprised 0.28 ha planted with 'Rio Red' grapefruit trees (*Citrus x paradisi* Mac.) newly grafted onto five-year-old macrophylla rootstock (*Citrus macrophylla*) at the beginning of the experiment. The trees were spaced at intervals of 5.5 by 3.5 m. This particular specie was selected due to the widespread cultivation of citrus in Europe and the Mediterranean region, as well as its sensitivity to B excess

2.2. Irrigation treatments and water quality

Two water sources were available at the farm: (i) DSW provided by the coastal desalination plant of Escombreras (30 km from the farm); and (ii) fresh water provided by the Campo de Cartagena irrigators community (FW). For the trial, both sources were used alone and as a blend in equal proportions of both sources (MW = 50% DSW + 50% FW). The price of the DSW available throughout the experiment increased from 0.60 € m^{-3} in 2019 to 1.10 € m^{-3} in 2022, whilst the price of the FW stayed steady at 0.35 € m^{-3}. In addition, it must be highlighted that the Escombreras DSW presented a B concentration of around 0.95 mg L^{-1}, since DSW production in Spain was regulated by the Royal Decree 140/2003, which indicated the sanitary criteria for the quality of DSW for human consumption and set a maximum B concentration of 1 mg L^{-1}. This might lead to phytotoxicity and harmful effects for crop productivity if DSW was permanently used for irrigation (Martínez-Alvarez et al., 2019), according to citrus bibliographic thresholds for B (Maas, 1990; Nable, 1997; Grattan et al., 2015). Moreover, the current Royal Decree 3/2023 has recently allowed an even higher B concentration of up to 2.4 mg L^{-1} in water from desalination, which could further jeopardize the maintenance of woody crops production. Therefore, an on-farm reverse osmosis (RO) system, fully described in Imbernón-Mulero et al. (2022), was used to reduce the B concentration in the DSW by up to between 0.2 and 0.4 mg L^{-1} (DSW−B) in order to assess the effects of low, mid, and high concentrations of B in the irrigation water.

A total of four irrigation treatments were then applied: FW, DSW, MW, and DSW−B (Fig. 1). The experiment took the form of three completely randomized groups, with each group having four experimental plots (one plot per water treatment) of 4 × 3 trees. In each plot, border trees were excluded from the study to eliminate potential edge effects, with only the two central trees being carefully monitored.

Water samples were collected in glass bottles for each water source on a monthly basis during the experiment. They were then transported in an icebox to the laboratory and stored at 5 ºC before processing for physical and chemical analyses. The electrical conductivity (EC) of the water was measured with a conductivity instrument GLP-31 (Crison Instruments S.A., Barcelona, Spain), and the pH with a pH-meter GLP-21 (Crison Instruments S.A., Barcelona, Spain). Inductively coupled plasma (ICP-MS Agilent Technologies, Model 7900, Santa Clara, CA, USA) was used to determine the concentrations of Na^+, K^+, NH_4^+, Ca^{2+}, Mg^{2+}, and B^{3+}. Anions (Cl^-, NO_3^-, PO_4^{3-} and SO_4^{2-}) were quantified by ion chromatography with a liquid chromatograph (Thermo Scientific Dionex, Model ICS-2100, Thermo Scientific, Basel, Switzerland).

2.3. *Irrigation system and water management*

The irrigation system consisted of two polyethylene drip lines laid on the soil surface, one on either side of the tree. Four self-pressure compensating emitters per tree provided a discharge of 4 L h^{-1} each. Emitters were placed at 0.50 m from the trunk and spaced 1.00 m apart. The irrigation doses were scheduled on the basis of the daily crop evapotranspiration (ET_c) accumulated during the previous week. The daily ET_c values were estimated by multiplying the daily reference evapotranspiration (ET_0), calculated with the Penman–Monteith methodology, by the month-specific crop coefficients for citrus, and considering possible precipitation. The meteorological data to calculate ET_0 and to obtain rainfall measurements were gathered from the nearest automatic weather station (CA-42) belonging to the *Agrarian Information Service of Murcia Region*. Additionally, two soil water content probes (HydraProbe II—Stevenswater, Portland, OR, USA) per plot were installed at 0.25 m and 0.50 m depths and connected to an automatic datalogger CR1000 (Campbell Scientific, Logan, UT, USA) for continuous soil moisture monitoring and to ensure an accurate and adequate supply of water during the experimental work.

The irrigation head consisted of a principal feed pump, electrovalves, five fertilizer injection lines, disk filters, an electrical subsystem and the automatic fertigation programmer for optimal water and fertilizer management. All the treatments received identical amounts of fertilizer (N, P, K, Ca, Mg, Cu, and Fe) supplied through the drip irrigation system, regardless of the water quality (see Table 1). This enables the possible effects of the implementation of DSW to be analyzed, which could otherwise be potentially hidden if the fertilizer supply had been adjusted based on the nutrient contents of the irrigation water and the crop requirements. Pest control practices and pruning were those commonly used by farmers in the area, and no weeds were allowed to develop within the orchard.

It must be highlighted that the nutrient requirements referred to in Table 1 may differ from the recommendations for the Rio Red grapefruit variety found in the literature (Wiedenfeld et al., 2009; Legaz et al., 2010; Pérez-Pérez et al., 2015). These differences are mainly due to the fact that the farm is located in a Nitrates Vulnerable Zone (NVZ), where farmers must comply with fertilizer control laws (Royal Decree 261/1996, Law 3/2020 of recovery and protection of Mar Menor, and Order 12/2019 of Nitrates Vulnerable Zones). Table 2 shows the fertilizers used during the experimental work.

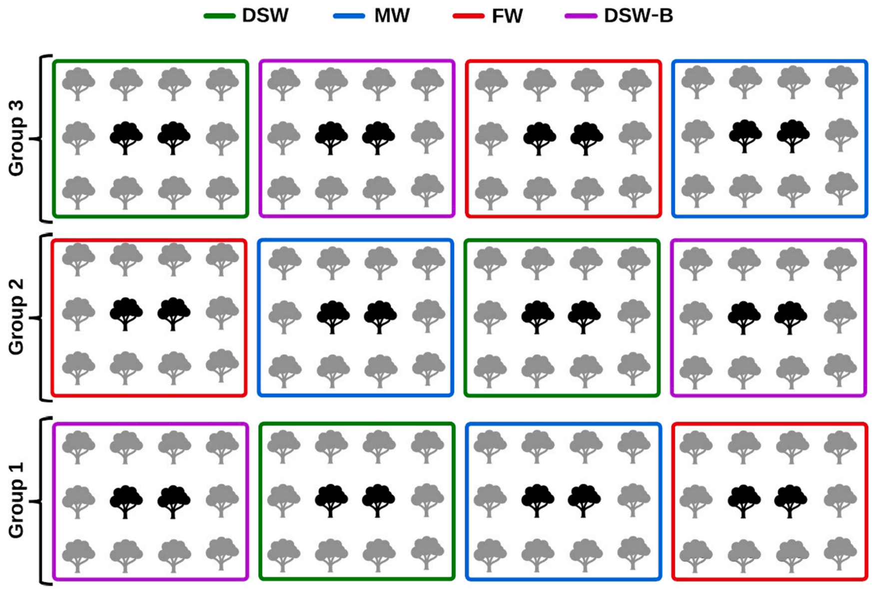

Fig. 1. Configuration of the grapefruit orchard and irrigation treatments (Desalinated seawater; DSW, Mixed water; MW, Fresh water; FW, Desalinated seawater with reduced boron; DSW−B). Black trees were monitored for plant determinations.

Table 1
Citrus x paradisi (*cv.* Rio Red) nutrient requirements supplied during the experimental work (June 2019 to December 2022).

Year	N (kg ha^{-1} $year^{-1}$)	P (kg ha^{-1} $year^{-1}$)	K (kg ha^{-1} $year^{-1}$)	Ca (kg ha^{-1} $year^{-1}$)	Mg(kg ha^{-1} $year^{-1}$)	Cu (kg ha^{-1} $year^{-1}$)	Fe (kg ha^{-1} $year^{-1}$)
2019*	22.64	3.19	17.68	0.00	0.00	0.00	0.49
2020	41.71	3.19	15.49	8.62	3.12	0.00	0.41
2021	46.46	0.82	17.36	10.52	3.96	0.39	1.51
2022	144.92	7.43	66.03	29.79	5.52	0.64	2.08

[*] Only 7 months of fertilization (June-December) were considered after the grafting in June 2019.

Table 2
Main characteristics of the fertilizers used during the experimental work.

Commercial fertilizer	N−P−K + Ca + Mg richness	Complementary supply	Price (€ L^{-1}, € kg^{-1})
Novatec fluid engorde	7.5−1.1−5.6	-	0.27
Novatec fluid maduracion	4.6−1.0−5.7	-	0.38
Brotolim primavera + Ca + Mg	10−0.9−4.2 + 2.5 + 0.9	-	0.45
Brotolim primavera MM + Ca + Mg	10−0−4.2 + 2.1 + 0.9	-	0.55
Brotolim engorde + Ca	8−0.9−5 + 1.8	-	0.56
Brotolim eco N-AA	8.2−0−0	12% amino acids	1.95
Calcytron	8−0−0 + 11.1	-	0.24
Vitaseve (Biostimulant with micronutrients)	-	Mg 3% + Mo 0.1% + B 0.2% + Mn 0.5% + Zn 0.5%	9.00
Unicquel (Iron chelate)	-	Fe 6%	6.90
Copper shuttle	-	Cu 6.13%	8.50
SoluBlack H-87	1.2−0.4−6.6 + 2.6 + 0.1	70% humic acids + 15% fulvic acids	7.00

2.4. Soil characterization

The area surrounding one central tree in each replicate was selected to collect data for the analyses. Three soil samples of each irrigation treatment were collected per replicate three times per year at 0–0.25 m and 0.25–0.50 m depths and 0.30 m away from the emitter. A total of 264 soil samples were collected during the experiment. Soluble salt contents were determined in the saturated paste extract as described by Rhoades (1982). The EC of the saturated paste extract (EC_e) and the pH were measured as previously detailed in Section 2.2. An inductively coupled plasma (ICP-MS Agilent Technologies, Model 7900, Santa Clara, CA, USA) was used to determine the concentration of water-soluble Cl^-, Na^+, Ca^{2+} and Mg^{2+}. The sodium adsorption ratio (SAR_e) was also calculated from the concentration of Na^+, Ca^{2+}, and Mg^{2+} measured in the saturated paste extract. The sodicity risk due to the irrigation water quality was analyzed based on the relationship between the SAR_W and the EC_W (Mass and Hoffman, 1977). Extractable B was determined in soil samples by refluxing 20 g soil with 40 mL hot water (boiling) for a period of 5 min. One aliquot from the filtered extract was then used for measuring B^{3+} using an inductively coupled plasma (ICP-MS Agilent Technologies, Model 7900, Santa Clara, CA, USA).

2.5. Plant determinations

Plant determinations were conducted in the same trees, the two central trees of each group (Fig. 1) were selected for leaf mineral analysis and to evaluate the yield and the fruit quality. In addition to the analyses detailed in the following Sections 2.5.1 and 2.5.2, the stem and leaf water and osmotic potentials were measured periodically in order to ensure the adequate condition of the trees (Supplementary information, Table S1).

2.5.1. Leaf mineral analysis

Leaf samples were periodically taken for mineral analysis of leaf macronutrients and micronutrients. Two types of leaves (old and young leaves) were studied throughout the experiment. The oldest leaves of the trees were considered ‘old’ while spring bud leaves were considered as ‘young’. A random sample procedure of 16 leaves was conducted, four leaves from each cardinal direction. Old leaves were taken every four months from the planting onwards, in February, June, and October, whilst spring bud leaves were studied every month from May to November, focusing on the development of new sprouts. In each sampling, six samples were taken per treatment. The leaves were briefly rinsed in deionized water, freeze-dried, and ground for analytical determinations. The dried and ground leaf tissue was dissolved in 0.7 N HNO_3 for macronutrients (P^{3+}, K^+, Ca^{2+}, and Mg^{2+}), micronutrients (Fe, Cu, Mn, and Zn), and phytotoxic elements (Na^+ and B^{3+}) determination by inductively coupled plasma optical emission spectrometry (Varian ICP-OES Vista MPX). Cl^- and NO_3^- were extracted from 50 mg of ground plant material with 25 mL of deionized water and measured by ion chromatography with a liquid chromatograph (Model ICS-3000, Thermo Fisher Scientific Inc., USA). The nitrogen concentration was determined with a LECO FP−428 protein detector.

2.5.2. Yield and fruit quality

In early February 2022 and late December 2022, the individual tree yield was analyzed in six trees per treatment (two trees per group). The number of fruits and the total fruit weight of each tree were measured. A sample of 15 fruits per tree was collected, randomly, from the six trees per treatment, for fruit quality analysis. The external peel colour was measured using a tri-stimulus colour difference meter (Minolta CR-300), at three locations around the equatorial plane of the fruit. The Hunterlab parameters L, a* and b* were used, and the external colour index (ECI) was calculated using the equation:

$$ECI = \frac{a^* * 1000}{L * b^*} \tag{1}$$

where *L* indicates lightness, while a* and b* are the chromaticity coordinates.

The fruits were cut in the equatorial area and the peel thickness (PT) was measured at three points with a digital caliper. The peel thickness index (PTI) was calculated using the following equation:

$$PTI = \frac{PT * 2 * 100}{ED} \tag{2}$$

where *PT* indicates peel thickness (mm) and *ED* the equatorial diameter (mm).

The side index (SI) and the shape index (ShI) were calculated as follows:

$$SI = \frac{ED + LD}{2} \tag{3}$$

$$ShI = \frac{LD}{ED} \tag{4}$$

where *ED* and *LD* indicate equatorial and longitudinal diameters respectively.

The fruits were squeezed, and the juice was filtered to measure the

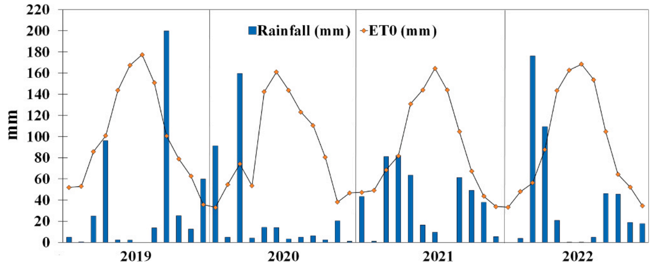

Fig. 2. Distribution of reference evapotranspiration (ET_0; mm) and precipitation (mm) throughout the experiment. Data collected from the nearest automatic weather station (CA–42, Fuente Alamo, Balsapintada) belonging to the *Agrarian Information Service of Murcia Region*.

total soluble solids (TSS) and TA (titratable acidity). The maturity index (MI) was expressed as the TSS×10/TA ratio. The TSS of the juice was measured at 25 °C with a digital refractometer (Atago, Palette PR100) and the TA (expressed as percentage of citric acid in the juice) was determined by titration with 0.1 N NaOH to pH 8.1, using an automatic titrator (CRISON TitroMatic 2 S, Crison Instruments S.A., Barcelona, Spain). Mineral analysis of the juice was conducted after centrifugation at 4500 rpm using an inductively coupled plasma optical emission spectrometry Varian ICP-OES Vista MPX (K^+, Ca^{2+}, Mg^{2+}, Na^+, and B^{3+}).

2.6. *Economic assessment*

An elementary economic assessment was performed to evaluate the economic impact of implementing DSW in irrigation. The analysis considered the cost of the irrigation water required for each treatment (DSW, MW, FW, and DSW–B) and the fertilizer cost as outcomes, whilst the economic return calculated for the sale of the fruit each season (0.27 € kg^{-1}; MAPA, 2022) was the main income. The analysis was performed considering the same fertilizer requirement regardless of the nutrient contents of the irrigation water and the crop requirements as mentioned in Section 2.3. Additionally, in order to assess the hypothetical impact of an adjusted fertilization, the economic impact was also conducted evaluating variable fertilizer supply depending on the nutrient contents of each irrigation water.

2.7. *Statistical analysis*

Statistical analysis was performed as a weighted analysis of variance (ANOVA; statistical software IBM SPSS Statistics v. 21 for Windows). The Shapiro–Wilk test ($p < 0.05$) was used to evaluate the normality of the data. Tukey's Honestly Significant Difference (HSD) test ($p \leq 0.05$) was used for mean separation. Unless otherwise stated, the significance level was $p \leq 0.05$.

3. Results and discussion

3.1. *Irrigation water quality and volume supplied*

All the experimental treatments received the same amount of irrigation water (930.9 m^3 ha^{-1} between June 2019 and December 2019; 1313.3 m^3 ha^{-1} in 2020; 2409.8 m^3 ha^{-1} in 2021; and 3145.7 m^3 ha^{-1} in 2022). It should be noted that the clear difference in water consumption between 2020 and 2022 occurred due to the accelerated growth of the trees after grafting on five-year-old rootstock, as well as the trees entering their productive phase. In addition, precipitation contributed 313.04 mm between June 2019 and December 2019, 326.15 mm in 2020, 450.03 mm in 2021, and 443.40 mm in 2022 (Fig. 2).

Table 3 displays the water quality data for the DSW, FW, MW, and DSW–B treatments used during the experimental work, indicating particular differences among them; especially with respect to the DSW–B. The DSW had a slightly higher pH (pH = 8.2) compared with the FW (pH = 7.7), which remained almost neutral throughout the experiment. In contrast, the DSW–B pH was strongly basic (pH around 9.5) due to the addition of NaOH to reduce the B concentration in the DSW. The EC_w of the DSW was 0.92 dS m^{-1} due to the large removal of salt in the one-stage RO process in the Escombreras desalination plant, whilst the DSW–B presented a much lower value (0.23 dS m^{-1}) since the DSW was treated on-farm by a second RO stage. Nevertheless, the higher concentration of Na^+ around 140 mg L^{-1} and the lower concentrations of both Ca^{2+} and Mg^{2+} in the DSW led to higher SAR_w values than the FW; 5.87 and 2.88 meq L^{-1}, respectively. These findings concur with previous studies that have already used DSW and FW for crop irrigation in southeastern Spain (Maestre-Valero et al., 2020; Navarro et al., 2022; Vera et al., 2023). Although RO membranes allow a high reduction of undesirable salts from seawater (> 95%), they also remove, owing to the different selectivity for each ion (Kayaci et al., 2020), nutrients that are essential for plant growth, such as Ca^{2+}, Mg^{2+}, and SO_4^{2-} (Yermiyahu et al., 2007). In this sense, a one-stage RO process can effectively retain

Table 3
Price and values of physical and chemical properties of the water sources used during the experimental work and B, Na^+, and Cl^- phytotoxicity thresholds proposed for citrus crops. Data were averaged from 40 samples taken between June 2019 and December 2022.

Water resource	DSW	MW	FW	DSW–B
pH	8.22 ± 1.17^b	7.82 ± 0.58^b	7.74 ± 0.27^b	9.49 ± 0.12^a
EC_w (dS m^{-1})	0.92 ± 0.33^{ab}	1.07 ± 0.33^a	1.22 ± 0.30^a	0.23 ± 0.10^b
Cl^- (mg L^{-1})	226.53 ± 79.79^a	215.21 ± 77.59^a	198.10 ± 31.62^a	7.53 ± 6.68^b
NO_3^- (mg L^{-1})	2.90 ± 2.16	4.36 ± 2.68	5.71 ± 3.58	1.79 ± 1.25
PO_4^{3-}(mg L^{-1})	2.87 ± 1.64	2.56 ± 1.63	2.03 ± 1.60	1.66 ± 0.94
SO_4^{2-}(mg L^{-1})	9.61 ± 6.42^c	105.80 ± 58.63^{ab}	215.66 ± 75.50^a	1.47 ± 1.02^d
NH_4^+ (mg L^{-1})	0.00^b	2.21 ± 2.11^a	2.79 ± 1.98^a	0.00^b
K^+ (mg L^{-1})	8.14 ± 5.40	7.05 ± 3.84	6.49 ± 3.61	1.83 ± 1.76
Ca^{2+} (mg L^{-1})	32.85 ± 22.49^a	47.57 ± 14.14^a	73.48 ± 19.41^a	2.61 ± 1.30^b
Mg^{2+} (mg L^{-1})	6.11 ± 5.68^b	23.69 ± 9.81^{ab}	44.75 ± 16.70^a	1.65 ± 0.98^b
Na^+ (mg L^{-1})	139.83 ± 50.31^a	133.55 ± 47.03^a	126.90 ± 21.11^a	13.78 ± 11.44^b
B (mg L^{-1})	0.92 ± 0.17^a	0.69 ± 0.19^{ab}	0.44 ± 0.13^b	0.32 ± 0.08^b
SAR_w (meq L^{-1})	5.87 ± 1.20^a	4.01 ± 1.00^{ab}	2.88 ± 0.70^{ab}	1.64 ± 1.64^b
[Na^+] threshold for citrus	115 mg L^{-1} (Maestre-Valero et al., 2020)			
[Cl^-] threshold for citrus	350 mg L^{-1} (Hanson et al., 2006); 152–238 mg L^{-1} (Grattan et al., 2015)			
[B] threshold for citrus	0.50 mg L^{-1} (Maas, 1990; Nable et al., 1997)			
Price (€ m^{-3})*	0.60–1.10	0.48–0.73	0.35	0.93–1.43

* The prices of MW and DSW–B resources varied due to the increase in DSW price throughout the experiment. In each year, means with different letters indicate significance according to Tukey's HSD test ($p \leq 0.05$), while no letter indicates non-significant differences.

99.81% and 98.93% of Na^+ and Cl^-, respectively (Jones et al., 2019). Nevertheless, both ions represent the main source of salt in seawater (30.7% and 55.2%, respectively) (Murugaiyan and Sivakumar, 2008), and hence, even with such a removal percentage, a higher presence of both ions is found in DSW compared to FW. Additionally, the high B concentration in the DSW is commonly explained by the poor selectivity of the membranes for this ion (50–80% at normal feedwater pH values) (Dydo et al., 2014). The DSW hence presented B concentrations of 0.92 ±0.17 mg L^{-1}, 0.44±0.13 mg L^{-1} in FW, and 0.32±0.08 mg L^{-1} in DSW−B. In short, the concentration of B in the DSW and MW and of Na^+ in all sources except for the DSW−B exceeded the maximum threshold referenced for citrus irrigation, meaning that the crop might be harmed. The Cl^- level remained within the bounds of phytotoxicity throughout the experiment (Table 3). These concentrations were within the range reported in previous studies (180–250 mg L^{-1}) (Díaz et al., 2013; Maestre-Valero et al., 2020; Vera et al., 2023). It is of note that the second on-farm RO stage produced DSW−B with Cl^-, Na^+, and B concentrations below their phytotoxic thresholds (7.5, 13.0 and 0.3 mg L^{-1}, respectively), hence avoiding possible detrimental effects.

3.2. Evolution of soil salinity, sodicity and toxic elements

The soil in the agricultural plot was primarily sandy (62%; 20% clay; 18% slime), with a basic pH between 8 and 9 and a calcium carbonate presence of 44.6%. Supplementary information (Table S2) provides the average soil composition at the beginning of the experiment, which was used to devise the necessary fertigation plan to meet the nutritional requirements of the crop. Table 4 shows the evolution of EC_e, SAR_e, water soluble Cl^- and Na^+ and soil extractable B for each irrigation treatment (DSW, MW, FW, and DSW−B) from June 2019 to October 2022, at depths of 0−0.25 m and 0.25−0.50 m. Noticeably wide variations in EC_e, SAR_e, and ions were measured at the beginning of the experiment among the samples collected at different points in the orchard. This non-homogeneity could be explained by the soil reconditioning performed to enhance the crop ridges as well as a 90 mm rain in April 2019 (Fig. 2). That figure displays the monthly ET_0 and precipitation (mm) throughout the study period, with two main severe and sudden rainfall periods, *i.e.*, March−April and September−October, which could have negatively affected the soil stability (Šarapatka and Bednář, 2022). Considering these circumstances, EC_e and SAR_e showed continuous intervals of leaching and accumulation periods, mainly caused by the high frequency of irrigation and said rainfall events.

The soil irrigated with the DSW showed significantly lower EC_e than with FW irrigation due to the lower salt content of the DSW (Ben-Gal et al., 2009; Vera et al., 2023). In spite of this positive effect and bearing in mind the relationship between EC_w and SAR_w, irrigation with DSW, MW and, especially DSW−B, could induce a slight to moderate sodicity risk into the soil (Tables 3 and 4), due to the high Na^+/Ca^{2+} and Na^+/Mg^{2+} rates. However, as these waters present low EC_w, this negative impact could be mitigated to a certain extent by increasing the

Table 4

Yearly average soil electrical conductivity (EC_e; dS m^{-1}), sodium adsorption ratio (SAR_e; meq L^{-1}), water soluble Cl^- and Na^+ (mg L^{-1}) and extractable boron (B; mg kg^{-1}) at 0−0.25 m and 0.25−0.50 m depths and for each irrigation water.

Water resource	Parameter	2019*	2020	2021	2022	Average (2019−2022)
DSW	**EC_e**	2.72 ± 0.21^{bc}	2.31 ± 0.36^{b}	1.93 ± 0.62^{b}	2.96 ± 0.24	2.48 ± 0.41^{ab}
		1.96 ± 0.31	2.22 ± 0.33^{ab}	2.07 ± 0.22^{b}	3.46 ± 0.33^{ab}	2.43 ± 0.30^{ab}
	SAR_e	2.38 ± 0.71	5.37 ± 0.21^{c}	5.30 ± 0.32^{a}	4.31 ± 0.43^{a}	4.34 ± 0.42^{a}
		2.01 ± 0.59	4.16 ± 0.50^{a}	4.72 ± 0.28^{a}	4.46 ± 0.39^{a}	3.84 ± 0.44^{a}
	Cl^-	249.42 ± 104.98^{ab}	475.81 ± 50.69^{a}	286.79 ± 41.17^{b}	247.66 ± 43.04	314.92 ± 59.97^{a}
		153.69 ± 73.98	315.75 ± 67.17^{a}	272.18 ± 26.98^{a}	295.31 ± 61.86^{ab}	259.23 ± 57.50^{a}
	Na^+	225.38 ± 106.49	504.27 ± 24.37^{a}	383.80 ± 27.75^{a}	287.25 ± 48.31	350.18 ± 51.73^{a}
		170.94 ± 57.27	354.03 ± 31.03^{a}	342.79 ± 23.35^{a}	323.97 ± 37.53	297.93 ± 37.30^{a}
	B	1.57 ± 0.36	1.95 ± 0.22^{a}	2.10 ± 0.27^{a}	1.75 ± 0.22	1.84 ± 0.27
		1.23 ± 0.31	1.68 ± 0.31	1.72 ± 0.28	1.87 ± 0.14^{a}	1.62 ± 0.26
MW	**EC_e**	3.36 ± 0.58^{ab}	3.74 ± 0.46^{a}	3.86 ± 0.88^{a}	3.19 ± 0.84	3.54 ± 0.69^{ab}
		2.45 ± 0.55	2.63 ± 0.26^{ab}	3.38 ± 0.70^{ab}	3.96 ± 0.74^{ab}	3.11 ± 0.56^{ab}
	SAR_e	2.79 ± 0.31	2.62 ± 0.49^{b}	2.93 ± 0.60^{b}	2.84 ± 0.49^{b}	2.79 ± 0.47^{b}
		2.15 ± 0.54	2.45 ± 0.23^{b}	3.30 ± 0.89^{b}	3.62 ± 0.35^{ab}	2.88 ± 0.50^{ab}
	Cl^-	265.61 ± 27.21^{ab}	390.51 ± 52.00^{ab}	315.96 ± 35.63^{ab}	337.78 ± 46.55	327.47 ± 40.35^{a}
		136.02 ± 47.44	300.87 ± 40.15^{a}	258.13 ± 42.09^{a}	389.39 ± 68.48^{ab}	271.10 ± 49.54^{a}
	Na^+	244.33 ± 36.69	252.69 ± 49.76^{b}	258.99 ± 60.19^{b}	309.24 ± 150.03	266.31 ± 74.17^{ab}
		172.17 ± 57.29	217.37 ± 19.91^{b}	277.07 ± 73.03^{a}	361.82 ± 89.58	257.11 ± 59.95^{ab}
	B	1.65 ± 0.35	1.69 ± 0.17^{ab}	1.59 ± 0.27^{ab}	1.52 ± 0.25	1.61 ± 0.26
		1.15 ± 0.28	1.50 ± 0.28	1.39 ± 0.27	1.55 ± 0.27^{ab}	1.40 ± 0.27
FW	**EC_e**	3.93 ± 0.47^{a}	3.81 ± 0.41^{a}	3.48 ± 0.57^{a}	4.35 ± 0.89	3.89 ± 0.58^{a}
		2.77 ± 0.59	3.13 ± 0.44^{a}	3.75 ± 0.78^{a}	4.69 ± 0.53^{a}	3.59 ± 0.59^{a}
	SAR_e	2.25 ± 0.89	2.08 ± 0.28^{b}	2.44 ± 0.56^{bc}	2.48 ± 0.41^{b}	2.31 ± 0.54^{bc}
		1.87 ± 0.51	1.98 ± 0.44^{b}	2.47 ± 0.50^{bc}	3.06 ± 0.54^{b}	2.34 ± 0.50^{bc}
	Cl^-	352.06 ± 122.81^{a}	286.36 ± 49.06^{b}	370.60 ± 24.12^{a}	319.84 ± 33.54	332.21 ± 57.38^{a}
		126.62 ± 75.83	264.24 ± 41.81^{a}	335.35 ± 32.14^{a}	425.66 ± 92.24^{a}	287.97 ± 60.51^{a}
	Na^+	245.95 ± 90.46	172.98 ± 19.67^{c}	251.46 ± 65.97^{b}	242.87 ± 86.58	228.31 ± 78.17^{ab}
		167.45 ± 79.95	168.26 ± 31.33^{b}	259.43 ± 54.34^{a}	304.94 ± 116.73	225.02 ± 71.09^{ab}
	B	1.25 ± 0.40	1.30 ± 0.12^{b}	1.37 ± 0.11^{b}	1.29 ± 0.12	1.30 ± 0.19
		1.15 ± 0.21	1.21 ± 0.24	1.28 ± 0.19	1.24 ± 0.20^{b}	1.22 ± 0.21
DSW−B	**EC_e**	2.16 ± 0.31^{c}	2.05 ± 0.27^{b}	1.94 ± 0.64^{b}	2.60 ± 0.80	2.19 ± 0.51^{b}
		2.18 ± 0.19	1.98 ± 0.38^{b}	1.99 ± 0.64^{b}	2.79 ± 0.83^{b}	2.23 ± 0.51^{b}
	SAR_e	1.45 ± 0.12	0.77 ± 0.09^{c}	1.56 ± 0.18^{c}	2.32 ± 0.29^{b}	1.53 ± 0.17^{c}
		1.84 ± 0.20	1.00 ± 0.10^{c}	1.52 ± 0.12^{c}	2.53 ± 0.51^{b}	1.72 ± 0.23^{c}
	Cl^-	70.40 ± 7.48^{b}	50.62 ± 6.18^{c}	114.41 ± 12.65^{c}	252.05 ± 31.88	121.87 ± 14.55^{b}
		58.34 ± 4.95	61.28 ± 6.35^{b}	121.72 ± 7.72^{b}	219.04 ± 42.45^{b}	115.09 ± 15.37^{b}
	Na^+	120.31 ± 7.10	64.39 ± 5.03^{d}	125.47 ± 13.07^{c}	175.78 ± 45.96	121.49 ± 17.79^{b}
		154.65 ± 12.79	79.30 ± 8.17^{c}	124.13 ± 14.78^{b}	194.42 ± 42.33	138.12 ± 19.52^{b}
	B	1.24 ± 0.13	1.25 ± 0.22^{b}	1.29 ± 0.26^{b}	1.29 ± 0.26	1.27 ± 0.22
		1.17 ± 0.14	1.13 ± 0.12	1.25 ± 0.28	1.27 ± 0.15^{b}	1.20 ± 0.17

[*] Values of two sampling repetitions (June and October); light and dark shading mean surface (0−0.25 m) and depth (0.25−0.50 m) samples, respectively. In each year, means with different letters indicate significance according to Tukey's HSD test ($p \leq 0.05$), while no letter indicates non-significant differences.

amount of Ca^{2+} and Mg^{2+} in the fertigation so as to displace Na^+ from the soil exchange complex (Maestre-Valero et al., 2020). In fact, this is especially required in the DSW and DSW−B irrigation cases, which are often characterized by the lack of Ca^{2+} and Mg^{2+} (lower than 30 and 6 mg L^{-1}, respectively) because of the single and/or double RO processes, respectively. Therefore, these results suggest that continuous soil monitoring is firmly recommended to avoid possible Na^+ damages, such as the structural collapse of soil aggregates, erosion problems and soil compaction (Muyen et al., 2011; Grattan et al., 2015), especially when DSW is not blended with other water resources (Maestre Valero et al., 2020).

The Cl^- and Na^+ concentrations fluctuated throughout the study, owing to possible and continuous soil leaching by irrigation and rain and intermittent absorption of nutrients by the trees. In both cases, the lower values cases were found in 2019 and 2021, after strong rain periods, whereas maximum values were measured during 2020, with soil in DSW treatment accumulating up to 476 mg L^{-1} of Cl^- and 504 mg L^{-1} of Na^+. However, three significant trends were observed in all treatments: firstly, there was a lower variability between the samples taken within the same irrigation treatment as the study proceeded, likely attributed to the soil layers becoming more stabilized over time; *i.e.* less deviation due to nutrient stratification (Rahman et al., 2021; Wacker et al., 2021). Secondly, higher Na^+ and Cl^- concentrations were observed in the surface samples at the beginning of the trial (2019), whereas higher concentrations were found in deeper samples at the end of the trial (2022); this response could be explained by the salt leaching during the trial (Wacker et al., 2021). Finally, notably high Cl^- and Na^+ concentrations were found in the soil irrigated with the FW, even though the DSW had higher concentrations (Table 3). These latter two behaviors might have been related to the low EC_w of the DSW (0.92±0.33 ds m^{-1}). In fact, it has been showed that the low EC_w in the DSW can decrease EC_e by salt leaching to soil lower layers, thereby reducing the presence of salts around roots (Silber et al., 2015). Such an effect would seem to be the case when comparing the results between the DSW, MW, and FW samples (Table 4).

On the contrary, the pattern did not occur for B, in which the soil irrigated with the DSW showed the largest content, associated to its higher concentration in water. Then, the lower the proportion of raw DSW included in the irrigation blend was, the lower the concentration of B in soil was (MW > FW > DSW−B; Table 4). In all treatments, B experienced decreases and increases corresponding to leaching caused by rainfall events and significant supplies from irrigation water, respectively. However, since the presence of B was higher as the presence of raw DSW increased, the B content in the soil was also higher. In any case, B concentration in all the treatments did not exceed common levels found in agricultural soils; 30 mg kg^{-1} according to Vera et al. (2023).

In addition, the potential relationship between B and total N in the soil is worth noting, highlighting its importance especially in NVZ, where the experiment was conducted. Vera et al. (2019), (2021) suggested that B may be involved in the soil nitrogen cycle, and it has been described that it is able to inhibit the nitrate (NO_3^-) reductase enzyme, thereby increasing the available N content for the plant in the soil (Ouzounidou et al., 2013), especially in NO_3^- form (Vera et al., 2023). In our study, the N concentration in the soil, despite being quite alike among treatments, showed variations during the experiment (data not shown in the manuscript). In this context, the widespread adoption of DSW in place of conventional resources for irrigation may lead to potential soil NO_3^- increases, a phenomenon that warrants consideration in future research.

3.3. *Leaf mineral analysis and phytotoxic elements*

During the experiment, both the water and osmotic potentials of leaves and midday stems remained within adequate ranges. It is known that leaf and root mineral nutrition can be modified by irrigating with different mineral composition waters (Syvertsen and Lloyd, 1994). The variable presence of nutrients shown in irrigation waters (Table 3), together with high Na^+ or Cl^- concentrations may produce an imbalance of essential nutrients (Navarro et al., 2022). In fact, the large presence of these ions, especially in the case of DSW irrigation, can even reduce the nutrient uptake by plants due to direct competition between ions (Navarro et al., 2023). As a result, the nutritional balance of plants may be altered, and high and inconvenient Na^+/Ca^{2+}, Na^+/Mg^{2+} ratios, among others, can be found in their tissues, as previously observed by Navarro et al. (2022) when DSW has been used for citrus irrigation.

In the experiment, the mineral nutrition of spring bud and old leaves was affected by the type of irrigation water (Table 5). For example, the treatments with desalinated seawater (DSW, MW, and DSW−B) led to an increase in the Na^+/Ca^{2+} and Na^+/Mg^{2+} ratios, attributed to the higher presence of Na^+ and low concentrations of Ca^{2+} and Mg^{2+}, owing to the RO process used for seawater desalination. However, due to the

Table 5
Effects of the irrigation water on the mineral nutrition in spring bud and old leaves of 'Rio Red' grapefruit trees. N, P^{3+}, K^+, Ca^{2+}, and Mg^{2+} in g 100 g^{-1} DW.

Water resource	**DSW**	**MW**	**FW**	**DSW−B**	***ANOVA***
Spring bud leaves					
N	3.05 ± 0.06	2.94 ± 0.06	2.89 ± 0.06	2.89 ± 0.03	ns
P^{3+}	0.082 ± 0.001	0.084 ± 0.003	0.081 ± 0.003	0.082 ± 0.002	ns
K^+	1.18 ± 0.02	1.13 ± 0.04	1.16 ± 0.05	1.20 ± 0.04	ns
Ca^{2+}	3.20 ± 0.02	3.04 ± 0.09	3.12 ± 0.17	3.24 ± 0.09	ns
Mg^{2+}	0.198 ± 0.002	0.198 ± 0.003	0.203 ± 0.005	0.197 ± 0.005	ns
Na^+/K^+	0.101 ± 0.004	0.099 ± 0.002	0.093 ± 0.001	0.092 ± 0.003	ns
Na^+/Ca^{2+}	0.042 ± 0.003	0.038 ± 0.001	0.037 ± 0.002	0.037 ± 0.001	ns
Na^+/Mg^{2+}	0.71 ± 0.05	0.66 ± 0.01	0.61 ± 0.02	0.63 ± 0.02	ns
Old leaves					
N	3.20 ± 0.04a	3.12 ± 0.02ab	3.03 ± 0.04b	3.06 ± 0.03b	*
P^{3+}	0.076 ± 0.001	0.074 ± 0.000	0.071 ± 0.002	0.075 ± 0.002	ns
K^+	1.43 ± 0.06	1.40 ± 0.10	1.35 ± 0.07	1.45 ± 0.02	ns
Ca^{2+}	3.50 ± 0.06	3.46 ± 0.12	3.46 ± 0.10	3.49 ± 0.04	ns
Mg^{2+}	0.140 ± 0.004	0.148 ± 0.003	0.146 ± 0.005	0.148 ± 0.006	ns
Na^+/K^+	0.107 ± 0.001	0.095 ± 0.005	0.097 ± 0.003	0.092 ± 0.004	ns
Na^+/Ca^{2+}	0.043 ± 0.001a	0.037 ± 0.002b	0.037 ± 0.001b	0.039 ± 0.001ab	*
Na^+/Mg^{2+}	1.15 ± 0.06a	0.92 ± 0.02b	0.90 ± 0.01b	1.00 ± 0.05b	*

[*] In each case, different letters indicate significance and *ns* indicates no significance, according to Tukey's multiple range test at the 99% confidence level ($p \leq 0.01$).

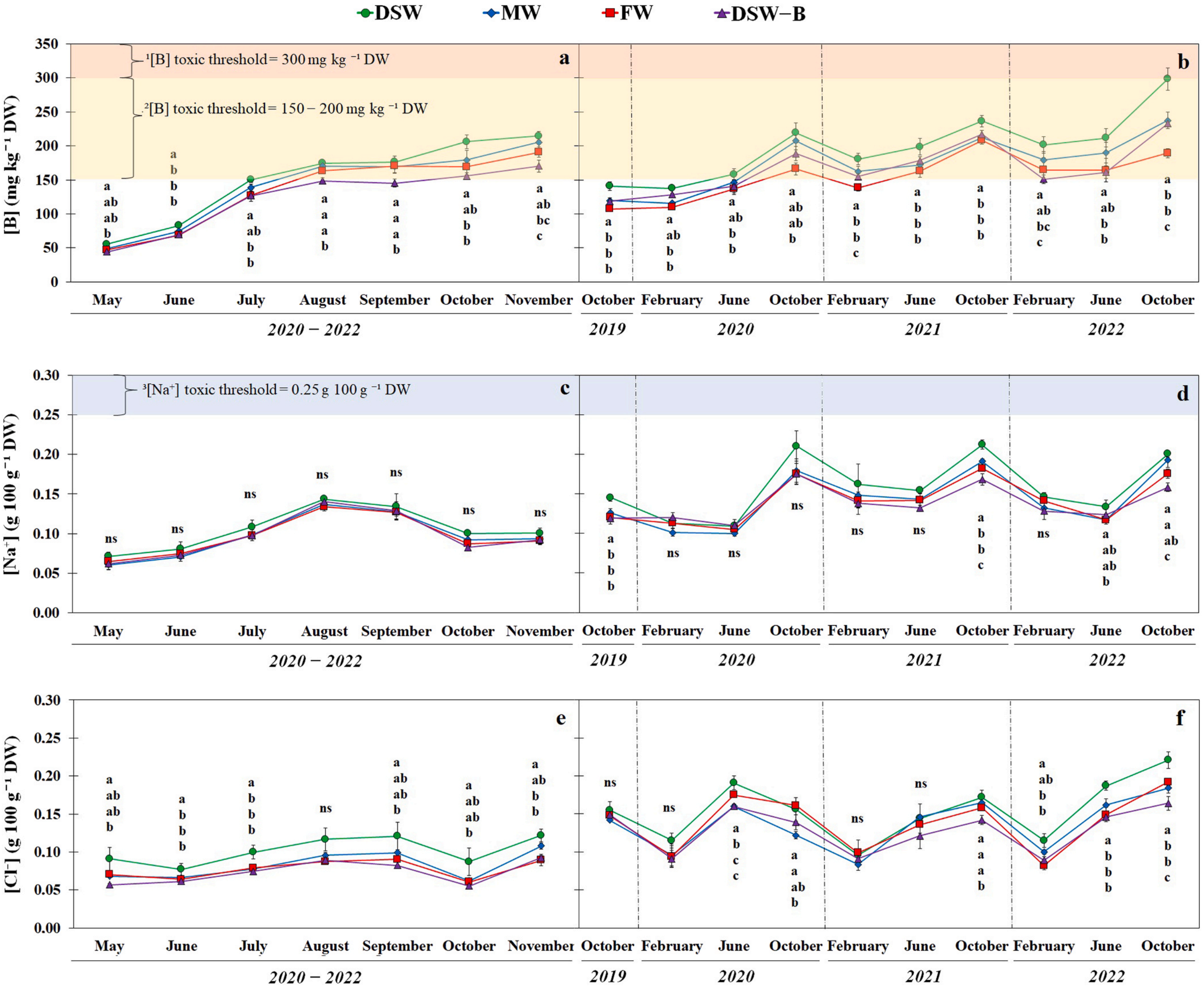

Fig. 3. Concentration of boron (B, mg kg^{-1}), sodium (Na^{+}, g 100 g^{-1} dry weight; DW), and chloride (Cl^{-}, g 100 g^{-1} DW) in spring bud (average of 2020, 2021, and 2022) and old leaves (2019–2022) for the four irrigation treatments (Desalinated seawater; DSW, Mixed water; MW, Fresh water; FW, Desalinated seawater with reduced boron; DSW−B) throughout the experiment. Each year new spring bud leaves were studied from May to November, while the oldest available leaves of the trees were considered as 'old' in each sampling procedure. On each date, different letters indicate significance and *ns* indicates no significance according to Tukey's multiple range test at the 95% confidence level. Toxic thresholds in citrus leaves: ^{1}300 mg kg^{-1} DW (Grattan et al., 2015); ^{2}150–200 mg kg^{-1} DW (Alfonso et al., 2018; Veridiana-Krug et al., 2023); ^{3}0.25 g 100 g^{-1} DW (Grattan et al., 2015); ^{4}0.6 g 100 g^{-1} DW (Romero-Trigueros et al., 2014).

subsequent water remineralization and an identical and sufficient nutrient supply during fertilization, non-significant differences were observed in the availability of elements in the plants, indicating adequate nutrition overall, apart from phytotoxic elements.

Additionally, concerning the abovementioned relationship between N and B in soil, intriguing differences were also observed among treatments when analyzing old-leaf nutrient contents. Table 5 shows that the N concentration in DSW−B old leaves (3.06±0.03 g 100 g^{-1} dry weight; DW) was significantly lower than in those of the DSW (3.20±0.04 g 100 g^{-1} DW) and equal to those of the FW (3.03±0.03 g 100 g^{-1} DW), which may be related to the B concentration of each water resource (Table 3).

Regarding the phytotoxic elements, the evolution of the concentrations of B, Na^{+}, and Cl^{-} on spring bud and old leaves throughout the experiment and for the four irrigation treatments is presented in Fig. 3. The concentration of each element in spring bud leaves was very similar in the same month each year (2020, 2021 and 2022), as depicted in Fig. 3a, c and e, which show an average over the three years for each sampling month.

Regarding B, its increase was progressive in both the spring bud and the old leaves; however, its concentration was consistently higher in the old leaves, especially at the end of summer (October) after the peak irrigation period. In the DSW treatment, B concentration in young leaves increased similarly every year from 35 mg kg^{-1} in May to 150 mg kg^{-1} in October, while in old leaves, its presence and accumulation were slightly higher as the years progressed. The remaining treatments (MW, FW and DSW–B) exhibited similar accumulation trends, but with maximum values in both types of leaves being lower than those in the DSW case. The maximum B levels observed in young and old leaves in October were within the phytotoxicity thresholds proposed for citrus crops by Grattan et al. (2015) (300 mg kg^{-1}), but above other proposed thresholds (150–200 mg kg^{-1}) (Alfonso et al., 2018; Veridiana-Krug et al., 2023). These concentrations subsequently decreased below potential toxic levels, following a sustained period with much lower irrigation volumes (October to April). This trend was also observed in the concentrations of Na^{+} and Cl^{-}, which increased progressively as the irrigation volumes

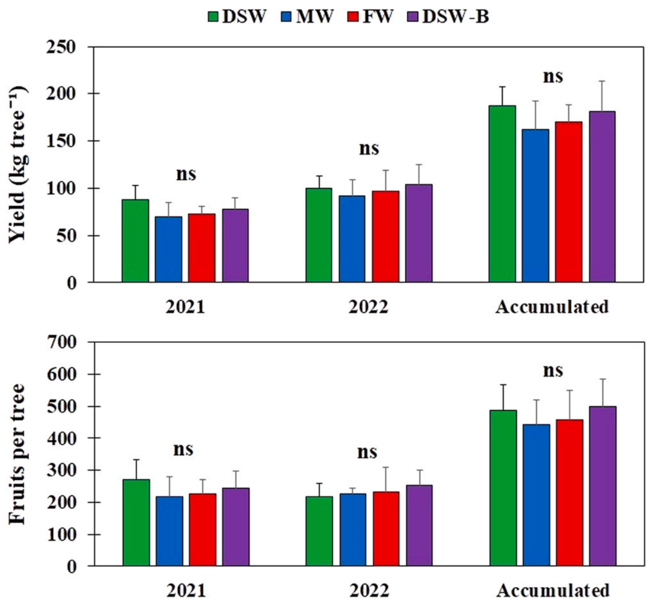

Fig. 4. Fruit yield (kg tree^{-1}) and fruits per tree obtained for 2021 and 2022 yields and accumulated values throughout the experimental period for the four irrigation treatments (Desalinated seawater; DSW, Mixed water; MW, Fresh water; FW, Desalinated seawater with reduced boron; DSW−B). In each case, *ns* indicates no significance according to Tukey's multiple range test at the 95% confidence level.

intensified and decreased during the winter period. In this latter case, their presences were similarly higher in the old leaves, following an unsteady trend throughout the year but never exceeding the proposed leaf toxic thresholds for Na^+ (0.25 g 100 g^{-1} DW) (Grattan et al., 2015) and Cl^- (0.6 g 100 g^{-1} DW) (Romero-Trigueros et al., 2014). On the contrary, spring bud leaves showed lower variability between treatments compared to B, especially in the case of Na^+, with no significant different throughout the years (Fig. 3a, c and e).

In general, the presence of phytotoxic elements was higher in the DSW compared to the FW, a phenomenon particularly observed during periods of notably higher irrigation volumes. It should be noted that the concentrations of B, Na^+ and Cl^- were within the bounds or exceeded the proposed toxic thresholds in irrigation water (Table 3) in the DSW, FW, and hence MW treatments, which may negatively impact on adequate crop development. This concentration was only lower than the thresholds in the DSW−B, due to the RO process conducted on-farm. These results concur with previous findings using DSW for citrus irrigation (Maestre et al., 2020; Navarro et al., 2022; Vera et al., 2023). Overall, while the trees did not exhibit phytotoxic effects, these early findings may suggest potential future accumulations surpassing critical thresholds, particularly regarding B.

3.4. *Yield and fruit quality*

Fig. 4 shows the effect of the different irrigation treatments on the fruit yield parameters analyzed in the productive campaigns. Because the trees were young, no yield was obtained in 2019 and 2020, whereas two harvests were conducted in February 2022 and December 2022 (referred to as the 2021 and 2022 harvests, respectively). Nonetheless, despite the fact that the trees were only three years old, it must be noted that the yields obtained were still low compared to those of commercial grapefruit yields.

The average yield in 2021 was 77 kg tree^{-1}, with a total number of fruits per tree of 240 and a mean weight of 327 g fruit^{-1}, whereas in 2022, the yield was higher (99 kg tree^{-1}), with a similar number of fruits per tree (232), but with heavier fruits than in 2021 (430 g fruit^{-1}). However, no significant effects between irrigation treatments were

Table 6
Chemical quality of the fruits harvested in 2021 and 2022.

Water resource	DSW	MW	FW	DSW−B	*ANOVA*
2021					
Diameter (mm)	99.41 ± 1.64	99.14 ± 1.21	99.81 ± 1.58	98.71 ± 1.37	ns
Peel thickness (mm)	7.71 ± 0.41	7.79 ± 0.40	7.94 ± 0.25	7.54 ± 0.31	ns
Peel Thickness Index	16.25 ± 0.69	15.71 ± 0.79	15.94 ± 0.61	15.28 ± 0.66	ns
Side Index	88.47 ± 1.33	88.59 ± 1.27	88.89 ± 1.19	87.91 ± 0.74	ns
Shape Index	0.777 ± 0.005	0.787 ± 0.008	0.782 ± 0.006	0.782 ± 0.012	ns
External Color Index	4.52 ± 0.43	4.71 ± 0.45	4.05 ± 0.22	4.66 ± 0.32	ns
TSS (°Brix)	11.3 ± 0.1	11.5 ± 0.2	11.9 ± 0.3	11.6 ± 0.3	ns
TA (g L^{-1})	23.0 ± 0.2	22.7 ± 0.8	22.6 ± 0.5	23.4 ± 0.3	ns
MI	4.91± 0.04	5.12 ± 0.25	5.30 ± 0.06	4.96 ± 0.08	ns
Na^+ (mg L^{-1})	nd	nd	nd	nd	-
P^{3+} (mg L^{-1})	66.7 ± 1.65^{c}	78.8 ± 3.0^{ab}	70.49 ± 4.7^{bc}	85.3 ± 3.3^{a}	**
Mg^{2+} (mg L^{-1})	75.5 ± 1.6	79.1 ± 2.3	75.4 ± 3.8	82.3 ± 1.7	ns
2022					
Diameter (mm)	104.60 ± 2.77	101.14 ± 1.97	105.61 ± 1.88	101.53 ± 2.73	ns
Peel thickness (mm)	9.94 ± 0.30a	9.05 ± 0.17b	10.10 ± 0.16a	9.80 ± 0.25a	*
Peel Thickness Index	19.11 ± 1.02	18.16 ± 0.10	19.13 ± 0.15	19.35 ± 0.50	ns
Side Index	93.52 ± 2.13	89.93 ± 1.87	94.80 ± 1.83	92.69 ± 1.35	ns
Shape Index	0.789 ± 0.016	0.778 ± 0.010	0.795 ± 0.006	0.790 ± 0.012	ns
External Color Index	5.95 ± 0.13ab	4.08 ± 0.33b	7.38 ± 1.12a	5.53 ± 0.20ab	*
TSS (°Brix)	10.8 ± 0.1	10.9 ± 0.2	10.2 ± 0.2	10.4 ± 0.2	ns
TA (g L–1)	17.6 ± 0.4	18.2 ± 0.2	18.9 ± 0.7	18.6 ± 0.2	ns
MI	5.80 ± 0.12	5.93 ± 0.05	5.78 ± 0.14	5.73 ± 0.13	ns
Na+ (mg L–1)	9.0 ± 0.3	5.7 ± 1.9	8.9 ± 1.7	9.7 ± 1.7	ns
P3+ (mg L–1)	118.4 ± 18.7a	116.2 ± 8.5a	78.4 ± 3.6b	68.7 ± 2.3b	**
Mg2+ (mg L–1)	83.1 ± 1.3ab	73.0 ± 6.6b	90.4 ± 1.3a	86.5 ± 1.0a	*

[*] $p \leq 0.05$, ** $p \leq 0.01$; On each date, different letters indicate significance among irrigation treatments and *ns* indicates no significance according to Tukey's multiple range test at the 95% and 99% confidence level, respectively. *nd* means not detected.

observed in any of the fruit yield parameters, including the cumulative tree yield during the experiment. Storey and Walker (1999) detailed that Cl^- and Na^+ accumulation in the leaves and relatively low salinity levels may lead to reductions in growth and fruit yield. However, other studies showed similar results when comparing the effect of DSW with FW irrigation in a young orchard of mandarin trees, with no significant differences being found (Maestre-Valero et al., 2020).

Concerning the physical characterization of the fruits, after three years of specific irrigation, only slight differences were found in some parameters in 2022 (Table 6). In that case, fruits from MW irrigation had significantly lower peel thickness (9.05±0.17 mm) and ECI (4.08±0.33) than the rest of the treatments (above 9.80 mm and 5.53, respectively). Pérez-Pérez et al. (2015) showed that fruit size and ECI were affected when irrigating grapefruit trees with concentrations up to 920 mg L^{-1} of Na^+ and 1400 mg L^{-1} of Cl^-, concentrations which were significantly higher than those used in this experiment. However, it is noteworthy that with the DSW treatment such effects were not found despite having higher concentrations of both elements than the MW in its composition.

Moreover, no differences were found in the TA, TSS or MI levels of the grapefruit juice obtained in 2021 or 2022. Therefore, it would seem that the internal fruit maturation of grapefruits was not affected by the irrigation using different types of water. Nevertheless, the mineral composition of the juice was slightly modified by irrigation (Table 6). In 2021, those trees irrigated with the DSW yielded fruits with the lowest P^{3+} concentration in their juice (66.7±1.65 mg L^{-1}), whereas the opposite occurred in 2022. The fruits exhibited the highest concentration of P^{3+} reaching 118 mg L^{-1}, and the lowest presence of Mg in the DSW (83.1±1.30 mg L^{-1}) and MW (73.0±6.60 mg L^{-1}) treatments. The levels of PO_4^{3-} were very similar among irrigation waters, whilst the total P supply through fertilization was identical (Table 1). Therefore, long-term studies are needed in order to determine how the presence of P^{3+} in the fruit evolves in relation to DSW irrigation, since no apparent cause was demonstrated.

In general, the physical and chemical parameters measured were in accordance with previous results of grapefruit trees irrigated with FW in southeastern Spain (Navarro et al., 2015; Pérez-Pérez et al., 2015). However, to date, no results have been found regarding irrigation with DSW in grapefruits.

3.5. *Economic assessment*

The cost of water and fertilizers and the difference in income from selling the fruit for the four irrigation waters (DSW, MW, FW and DSW−B) and two fertilization scenarios (with vs. without nutritional adjustment) are shown in Table 7. Concerning the water cost, irrigation with DSW was 2.4 times more expensive compared to FW irrigation, due to the appreciable difference in water prices. Moreover, B removal process increased the irrigation cost by 38.82% in the DSW−B treatment (Imbernón-Mulero et al., 2022; increase of 0.33 € m^{-3}), which may imply even greater profitability losses.

The fertilizer cost was calculated for both a constant fertilizer supply (real supply performed at field) and a variable fertilizer supply (estimated) depending on the nutrient content of the irrigation water (superscripts ^{1} and ^{2}, respectively, in Table 7). Technicians and farmers heretofore calculated fertilizer supplies based on their composition and isolated irrigation water samples analysis. Nevertheless, several tools have been developed to easily automate fertilization and adapt it to the available irrigation water and the best combination of fertilizer (Reca et al., 2018; Gallego-Elvira et al., 2021). In this sense, the nutritional adjustment performed could enable a reduced fertilizer cost, especially when a more nutrient-dense irrigation water was used. However, this cost reduction appeared to be less than that previously obtained in previous research (up to 40%) (Pagán et al., 2015; Bueno-Delgado et al., 2016; Imbernón-Mulero et al., 2023). This was explained by the use of complex fertilizers which can provide three or more essential nutrients simultaneously. Therefore, the fertilizer consumption must be adjusted to the most restrictive nutrient (mainly nitrogen), thus hindering a more precise adjustment and showing a smaller reduction in fertilizer cost of up to 5.22% in 2022 (Table 7).

Regarding the total balance, major significant differences were

Table 7
Economic assessment of the grapefruit production under the four irrigation treatments and the two fertilizer cost scenarios selected.

Water resource	**Outcomes (€ ha^{-1} $year^{-1}$)**			**Incomes (€ ha^{-1} $year^{-1}$)**	**Income-Outcome[a] (€ ha^{-a} $year^{-1}$)**	**Income-Outcome[b] (€ ha^{-1} $year^{-1}$)**
	Water	**Fertilizer[a]**	**Fertilizer[b]**	**Fruit Selling**		
June 2019 – December 2019						
DSW	791.27^{b}	150.47	144.35	0.00	-941.74^{b}	-935.61^{b}
MW	558.54^{c}	150.47	143.68	0.00	-709.01^{c}	-702.22^{c}
FW	325.82^{d}	150.47	144.59	0.00	-476.29^{d}	-470.41^{d}
DSW-B	1098.46^{a}	150.47	149.47	0.00	-1248.93^{a}	-1247.93^{a}
January 2020 – December 2020						
DSW	1116.31^{b}	231.68	225.03	0.00	-1347.99^{b}	-1341.33^{b}
MW	787.98^{c}	231.68	219.80	0.00	-1019.66^{c}	-1007.78^{c}
FW	459.66^{d}	231.68	219.46	0.00	-691.34^{d}	-679.11^{d}
DSW-B	1549.69^{a}	231.68	230.65	0.00	-1781.38^{a}	-1780.34^{a}
January 2021 – December 2021						
DSW	2048.33^{b}	540.57	535.61	12,266.75 ± 2135.48	9677.85 ± 453.42	9682.85 ± 448.46
MW	1445.88^{c}	540.57	534.97	9837.83 ± 1996.49	7851.38 ± 10.04	7856.98 ± 15.64
FW	843.43^{d}	540.57	526.63	10,259.03 ± 1095.12	8875.03 ± 288.88	8888.97 ± 274.94
DSW-B	2843.56^{a}	540.57	538.20	10,850.11 ± 1753.60	7465.98 ± 1630.54	7468.35 ± 1628.17
January 2022 – December 2022						
DSW	2673.85^{b}	1438.41	1426.51	13,999.28 ± 1829.55	9887.03 ± 2282.71	9898.93 ± 2270.81
MW	1887.42^{c}	1438.41	1363.42	12,905.57 ± 2445.04	9579.74 ± 880.79	9654.74 ± 805.80
FW	1101.00^{d}	1438.41	1363.28	13,651.09 ± 3027.31	11,111.69 ± 487.90	11,186.81 ± 563.03
DSW-B	3711.93^{a}	1438.41	1436.99	14,525.78 ± 3006.16	9375.45 ± 2144.18	9376.87 ± 2142.76
Summation from June 2019 to December 2022[c]						
DSW	6629.76	2361.13	2331.5	26,266.03	17,275.14	17,304.77
MW	4679.82	2361.13	2261.87	22,743.4	15,702.45	15,801.71
FW	2729.91	2361.13	2253.96	23,910.12	18,819.08	18,926.25
DSW-B	9203.64	2361.13	2355.31	25,375.89	13,811.12	13,816.94

[a] Cost calculated considering constant fertilizer supply;

[b] Cost calculated considering variable fertilizer supply depending on the nutrient content of the irrigation water. In each year, means with different letters indicate significance according to Tukey's HSD test ($p \leq 0.05$), while no letter indicates non-significant differences.

[c] Note that the summation from 2019 to 2022 does not consider any statistical analysis.

obtained during the unproductive stage of the trees and the beginning of the youth period (2019−2020), whilst no differences were observed in the income-outcome results from 2021 and 2022. This was attributed to the large variability in yield, which may hide the greater irrigation water cost when DSW and DSW−B are used for irrigation. Therefore, larger differences are to be expected in upcoming years, once the variability in the crop yield among the trees within the same treatment decreases, and the noticeable prices of each water resource accentuate fertigation costs.

4. Conclusions

The study aimed to explore the agronomic impact of DSW irrigation on grapefruit trees' physiology and productivity. Results indicated that high concentration of Na^+ in DSW irrigation increased Na^+/Ca^{2+} and Na^+/Mg^{2+} ratios, potentially leading to soil sodification and nutrient competition. However, the low conductivity of DSW might counterbalance these deficiencies by allowing for Ca^{2+} and Mg^{2+} supplementation through fertigation. Moreover, elevated levels of Cl^- and B in DSW resulted in soil accumulation, posing similar concerns as with Na^+, especially in exclusive DSW irrigation scenarios.

Physiologically, Na^+ and B concentrations reached foliar toxicity thresholds in spring buds and old leaves. Nevertheless, plant development and productivity remained unaffected, with consistent harvest observed across treatments, albeit with tree-to-tree variability. However, prolonged exposure to these elements could potentially trigger phytotoxic reactions such as chlorosis or wilting.

Economically, minor differences were noted in nutrient content among water sources, with DSW and DSW–B being costlier and exhibiting significant harvest variability, particularly impacting the 2021 income-outcome balance. The study accounted for three influencing factors: accelerated growth due to grafting onto five-year-old roostock, limited fertilization due to NVZ regulations, and unadjusted fertilization to irrigation treatment, theoretically considered in the economic assessment.

Our findings provide insights into DSW irrigation for sensitive crops, in particular for preventing potential soil and plant harm from early accumulation of phytotoxic elements. The results of the study emphasize the need for long-term assessments to anticipate future effects, particularly as tree growth stabilizes and productivity differences emerge. These studies are crucial for determining the feasibility of DSW as a primary irrigation source.

CRediT authorship contribution statement

Jose Francisco Maestre-Valero: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Josefa María Navarro:** Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation. **Juan Miguel Robles:** Writing – review & editing, Methodology, Investigation. **Vera Antolinos:** Writing – review & editing, Investigation. **José Alberto Acosta-Avilés:** Writing – review & editing, Methodology, Investigation. **Victoriano Martínez-Alvarez:** Writing – review & editing, Investigation, Conceptualization. **Belén Gallego-Elvira:** Writing – review & editing, Investigation. **Alberto Imbernón-Mulero:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jose Francisco Maestre Valero reports financial support was provided by Spain Ministry of Science and Innovation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgments

This research and the APC were by the Ministry for Science and Innovation and the State Research Agency (MCIN/AEI/10.13039/501100011033, Spain) and the European Regional Development Fund (ERDF, EU) in the framework of the projects SEARRISOST (RTC-2017–6192-2) and SEA4CROP (PID2020–118492RA-C22). Additionally, this work is a result of the AGROALNEXT program and was supported by MCIN with funding from European Union NextGenerationEU (PRTR-C17.I1) and by Fundación Séneca with funding from Comunidad Autónoma Región de Murcia (CARM). A. Imbernón-Mulero acknowledges the support for his PhD work from the project SEA4CROP and the predoctoral program of the Technical University of Cartagena (RV-484/21, UPCT, Spain). B. Gallego-Elvira acknowledges the support from the Spanish Ministry of Universities ("Beatriz Galindo" Fellowship BEAGAL18/00081). The collaboration of Catedra Trasvase y sostenibilidad−Jose Manuel Claver is acknowledged. We would like to thank J.A. Palazón and F.M. Hernández for their assistance in the field, and E.M. Arques for her support in laboratory analyses.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2024.108877.

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