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Multidisciplinary assessment of the agricultural supply of desalinated seawater in south-eastern Spain

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HIGHLIGHTS

- First multidisciplinary approach to assess local and regional DSW use in agriculture
- Favourable joint agronomic impact, especially in salinity-sensitive crops
- The environmental load increased in line with the proportion of DSW
- Economic impact very sensitive to DSW cost, and with heterogeneous results per crop
- The blended use of DSW was more recommendable from all perspectives.

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ABSTRACT

Desalinated seawater (DSW) has provided a steady supply of agricultural water for the last decade in south-eastern (SE) Spain, overcoming climatological and hydrological constraints. This article analyses the impacts of the progressive replacement of traditional irrigation water resources with DSW on the main crops of SE Spain, from agronomic, environmental, and economic perspectives, for the first time. The regional magnitude and spatial variability of these impacts have also been evaluated. To that end, six impact indicators were identified and calculated for three water supply scenarios using increasing proportions of DSW, which is representative of the current and possible future situations.

The results reflect the high variability of the impact indicators for the different crops. The agronomic impact is favourable but the benefits of reducing water salinity become saturated when DSW exceeds 50 %. The detrimental environmental impact is due to the higher specific energy consumption associated with increased DSW supply, although this is not an intrinsic problem of seawater desalination since it could be mitigated using renewable energies. The economic impact is very sensitive to the cost of DSW and offers heterogeneous results for the different crops. The results show that the combined use of DSW with traditional resources is the most efficient option from the different perspectives of the study, rather than irrigating with DSW alone. The insights from this study could be useful for the assessment of the feasibility of integrating DSW to support agriculture in other regions where desalination plants are being considered to support the water supply.

1. Introduction

The development of irrigated agriculture, in response to the growing demand for food, is the main driver of increased water demand worldwide [1]. In water-scarce regions, such as the Mediterranean area, agriculture is under pressure to improve water management and explore new options to satisfy the ever-increasing demand [2,3]. Climate change additionally points to the situation being likely to worsen in the future [4]. Consequently, innovative initiatives and adaptive measures are required to enhance the climate resilience of irrigated agriculture [5,6]. The use of desalinated seawater (DSW) could guarantee long-term food security and socio-economic stability in coastal regions where water supplies are scarce or unreliable [7].

Large-scale supply with DSW has emerged as a promising water source in the last 15 years for sustaining irrigated agriculture in some

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Abbreviations

a	soil electrical conductivity threshold (ds/m)
b	slope of the decreasing model
CPV	crop production value (€/ha)
DSW	desalinated sea water
EC_e	soil saturation extract electric conductivity (ds/m)
EC_w	electrical conductivity of the irrigation water (ds/m)
EUP	eutrophication potential (kg PO_{4eq}/ha)
FPC	fertilisation programme cost (€/ha)
GWP	global warming potential (kg CO_{2eq}/ha)
ID	irrigation district
LCA	life cycle assessment
N_n	crop net needs
N_t	total irrigation needs
REI	relative economic impact (€/ha)
LF	leaching fraction (%)
SE	south-eastern Spain
SLSQP	sequential least squares programming
SWDP	seawater desalination plant
TIR	total irrigation requirements (m^3/ha)
TSWT	tagus-segura water transfer
Y_r	relative yield of a crop

water-scarce Mediterranean regions growing high-return crops, such as south-eastern (SE) Spain [8] and Israel [9], as well as on islands lacking freshwater resources [10]. Its adoption is increasingly being considered as an alternative agricultural water supply in places such as Morocco [11], Tunisia [12], Saudi Arabia [13], Mexico [14], South Korea [15], Chile [16] or California [17]. This trend is expected to intensify in the near future [18,19], especially considering the continuous improvement in membrane-based technology for seawater desalination, as reverse osmosis is by far the leading system for agricultural purposes due to its lower energy use compared to other desalination systems [20,21].

A good example of massive agricultural supply with DSW is the Segura River basin, in SE Spain (Fig. 1). It is the basin with the highest level of water scarcity in Europe, suffering a persistent structural water deficit that mainly affects the over 250,000 ha of irrigated agricultural land [8]. Among the available water resources, there is an external transfer from the adjacent Tagus basin in central Spain (Tagus-Segura water transfer, TSWT), expected to provide one third of the basin's water resources. However, due to the progressive downward trend in the transferred volumes, related to climate change, changes in operation rules and, more recently, increases in the ecological flows of the Tagus basin, expectations have not been met, exacerbating the regional water deficit [22,23]. Consequently, the Spanish Government opted to implement large-scale seawater desalination to provide an alternative water resource amid rising pressure and competition for the scarce water resources in the basin [24,25]. Therefore, a progressive replacement of the waters commonly used for crop irrigation with DSW has been taking place in the Segura River basin, particularly in the irrigation districts supplied by the TSWT, which affects about 100,000 ha of crop land. As a result, both the cost and physicochemical conditions of irrigation water are undergoing continuous changes in those irrigation districts, with highly variable impacts on crop production - sometimes beneficial but also on occasions detrimental - causing heterogeneous attitudes toward DSW among farmers and water managers [26,27].

Many questions have been raised about the multiple impacts produced by the progressive substitution of conventional water sources with DSW, both per crop and on a regional scale, as well as its evolution under future scenarios with the progressive adoption of DSW. The most relevant studies on this topic [7,28–31] have shown both strengths and weaknesses, yet all agree that DSW is becoming a technically and economically feasible solution for high-return agriculture in coastal regions. On the positive side, they emphasize that DSW is not subject to climatological and hydrological constraints, making it strategically ideal for agricultural irrigation in deficit areas. Moreover, from an agronomic perspective, the low salinity of DSW boosts crop production, since it is often used to replace marginal low-quality waters, and hence also avoids leaching and soil deterioration [8,32,33]. Additionally, irrigating with low-salinity water leads to a reduction in total irrigation requirements, since the salt leaching fraction (LF) may be reduced or even negligible in comparison with medium to high salinity waters [9]. On the negative side, the main drawbacks are: the high energy consumption for DSW production and allocation, which results in farmers facing higher supply costs than for other water sources and thus jeopardising crop profitability [24,34]; its singular chemical composition, with a very low concentration of essential nutrients (calcium, magnesium and sulphate), requiring the adaptation of fertilisation programmes to prevent adverse effects on crop productivity, with the consequent increase in costs [30,35]; and the exacerbation of the water-energy nexus, since DSW production involves higher greenhouse gas emissions unless clean energy is used [36]. DSW is usually managed as a supplementary agricultural supply in SE Spain and Israel, often combined with other conventional irrigation waters to counterbalance its high costs and agronomic threats, which make its use affordable for a wider range of crops [26,30,35].

Several recent studies have assessed the viability and regional optimisation of DSW use in agriculture. Multsch et al. [13] addressed the economics of desalination for agriculture through the optimal planning and management of cropland and irrigation scheduling management in a region of Saudi Arabia, with particular emphasis on irrigation technology, water salinity and crop salt tolerance. Kaner et al. [33] evaluated the economic feasibility of DSW supply as an alternative to irrigation with brackish water in Israel, applying a biological-physical model for crop response to water salinity, coupled with economic calculations of farm-based costs and benefits. Slater et al. [37] assessed the benefits of large-scale desalination in Israel through its impact on irrigation-water salinity, comparing optimal water management at regional scale under several scenarios. Therefore, interest in desalination for the provision of irrigation water is on the rise, so local or regional approaches enabling the consideration of its feasibility based on agronomic, environmental, and economic considerations are needed.

The aim of the present study is to provide from a multidisciplinary (agronomic, environmental, and economic) perspective, an analysis of the impact on the main crops in the study area of the progressive replacement of the waters commonly used for crop irrigation (ground, surface, reclaimed, and TSWT) with DSW. To this end, six impact indicators have been identified for the agronomic (3), environmental (2), and economic (1) characterization of agricultural production; their values have been estimated under three irrigation water supply scenarios with increasing proportions of DSW. In addition, the impacts estimated per crop have been extrapolated to the irrigable area supplied by the TSWT in the Segura River basin to analyse the regional magnitude and the spatial variability of the impacts.

2. Methodology

Three impact indicators were selected for the agronomic analysis: the crop production value (CPV, €/ha), to assess the effects of water salinity on the agricultural production; the total irrigation requirements (TIR, m^3/ha), to evaluate the effect of water salinity on the salt leaching fraction and, consequently, on the total crop irrigation requirements; and the fertilisation programme cost (FPC, €/ha), which considers the

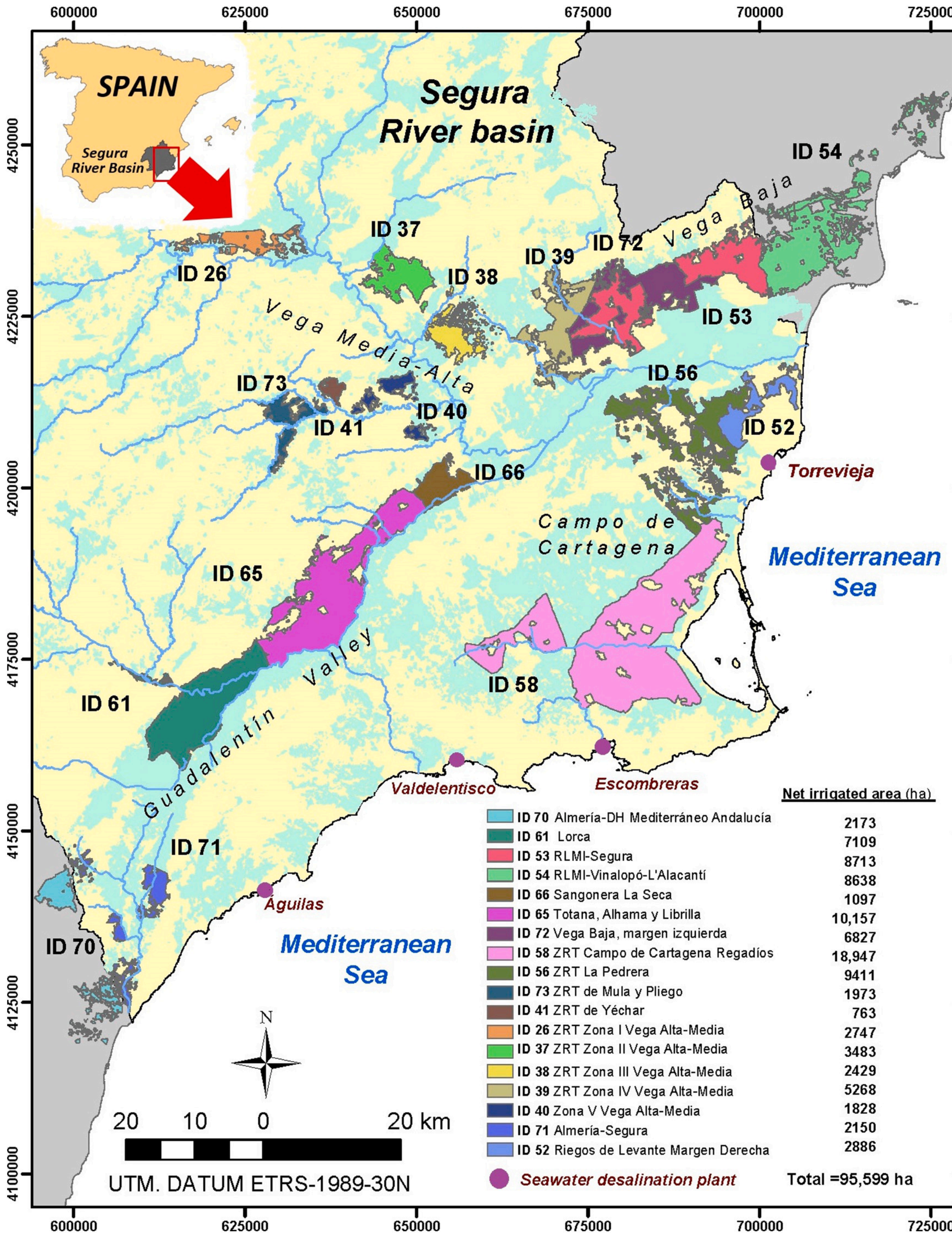

Fig. 1. Location of the study area and distribution of the irrigation districts (IDs) mainly supplied by the TSWT. The location of seawater desalination plants supplying the study area is also depicted.

impact of the lack of essential nutrients in the DSW on fertiliser dosing. Two life-cycle assessment (LCA) impact indicators were selected to assess the environmental effects of crop production: the eutrophication potential (EUP, kg PO_{4eq}/ha); and the global warming potential (GWP, kg CO_{2eq}/ha). Finally, the economic analysis was based on one indicator: the relative economic impact (REI, €/ha), which integrates the economic effect of the agronomic impacts and the changes in the irrigation water cost under the different water supply scenarios. Details of the estimation approach for these indicators are given below. Calculations were made using data from official sources (public administrations) and the scientific literature.

It should be noted that we opted for recognised but simple methodological approaches in the different disciplines of the study which could provide an overall insight of a highly complex study, considering the following constraints: (1) the limited amount of studies published to date concerning experimental evidence on agronomic issues for crops irrigated with DSW; (2) the high local variability of the agronomic factors to be considered (agroclimatology, crops, water quality, *etc.*); (3) the regional variability of water supply energy consumption and price, including DSW; and (4) the particularities of the economic factors for different farms and production periods, with large variations between seasons and even throughout the same season.

2.1. Study area

The Segura River basin is one of the most water stressed areas in the Mediterranean region. Its surface area is 19,025 km^2, with 52.1 % agricultural land, of which 13.8 % is irrigated land. The irrigated fruit and vegetable sector plays a major role in the regional economy in terms of production, employment, and exports [38].

According to the latest official estimation [38], the water resources available in the basin amount to an average of 1510 Mm^3/y, which includes surface and groundwater resources (756 Mm^3/y), external transferred water (TSWT, 312 Mm^3/y), reclaimed water (147 Mm^3/y), and DSW (305 Mm^3/y). That volume fails to meet the water demand in the basin, which is estimated at an average of 1697 Mm^3/y. This figure includes irrigated agriculture (1476 Mm^3/y), urban supply (200 Mm^3/y), and industrial uses (21 Mm^3/y). In addition, 94 Mm^3/y correspond to uses located outside the basin, but which are served with own resources. These figures show that there is an average water deficit in the basin system of about 281 Mm^3/y.

This persistent water shortage mainly affects irrigated agriculture, which amounts to 261,626 ha in the basin [38]. Two types of irrigation districts (IDs) can be distinguished; on the one hand those using the water resources generated within the basin; on the other hand, those that are mainly supplied by the TSWT. Our study targets the latter, which comprise a net irrigated area of 95,599 ha, organised into 18 IDs (Fig. 1). These districts are characterised for their high dependence on the TSWT supply, which theoretically represents 54.2 % of their irrigation water allocation [38]. However, because of the aforementioned progressive reduction in the TSWT allotment [22,23], this share currently accounts for only 31.1 % of their irrigation water allocation, so the regional supply of DSW is being concentrated in those IDs.

The massive agricultural DSW supply in the Segura River basin is linked to the enactment of the *Programa AGUA* in 2004, which was mainly aimed at building 21 large-scale seawater desalination plants (SWDP) along the Mediterranean coast with a combined production capacity of 1063 Mm^3/y for agricultural, urban and tourism uses [24,25]. There are four SWDPs supplying agriculture in the study area (Torrevieja, Valdelentisco, Águilas, and Escombreras; Fig. 1) with a current production capacity for irrigation of 195 Mm^3/y and with likely future expansions [8,38].

2.2. Water sources and supply scenarios

The source of the water supplied is a relevant factor when distinguishing scenarios, since it implies different physicochemical properties, specific energy consumptions and prices for farmers, and consequently, different agronomic, environmental, and economic effects. The classification used in the official basin planning [38] was followed: surface water, groundwater, reclaimed water, DSW, and TSWT. Table 1 shows the characteristics of these water sources in the study area.

The IDs mainly supplied by the TSWT have total irrigation water allocations of 633 Mm^3/y, which are composed of 17.0 % superficial water, 20.2 % groundwater, 6.3 % reclaimed water, 2.3 % DSW and 54.2 % TSWT water [38]. The current supply of DSW is much higher than that (about 25–30 %), although this irrigation water allocation has yet to be consolidated in the official basin planning. Furthermore, due to the progressive decrease of available TSWT caused by climate and environmental pressures, it is expected that DSW production will be required in the short-term to satisfy 50 % of the irrigation demand [23].

Three water supply scenarios were defined, with a progressive replacement of the waters commonly used for crop irrigation with DSW. These scenarios were representative of the official administrative water allocations, and represent current and possible future supply situations in the study area:

- Reference scenario. This represents the situation prior to the arrival of DSW and corresponds to a supply from the different water sources proportional to the irrigation water allocations recognised in the official planning [38], but without any DSW concession. It is a scenario with no DSW supply and is henceforth referred to as 0 %DSW.
- Combined source scenario. This represents a situation close to the current one, expected to be achieved in the short-medium term. In this case, 50 % of the irrigation water is DSW, whilst the remaining 50 % comes from all other sources in proportion to the official irrigation water allocations. This scenario is hereinafter referred to as 50 %DSW.
- Single source scenario. This represents a hypothetical future situation where all irrigation water supplies are replaced by DSW. This scenario is henceforth referred to as 100 %DSW.

Fig. 2 displays the proportions of the different water sources in each scenario. Their physicochemical properties, specific energy and water

Table 1
Main physicochemical properties, specific energy consumption and price for farmers of the different water sources and supply scenarios considered in the study.

Parameter	Superficial[c]	Ground[d]	Reclaimed[e]	DSW[d]	TSWT[d]	Reference S. (0 %DSW)	Combined source S. (50 %DSW)	Single source S. (100 %DSW)
pH	7.5	7.4	7.7	8.3	8.4	8.0	8.15	8.3
EC (dS/m)	2.41	4.51	1.80	0.46	0.86	1.95	1.20	0.46
Ca^{2+} (mg/L)	158	229	97	29	97	135	82	29
Mg^{2+} (mg/L)	98	99	39	4.3	40	62	33	4.3
Na^{+} (mg/L)	257	573	235	86	41	201	144	86
K^{+} (mg/L)	18.8	16.6	28.3	3.9	2.2	9.8	6.8	3.9
NH_4^- (mg/L)	7.2	1.7	3.1	0.1	0.2	1.9	0.9	0.0
B^{3+} (mg/L)	0.45	1.36	0.40	0.56	0.1	0.44	0.50	0.56
Cl^{-} (mg/L)	344	972	272	147	59	311	229	147
SO_4^{2-} (mg/L)	514	980	205	6.6	233	434	220	6.6
CO_3H^{-} (mg/L)	318	475	295	71	180	272	172	71
NO_3^- (mg/L)	10.6	60.6	14.7	1.0	1.7	16	8.6	1
PO_4^{3-} (mg/L)	2.65	0.3	1.23	0.2	0.1	0.7	0.4	0.2
SAR	4.0	8.0	5.4	3.0	1.1	3.6	3.4	3.0
Specific energy (kWh/m^3)[a,b]	0.06	0.95	0.78	3.49	1.21	0.93	2.21	3.49
Price (€/m^3)[c]	0.06	0.18	0.10	0.60	0.18	0.154	0.377	0.60

[a] Data from [39] for the specific energy of superficial, underground, reclaimed, and TSWT supply in the study area.
[b] Data from [34] for the specific energy of DSW supply in the study area.
[c] Data provided by the irrigation district managers in the study area.
[d] Data from [8] for the physicochemical properties of underground, DSW, and TSWT supply in the study area.
[e] Data from [40] for the physicochemical properties of reclaimed water in the study area

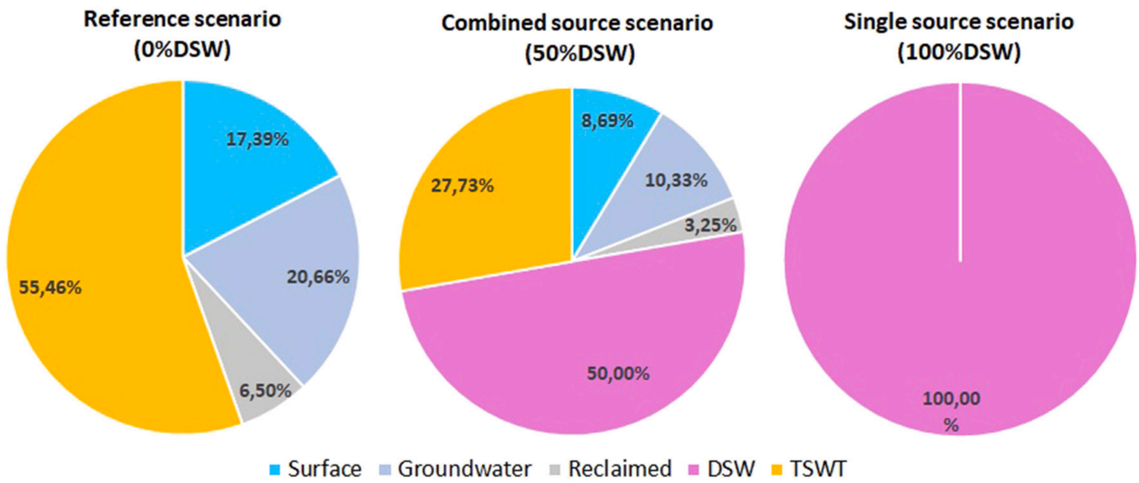

Fig. 2. Percentages of the different water sources in each water supply scenario.

price for farmers are calculated in Table 1.

2.3. Crop selection and crop groups

The ten irrigated crops with the largest surface area in the region in 2020 were selected [41]. These crops have been divided into four groups, following the same classification as in the Segura River basin official planning [38]: outdoor vegetables (artichoke, broccoli, lettuce, and melon); citrus trees (lemon, mandarin, and orange); non-citrus trees (apricot and peach); and almond trees (almond). These groupings were used for the regional upscaling of the study results.

The selected crops represented 80.1 %, 97.4 %, 84.8 %, and 100 % of the outdoor vegetables, citrus trees, non-citrus trees, and almond trees categories in the region, respectively. The proportion corresponding to IDs supplied by the TSWT, were 32.9 %, 39.2 %, 12.8 %, and 5.3 % of the total area for outdoor vegetables, citrus trees, non-citrus trees, and almond trees, respectively. Therefore, these groups represented 90.2 % of the crops grown in the study area, which highlights the regional representativeness of the study's results and conclusions.

2.4. Impact indicators

2.4.1. Agronomic indicators

The quality of irrigation water is an essential factor for crop yield, maintenance of soil productivity, and protecting the environment [42]. The physicochemical composition of DSW is quite different from other irrigation waters in the study area (see Table 1). This could affect the crop response and other agronomic questions if the water source is changed. The selected agronomic indicators seek to quantify these impacts that would lead to economic impacts.

The indicator ‘crop production value’ (CPV, €/ha) assesses the effect of water salinity on crop yield, an issue that has been extensively studied [43,44] and is addressed in the FAO technical manual Water Quality for Agriculture [42]. From this manual, the relative yield of a crop (Y_r), expressed as the yield obtained under salinity conditions divided by the yield obtained in the absence of salinity, was calculated with a linear analytical model as a function of soil saturation extract electric conductivity (EC_e):

$$Y_r = 100 - b(EC_e - a) \tag{1}$$

where a is the soil electrical conductivity threshold above which the crop starts to lose yield due to salinity, and b is the slope of the decreasing model. The value of EC_e is usually estimated as being 1.5 times the value of the electrical conductivity of the irrigation water (EC_w) [42]. The values of parameters a and b in Eq. (1) for the selected crops were obtained from the bibliography [42,44] and are shown in Table A1 (Appendix A).

Table 1 shows a progressive decrease in the salinity of irrigation water as the proportion of DSW increased in the different scenarios, which could result in a higher yield. The crop production value (€/ha) was considered, rather than the production itself (kg/ha) to enable the spatial aggregation among crops and regional upscaling. To do that, the official production value in the study area, published annually by the Spanish Government [45], was assigned to the reference scenario, and the value for the remaining scenarios was calculated by applying modelled variations in crop productivity.

The total irrigation requirements (N_t) of crops are higher than their consumptive or net needs (N_n), as additional quantities of water are needed to compensate for losses due to the conditions under which the crop is grown [46]. The indicator ‘total irrigation requirements’ (TIR, m^3/ha) accounted for the fact that as water salinity decreases (when higher proportion of DSW is used), the salt leaching fraction decreases, and therefore, the irrigation requirements (total water used) are lower. Following the FAO technical manual Guidelines for Predicting Crop Water Requirements [46], and leaving aside other local considerations on soil texture or emission uniformity of the irrigation system, the TIR for each crop and scenario was calculated as:

$$\text{TIR} = N_t = N_n/(1 - LF) \tag{2}$$

$$LF = EC_w/(2 \cdot maxEC_s) \tag{3}$$

where LF is the leaching fraction and $maxEC_s$ refers to the soil saturation extract electric conductivity producing a 100 % decrease in crop yield; these values were obtained from the bibliography [42,44] and are given in Table A1.

The DSW is characterised by a very low concentration of essential nutrients for crop development such as calcium, magnesium, and sulphate. Fertilisation programmes usually assign a secondary role to these nutrients in the study area, as they are relatively abundant in the surface, ground, reclaimed, and TSWT water sources (Table 1), and hence generally meet the crop needs [35,47]. The indicator ‘fertilisation programme cost’ (FPC, €/ha) assesses the cost of fertiliser dosing as the proportion of DSW increases. To do that, the optimization algorithm of Irriblend-DWS [48] was applied to calculate the optimal combination (type and quantity) of fertilisers to satisfy the total nutrient requirements of each crop at the lowest economic cost, considering the nutrients already present in the irrigation water for each scenario. The algorithm is coded in Python 3 and uses the *optimize.minimize* function of the scipy library for constrained minimization with the Sequential Least SQuares Programming (SLSQP) to minimize the fertilisation cost when given a set of available fertilisers (composition and prize) and a pre-set water blend of DSW with other resources, considering a set of constraints (salinity, nutrients, pH). Note that the amount of nutrients supplied to the crop is the same regardless the input water, only the amount of fertilisers to reach the crop nutrient needs varies among the studied scenarios. The algorithm had already been successfully used with a similar purpose in the study area by the authors [35], and had even been improved for optimising fertilisation simultaneously with the blending of water of different origins and qualities [48]. A detailed description of the model functioning and data requirements can be found in [35]. Since one of the model outputs is the cost of fertilisers, this information was taken as the FPC value for each crop and scenario.

2.4.2. Environmental indicators

Life Cycle Assessment (LCA) provides a quantitative multicriteria approach to evaluate the environmental performance of products or activities. Numerous LCA studies have been conducted to evaluate the environmental impacts caused by water supply systems [49,50], by crop irrigation systems [51], or by supply-irrigation systems [36,52]. Accordingly, the environmental impact produced by the selected crops under the considered water supply scenarios was quantified by the LCA methodology [36], following the protocols standardised by the ISO 14040/14044 [53,54]. The analysis was carried out from 'cradle to gate', covering all the input and output flows of resources and energy up to the farm gate. It is a compressive analysis that accounts for the energy and materials required for the production of agro-chemicals (fertilisers and pesticides), farm irrigation infrastructure (head, tanks, valves, programmer, pipes, reservoir *etc.*) and field machinery, taking into account the transport and packaging of primary and secondary materials, the synthesis of the chemical components and the waste treatment or disposal, and all field operations required by the crop production system.

The LCA mid-point impact categories selected as environmental indicators, due to their relevance to agricultural processes in an area particularly sensitive to nitrate contamination of groundwater and climate change impacts [22,38,55], were the 'eutrophication potential' (EUP) and the 'global warming potential' (GWP).

For the assessment of the impact categories presented in this paper, EUP (kg PO_{4eq}/ha) and GWP (kg CO_{2eq}/ha), the CML-IA methodology [56] was used with the software SimaPro 9.2.0.2 [57]. The EUP embodies the detrimental impacts caused by the emissions to air (including ammonia and nitrogen oxides) and water and soil (nitrates and chemical oxygen demand). The GWP is the result of the fossil fuel combustion to produce electricity for water transport and irrigation and for field operations and the electricity use for fertiliser production, as well as the release of carbon dioxide and dinitrogen monoxide during the manufacturing of synthetic fertilisers. In the scenarios where DSW is used GWP includes the emissions derived from electricity use for water desalination. Further information regarding: (i) the system boundaries for the cradle-to-gate production of vegetable and woody crops; (ii) the description of the agricultural stages; and (iii) the LCA inventory for the studied crops, can be found in a recently published manuscript by the authors [36].

2.4.3. Economic indicator

We used economic calculations of farm-based costs and benefits coupled with the agronomic impacts to analyse the economic performance of the progressive incorporation of DSW. Reference economic data for the different agricultural production systems in the study area came from the reports annually published by the Spanish Government [45], which are elaborated with information provided by the farmers. Table 2 presents a simplified adaptation of the characteristic economic balance for the selected crops in the study area when the supply of DSW was very limited or non-existent, so it can be assumed to correspond to 0 %DSW. For the 50 %DSW and 100 %DSW scenarios, the values of product revenues (*i.e.*, CPV), fertiliser cost (*i.e.*, FPC) and water cost (WC = TIR • water price) in Table 2 were updated with their corresponding values.

The economic indicator defined was the 'relative economic impact' (REI, €/ha), which was calculated as:

$$REI = (CPV_i - CPV_0) - (FPC_i - FPC_0) - (WC_i - WC_0) \quad (4)$$

The subindex i refers to the analysed scenario and the subindex *0* indicates the reference scenario (0 %DSW). Therefore, REI integrates all the effects of the considered agronomic impact indicators affected by the progressive incorporation of DSW and allows to jointly quantify their

Table 2
Characteristic economic balance for the selected crops in the study area for the reference scenario (0 %DSW).

Parameter (€/ha)	Artichoke	Broccoli	Lettuce	Melon	Lemon	Mandarin	Orange	Apricot	Peach	Almond
Product revenues[a] (1)	8253	5127	6967	8973	11975	5515	7575	16650	12613	4634
Direct costs (2)	5183	4255	4040	5672	3155	3730	4001	3012	4308	1338
Seeds and seedlings	1320	848	881	962	–	–	–	–	35	–
Fertilisers[b]	1412	1384	1478	1324	1018	1032	1202	910	1263	385
Phytosanitary prod.	822	842	746	1985	549	989	645	506	583	203
Water[c]	1627	1073	758	693	913	1017	769	869	889	586
Other supplies	1	108	177	707	676	692	1385	728	1537	165
Machinery (3)	1036	769	2915	816	708	578	554	686	678	609
Contracted works	193	59	2080	128	106	–	–	134	2	38
Fuels and lubricants	425	370	469	356	310	268	254	233	388	271
Repairs and spare parts	418	340	366	332	292	309	300	320	288	300
Salaried labor (4)	1645	1411	476	979	959	1182	482	2365	2869	238
Indirect costs (5)	3334	1611	2648	2613	3103	1724	2638	3325	4157	1399
Amortisations (6)	352	236	393	202	403	422	357	378	619	165
Total prod. costs (2 + 3 + 4 + 5 + 6)	11550	8282	10472	10282	8330	7636	8032	9767	12630	3749
Gross margin (7) (1-2-3-4)	389	−1308	−465	1506	7152	26	2539	10992	5547	2473
Net margin (8) (7-5-6)	−3297	−3155	−3506	−1308	3645	−2121	−457	7288	771	908
Subsidies and aids (9)	144	130	41	244	295	138	350	298	160	52
Production profit (10) (8 + 9)	−3153	−3024	−3465	−1064	3940	−1982	−106	7586	931	960

[a] Product revenues match with the impact indicator 'crop production value' (CPV, €/ha) for the reference scenario (0 %DSW).
[b] Fertilisers match with the impact indicator 'fertilisation programme cost' (FPC, €/ha) for the reference scenario (0 %DSW).
[c] Water cost is the impact indicator 'total irrigation requirements' (TIR, m^3/ha) multiplied by the water price in 0 %DSW.

economic impact in 50 %DSW and 100 %DSW with respect to 0 %DSW. For 0 %DSW, the REI has a value of zero, whereas for other scenarios positive REI values indicate a favourable economic impact to farmers, whilst negative values represent a reduction in their crop economic balances.

It should be noted that we selected this relative indicator because the value of other standardised alternatives (such as the gross margin, the net margin, or the profit) is highly conditioned by crop productivity and market price, which show great inter-annual variability because of agroclimatic and market conditions, respectively. Moreover, they presented negative values for some crops (Table 2), which would make the interpretation of the results more complex.

2.5. Extrapolation to the study area

Upscaling techniques with a geographic information system (ESRI ArcGIS) were applied to extrapolate the indicators' values to the entire target area. The territorial units for the calculations were the 18 IDs (Fig. 1). The adoption of the IDs as territorial units for the calculations also enabled the analysis of the spatial variability of the indicators. The steps followed were as follows:

1. Determination of the annual value of the indicators for each crop group and supply scenario.
2. Determination of the weight of each crop group in each ID and, subsequently, calculation of the annual values of the impact indicators for each ID and supply scenario.
3. Determination of the regional values of the impact indicators per scenario by aggregating the annual values of the impact indicators for each ID.
4. Spatial representation of the IDs' impact indicators for the analysis of spatial trends.

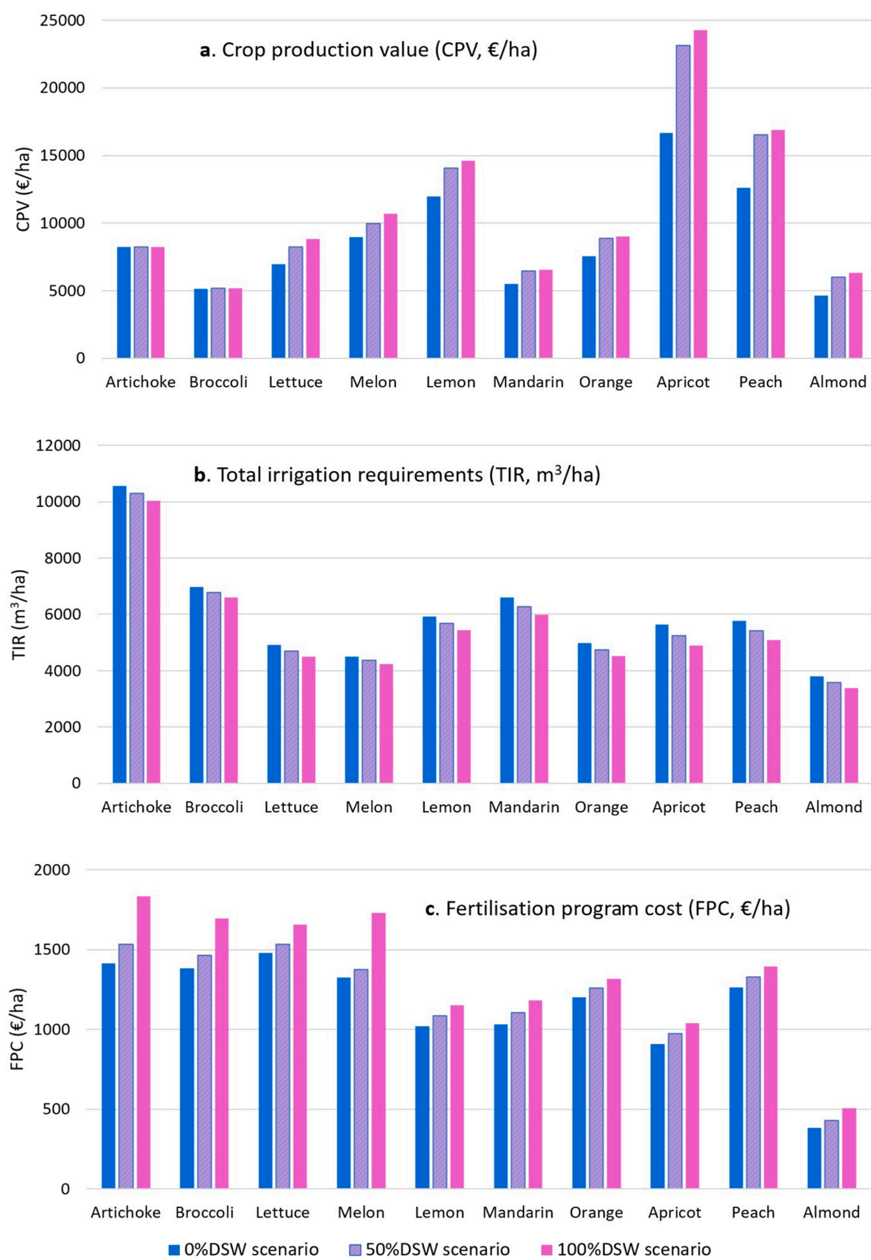

Fig. 3. Agronomic impact indicators for the selected crops and scenarios. Fig. 3a refers to the crop production value (CPV); Fig. 3b to the total irrigation requirements (TIR); and Fig. 3c to the fertilisation programme cost (PFC).

3. Results and discussion

3.1. Analysis by crops and crop groups

3.1.1. Agronomic indicators

The values of the agronomic impact indicators for the selected crops and scenarios are presented in Fig. 3, whereas the weighted values for crop groups are summarised in Table 3. The weights considered for calculating crop groups values were proportional to the surface area of each crop in the region in 2020 [41].

All the crops except artichoke, which is tolerant to salinity, had a relative yield below their full potential productivity in the absence of salinity for 0 %DSW. This is due to the fact that blended irrigation water generally presents an EC_w close to 2 dS/m (1.94 dS/m in 0 %DSW), which implies a systematic limitation in crop production; this became more important the greater the crop salinity sensitivity was. In 50 % DSW the EC_w decreased to 1.20 dS/m, a situation in which most crops were very close to their full potential productivity, although this was only reached by artichoke and broccoli. When EC_w decreased to 0.46 dS/m in 100 %DSW all the crops reached their full potential productivity in the absence of salinity. Accordingly, Fig. 3a depicts how for all the crops, except the most salinity-tolerant ones (artichoke and broccoli), CPV increased when moving from 0 %DSW to 50 %DSW, most markedly for peach, apricot, and almond. When moving from 50 %DSW to 100 % DSW, further increases in CPV were observed, albeit much smaller than in the previous case. Aggregating by crop groups (Table 3), the CPV rose for all crop groups as the percentage of DSW increased, a rise that was more relevant for non-citrus trees since they have the highest sensitivity to salinity. Moreover, the increase in CPV between 0 %DSW and 50 % DSW was more important than between 50 %DSW and 100 %DSW, which revealed some saturation at high proportions of DSW.

The salinity of the irrigation water also affected the leaching fraction. It decreased for all crops as the EC_w of irrigation water was reduced from 1.94 dS/m (0 %DSW) to 0.46 dS/m (100 %DSW). Both the LF value as well as its variation between scenarios presented moderate values for all crops, so large savings in TIR were not expected regardless of the proportion of DSW in the irrigation water. In agreement, the decrease in TIR (Fig. 3b) ranged from 2 % (artichoke) to 7 % (apricot) when moving from the 0 %DSW to the 50 %DSW scenario, the values practically doubled when moving to 100 %DSW. The aggregation per crop groups (Table 3) also showed that TIR decreased for all groups as the proportion of DSW increased, with no differences in behaviour among them. This moderate decrease behaved quasi-linearly to the proportion of DSW and represented a small agronomic benefit for farmers.

The incorporation of DSW also caused an increase in the nutrient inputs required, with a consequent increase in FPC for farmers. Fig. 3c shows that this increase was below 100€/ha for all crops when moving from 0 %DSW to 50 %DSW, and that it had a more than proportional rise when moving to 100 %DSW, with values of between 300 and 400 €/ha. Table 3 shows how the increase was more noticeable for outdoor vegetables than for woody crops (citrus, non-citrus, and almond), a behaviour justified by the higher intensity of fertilisation programmes in vegetables due to their seasonal growing cycle. The higher increase between 50 %DSW and 100 %DSW than between the 0 %DSW and 50 % DSW indicated that under the combined use of available water resources, the lack of nutrients in DSW is partially mitigated by other sources.

In summary, the agronomic results of the progressive replacement of the waters commonly used in the study area with DSW have a positive joint effect for all crop groups, since the detrimental increase in FPC when DSW is incorporated is considerably lower than the corresponding beneficial effects on CPV and TIR. This positive effect is clear when passing from the reference scenario (0 %DSW) to the combined source scenario (50 %DSW), although it is less relevant when moving from the combined to the single source scenario (100 %DSW).

3.1.2. Environmental indicators

Fig. 4a and b depict the values of EUP and GWP for the selected crops and scenarios, respectively. Their weighted values for crop groups are included in Table 3.

Comparing scenarios, both EUP and GWP values increased when moving to a scenario with more DSW proportion. GWP is more intensively impacted than EUP, since it is directly related to fossil fuel combustions, which increase with the progressive replacement of the waters commonly used with DSW, because of its high specific energy consumption (in Spain, 56.4 % of the electricity comes from non-renewable sources [58]). On average, EUP increased 21 % from 0 %DSW to 50 % DSW, with small variations among crops, and doubled (41 %) when passing from 0 %DSW to 100 %DSW. GWP increased more notably (41 %) its value when passing from 0 %DSW to 50 %DSW, and almost doubled (78 %) from 0 %DSW to 100 %DSW (Fig. 4a).

The results per crop group (Table 3) reflected a higher environmental

Table 3
Impact indicators value per crop group and scenario. The variation with respect to the reference scenario is also shown in brackets.

Crop groups	Impact indicator	0 %DSW scenario	50 %DSW scenario	100 %DSW scenario
Outdoor vegetables	CPV (€/ha)	12,864	14,301 (+11.2%)	15,047 (+17.0%)
	TIR (m^3/ha)	10,642	10,282 (−3.4%)	9947 (−6.5%)
	FPC (€/ha)	2548	2669 (+4.7%)	3063 (+20.2%)
	EUP (kg PO_{4eq}/ha)	43	52 (+20.9%)	55 (+27.9%)
	GWP (kg CO_{2eq}/ha)	12,833	18,065 (+40.8%)	20,865 (+62.6%)
	REI (€/ha)	0	−921	−2433
Citrus trees	CPV (€/ha)	10,215	11,984 (+17.3%)	12,396 (+21.3%)
	TIR (m^3/ha)	5865	5602 (−4.5%)	5361 (−8.6%)
	FPC (€/ha)	1053	1120 (+6.3%)	1186 (+12.6%)
	EUP (kg PO_{4eq}/ha)	25	31 (+24.0%)	36 (+44.0%)
	GWP (kg CO_{2eq}/ha)	8921	12,214 (+36.9%)	15,177 (+70.1%)
	REI (€/ha)	0	458	−267
Non-citrus trees	CPV (€/ha)	14,135	19,029 (+34.6%)	19,690 (+39.3%)
	TIR (m^3/ha)	5726	5349 (−6.6%)	5019 (−12.4%)
	FPC (€/ha)	1130	1195 (+5.7%)	1260 (+11.5%)
	EUP (kg PO_{4eq}/ha)	23	28 (+21.7%)	33 (+43.5%)
	GWP (kg CO_{2eq}/ha)	7488	10,457 (+39.7%)	12,997 (+73.6%)
	REI (€/ha)	0	3695	3452
Almond trees	CPV (€/ha)	4634	5992 (+29.3%)	6329 (+36.6%)
	TIR (m^3/ha)	3806	3579 (−6.0%)	3377 (−11.3%)
	FPC (€/ha)	385	428 (+11.2%)	507 (+31.8%)
	EUP (kg PO_{4eq}/ha)	18	21 (+16.7%)	23 (+27.8%)
	GWP (kg CO_{2eq}/ha)	4271	5963 (+39.6%)	7459 (+74.6%)
	REI (€/ha)	0	529	133

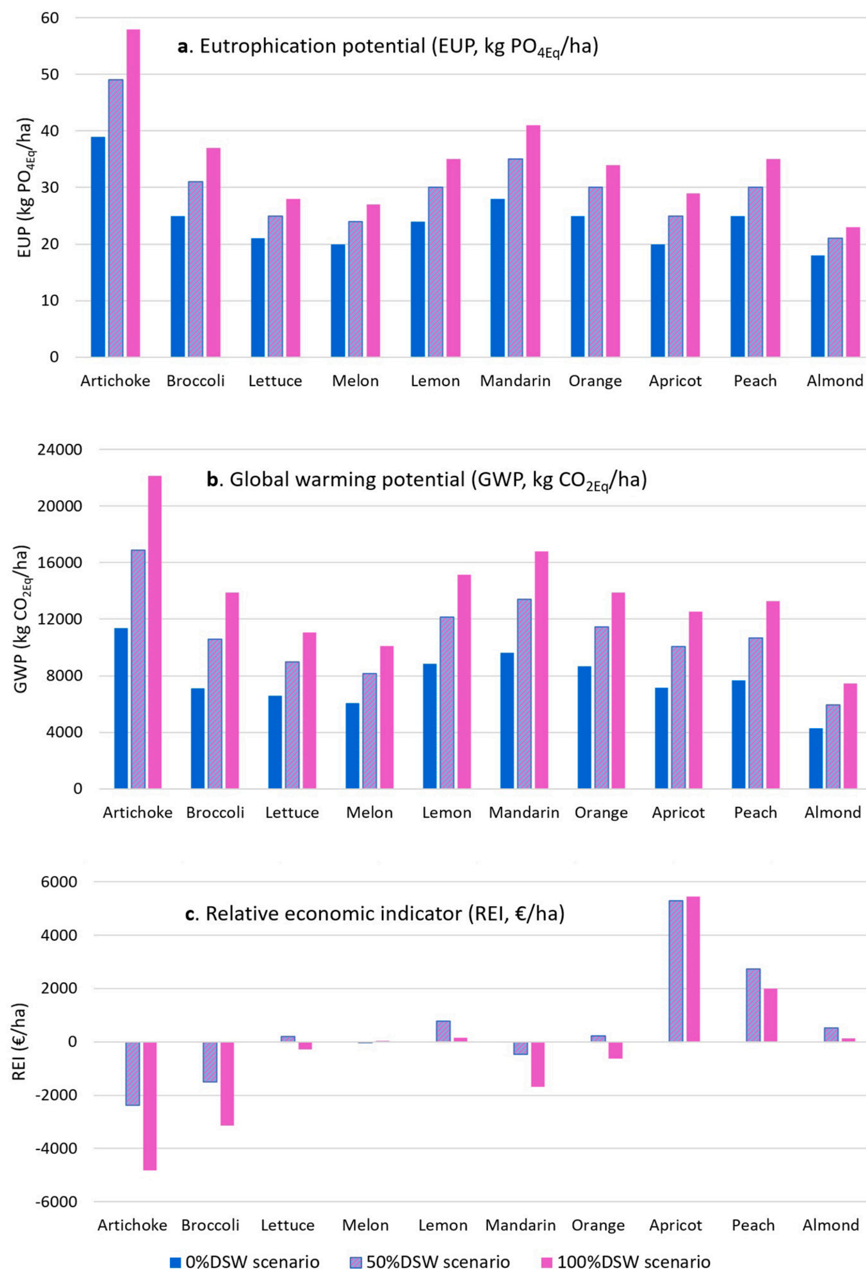

Fig. 4. Environmental and economic impact indicators for the selected crops and scenarios. Fig. 4a refers to the eutrophication potential (EUP); Fig. 4b to the global warming potential (GWP); and Fig. 4c to the relative economic impact (REI).

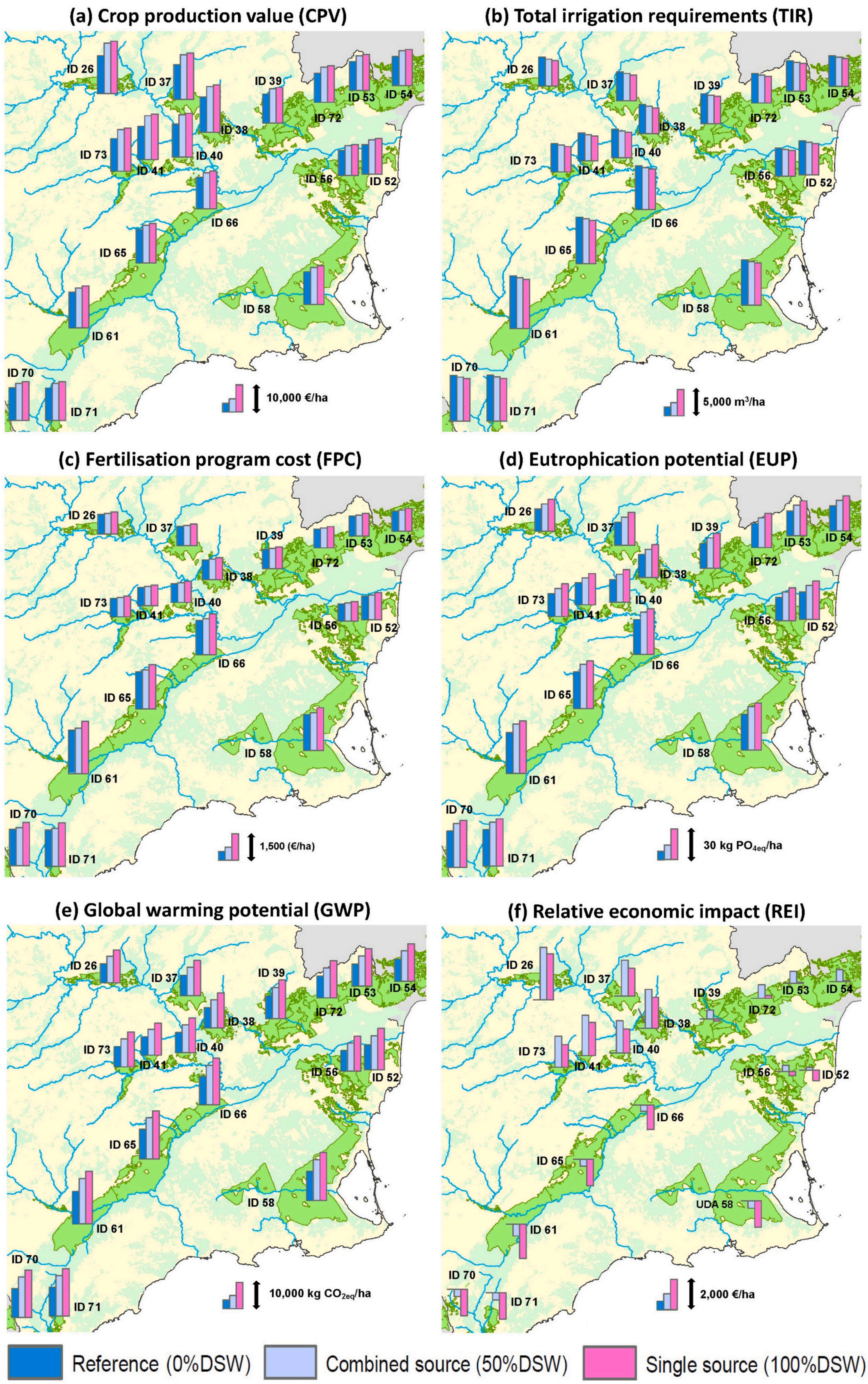

Fig. 5. Graphical representation of the area-weighted average value for the indicators and scenarios considered for the 18 irrigation districts (IDs) mainly supplied by the TSWT.

load for outdoor vegetables than for woody crops since their shorter cycle implies more intensive agricultural activity (seedling production, field works, irrigation, *etc.*), whilst almond orchards presented the lowest EUP and GWP.

The environmental analysis could also be presented per kg of product (kg PO_{4eq}/kg and kg CO_{2eq}/kg for EUP and GWP, respectively), considering the joint favourable agronomic effect of DSW in the scenarios. The analysis per mass unit (Table B1, Appendix B) revealed two different trends for outdoor vegetables and woody crops. On average, for outdoor vegetables, EUP per kg of product increased 17.2 % and 35.9 % when passing from 0 %DSW to 50 %DSW and from 0 %DSW to 100 % DSW, respectively. These increases for GWP were 37.8 % and 74.3 %, respectively. On the other hand, for woody crops, both EUP and GWP per kg of product significantly buffered their increase between scenarios. In fact, on average, the EUP even decreased by 4.6 % with the move from 0 %DSW to 50 %DSW, and rose 5.9 % when passing from 0 % DSW to 100 %DSW. The rises in GWP were 10.1 % and 31.9 %, also respectively. Therefore, the main difference between the analysis per unit mass and unit area were that in woody crops there was a decrease in the environmental load for the 50 %DSW, and a clear reduction of that load for the 100 %DSW.

In short, the impact indicators reflected that replacing the waters commonly used with DSW implied an environmental burden for all crops, which was proportional to the share of DSW in the irrigation water. The environmental load per unit area questions the sustainability of an increasing supply of DSW in agriculture. However, due to the agronomic benefits of DSW, this increase in the environmental load was buffered for all crop groups when the analysis was done by unit mass, and even implied a reduction in the environmental load for woody crops in 50 %DSW. These results highlight the relevance of the agronomic effects of low DSW salinity for the environmental sustainability of DSW agricultural use, since for some crops in the study area a target regional production could be obtained by irrigating a smaller surface area, and even reducing the regional environmental load under the combined source scenario. Increased use of renewable energies would also be an important contribution to mitigate the environmental load of DSW use

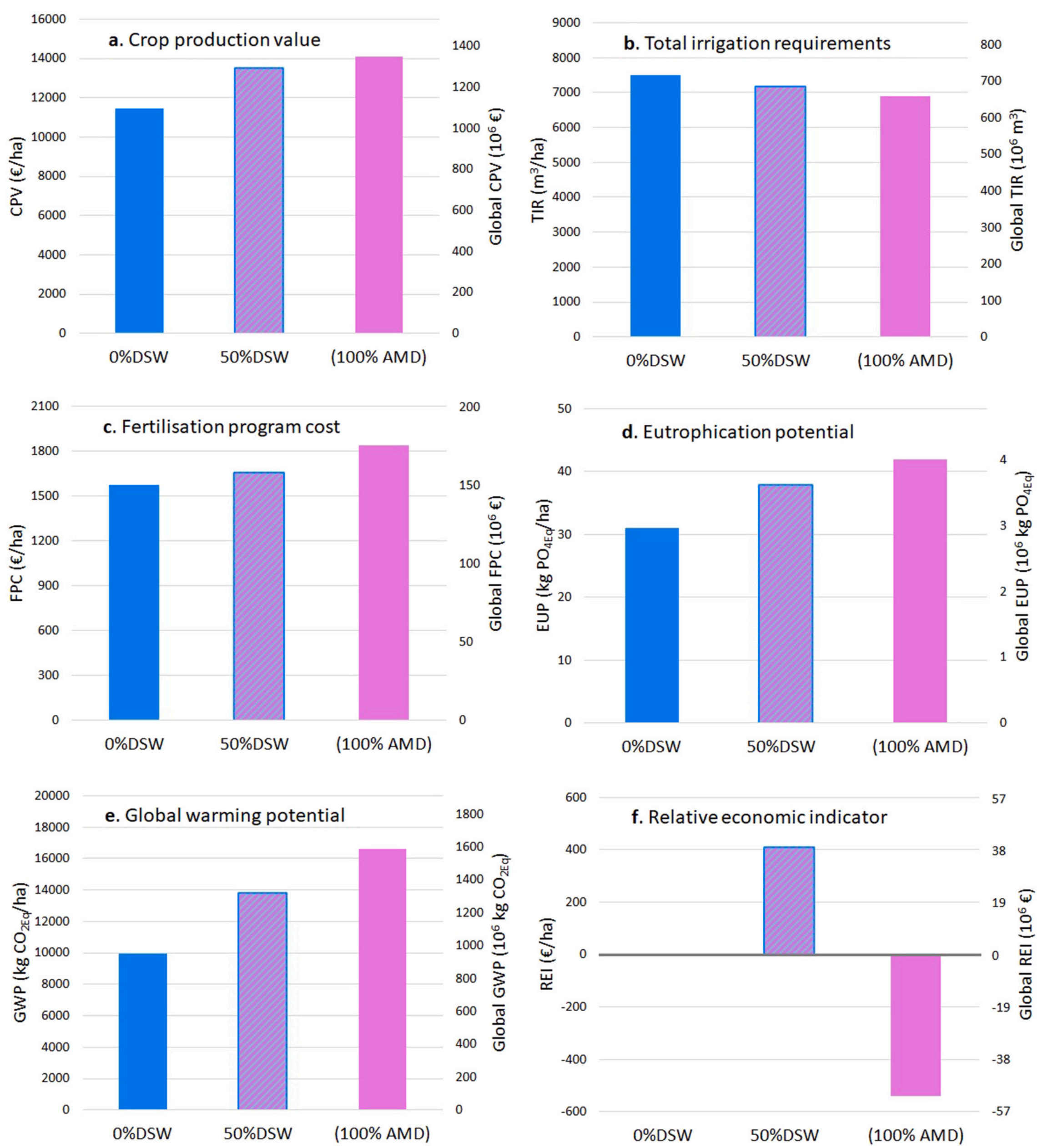

Fig. 6. Regional value for the indicators and scenarios considered in the study area.

in agriculture [59].

3.1.3. Economic indicator

Fig. 4c represents REI values for the selected crops and scenarios; its values by crop groups are included in Table 3.

REI reflects the economic impact of the progressive replacement of the waters commonly used with DSW in relation to the reference scenario (0 %DSW). REI showed a heterogeneous behaviour by crop, in that its value decreased in some crops as the proportion of DSW increased (artichoke, broccoli, and mandarin); others were hardly affected (melon); for some it increased in 50 %DSW and decreased in 100 %DSW (lettuce and orange); whilst in others it increased in both scenarios with DSW (lemon, apricot, peach, and almond). This behaviour was mainly explained by the level of tolerance or sensitivity of the crop to irrigation water salinity; for tolerant crops, such as artichoke, the progressive incorporation of DSW did not enhance production, but it did increase the water and fertiliser costs; for sensitive crops, such as apricot and peach, the progressive incorporation of DSW improved production in 50 % DSW, and even more so in 100 %DSW, thus compensating the additional water and fertiliser cost; and semi-tolerant or semi-sensitive crops showed intermediate behaviours without clear trends. In any case, the results showed that a combined water management (50 %DSW) is more interesting from an economic perspective than the use of only DSW (100 %DSW) for most crops (Fig. 4c). The best management recommendation for some crops (artichoke, broccoli, and mandarin) would be to avoid using DSW.

The behaviour of REI by crop groups was also heterogeneous (Table 3): for outdoor vegetables it decreased as the proportion of DSW increased; for citrus trees it showed an increase in 50 %DSW that changed into a decrease in 100 %DSW; and for non-citrus trees and almond trees it increased for both scenarios with DSW incorporation, although its value was more favourable under the combined source management (50 %DSW). In absolute terms, outdoor vegetables showed a loss in profitability of 921 €/ha and 2433 €/ha for 50 %DSW and 100 % DSW, respectively; in citrus trees, 50 %DSW provided a profit of 458 €/ha, whilst 100 %DSW yielded a loss of 267 €/ha; non-citrus trees showed gains of 3695 and 3452 for 50 %DSW and 100 %DSW, respectively; and almond trees of 529 €/ha and 133 €/ha, also respectively. In relative terms, for all crop groups 50 %DSW is more interesting economically than 100 %DSW, in agreement with recommendations by other authors [8,30,35]. A comparison of the above figures with the typical production costs of each crop (Table 4) also gives an idea of the significance of the economic impact of DSW use for crop irrigation, which is especially harmful in those crops that are salinity tolerant and do not benefit from production increases.

3.2. Regional extrapolation and analysis

The area-weighted average values of the impact indicators in each scenario, calculated for the 18 IDs mainly supplied by the TSWT are given in Fig. 5. Their area-weighted average values and the regional magnitudes for the entire study area in each scenario are depicted in Fig. 6. These area-weighted average values for the study area and their variation with respect to the reference scenario (0 %DSW) are summarised in Table 4. Regional magnitudes can be obtained by multiplying these values by the net surface of the TSWT irrigable areas (95,599 ha).

Table 4
Area-weighted average value of the impact indicators in each scenario for the study area. The variation with respect to the reference scenario is also shown in brackets.

Impact indicator	0 %DSW scenario	50 %DSW scenario	100 %DSW scenario
CPV (€/ha)	11,456	13,520 (+18.0%)	14,084 (+22.9%)
TIR, (m^3/ha)	7490	7177 (−4.2%)	6890 (−8.0%)
FPC, (€/ha)	1571	1653 (+5.2%)	1838 (+17.0%)
EUP (kg PO_{4eq}/ha)	31	38 (+22.0%)	42 (+35.4%)
GWP (kg CO_{2eq}/ ha)	9937	13,817 (+39.01%)	16,606 (+67.1%)
REI (€/ha)	0	409	−541

3.2.1. Global impacts for the study area

With regard to the agronomic indicators, the CPV grew for the study area as the proportion of DSW increased (Fig. 6a). The rise reached 18.0 % for 50 %DSW and 22.9 % for 100 %DSW (Table 4), *i.e.*, the positive effect on production of decreased irrigation water salinity was less important as the proportion of DSW increased, because the salinity for 50 %DSW was only a minor constraint for the production of most crops. The TIR showed a small decrease as the proportion of DSW increased (Fig. 6b); it behaved almost linearly, as the variation was −4.2 % for 50 %DSW and −8.0 % for 100 %DSW (Table 4). Finally, the FPC grew as the proportion of DSW increased (Fig. 6c), although it varied little (+5.2 %) in 50 %DSW and rose considerably (+17.0 %) in 100 %DSW, which means that the water sources other than desalination significantly mitigate the low mineralisation of DSW in the combined source scenario.

The environmental indicators, EUP and GWP, presented higher values as the proportion of DSW increased (Fig. 6d and e). The variation between scenarios was more important in GWP than in EUP (Table 4) since it is more closely linked to energy consumption. The variation of both indicators between scenarios was also higher than that of the other indicators, especially for GWP, which increased 67.1 % with the change from 0 %DSW to 100 %DSW (Table 4). These results are consistent with the fact that DSW has a very high specific energy compared to other water sources (Table 1) [34], resulting in a sharp increase in energy consumption with the progressive replacement of the waters commonly used and, consequently, a clear impact on the sustainability of irrigated agriculture.

The economic indicator (REI) showed a positive variation (+409 €/ha) with the move from 0 %DSW to 50 %DSW, indicating that the positive effects of DSW on the agricultural production and the total irrigation requirements were more relevant economically than the negative effects on water and fertiliser costs when a combined source supply is considered. However, the behaviour of the REI changed when considering the move from 0 %DSW to 100 %DSW, as it showed a negative variation (−451 €/ha), representing a significant economic drawback for farmers. This specific behaviour of the REI is justified by the lack of linearity in the growth of crop production as the proportion of DSW increases (Fig. 6a), since it is the leading factor in its increase, whereas the rise in the cost of irrigation water, as the main factor responsible for its decrease, showed a linear behaviour with the proportion of DSW. In summary, for the combined source scenario the economic value of the positive effects exceeds that of the negative ones,

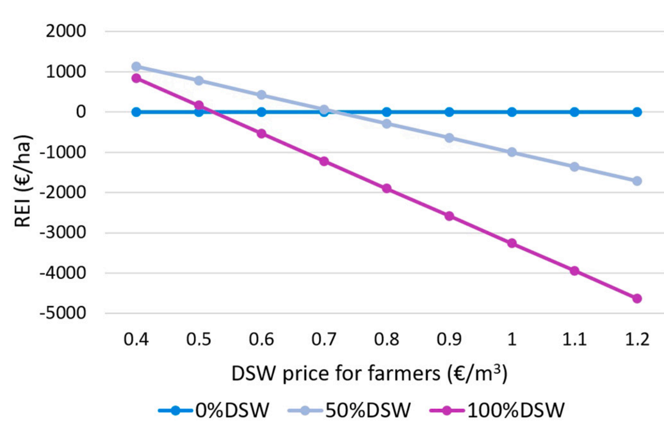

Fig. 7. Sensitivity of the relative economic impact (REI) to the DSW price for farmers in the study area under the considered scenarios.

whilst the opposite occurs for the single source scenario. Therefore, there should be an optimal percentage of DSW in the irrigation water depending on plot conditions (crops, available water resources, *etc.*), which could be particularly relevant to determine so as to optimise farming economic results. This result is in line with recent efforts to optimise water blending and fertilisation in crops irrigated with DSW [30,48].

The economic indicator REI is the highly dependent on the price of DSW for farmers. The latter has fluctuated greatly in the study area over the last years, with prices ranging from 0.4 to 1.2 €/m^3. In summer 2021, the DSW price of 0.6 €/m^3 was still a realistic price for the study area [34]. However, the significant increase in electricity prices in 2022 led to an increase in the DSW price to over 1 €/m^3. Moreover, under the current complex economic situation of agriculture and the drought period in Spain, the Spanish Government has enacted a decree [60] which adopts urgent measures to support the agricultural sector, including the establishment of a subsidised DSW price in the desalination plants supplying the study area, which ensures final prices for farmers of around 0.40–0.50 €/m^3. Considering these circumstances, a sensitivity analysis of the economic indicator REI to the DSW price was performed. Fig. 7 shows the variation of the REI with the price of DSW under the considered scenarios.

It can be seen that for a DSW price of 0.7 €/m^3 in 50 %DSW, the increase in water cost already offsets the agronomic benefits (*i.e.*, the REI becomes practically zero). For every 0.1 €/m^3 rise in the DSW price, there is a decrease of 355 €/ha. In the 100 %DSW case, the rise in the DSW cost offsetting the agronomics benefits was around 0.5 €/m^3, with a decrease of 682 €/ha in the indicator for every 0.1 €/m^3 increase in the DSW price. These figures once again highlight the significant economic impact of incorporating DSW into irrigated agriculture, justifying the ongoing concerns and the continued demand for a subsidised price for DSW supply by the region's farmers [26,27,34]. Moreover, it evidences the current need for subsidy policies to guarantee the economic viability when replacing the waters commonly used in the study area with DSW.

3.2.2. Spatial variability of impact indicators

The adoption of IDs as territorial units of calculation for the extrapolation of the results to the study area enabled the spatial variability of the indicators to be represented (Fig. 5) and analysed. This spatial variability was conditioned by the existing dominant crops, with a general distinction being made between three zones: the area with a predominance of outdoor vegetables, mainly located in the Guadalentín Valley and Campo de Cartagena (IDs 52, 58, 61, 65, 66, 70, and 71; see Fig. 1); the area with a predominance of citrus trees, located in the Vega Baja and its surroundings (IDs 53, 54, 56, 39 and 72, see Fig. 1); and the area with a predominance of non-citrus and almond trees, which is located in the Vega Media-Alta (IDs 26, 37, 38, 40, 41 and 73, see Fig. 1).

Regional differences in the behaviour of the agronomic indicators (CPV, TIR, and FPC) between scenarios were not observed, as they showed the same variation trend for all the crop groups (Table 3). When there were significant differences in the indicator value between crop groups (TIR and FPC), regional variations in the magnitude of the indicators were observed. Thus, the areas of the Guadalentín Valley and Campo de Cartagena showed higher values of TIR and FPC, as outdoor vegetables dominate there. The same occurred with the environmental impact indicators (EUP and GWP), which showed positive variations between scenarios for the whole study area, with higher values in their magnitude for the areas where outdoor vegetables predominate. Finally, the economic impact indicator (REI) showed clear behaviour differences in the study area: in the IDs located in the Vega Baja and surroundings, with a predominance of citrus, there was a small gain for 50 %DSW that practically disappeared for 100 %DSW; in the IDs located in the Vega Media-Alta, where non-citrus trees predominate, there was always an economic gain, which was more favourable for 50 %DSW; and in the IDs of the Guadalentín Valley and Campo de Cartagena, dominated by outdoor vegetables, there was always an economic loss, which was much more intense for the 100 %DSW than for the 50 %DSW scenario. This different economic response of crops suggests that in some areas there may be a shift in the predominant crops as the waters commonly used will be replaced by DSW.

4. Conclusions

Seawater desalination is expected to play an increasing role to support sustainable agricultural productivity, especially in water-scarce areas of regions with strong economies where low-quality waters are currently used in agriculture. A clear example of this is SE Spain, where DSW is progressively replacing other water sources commonly used for crop irrigation, leading to a new agricultural model that fosters irrigated agriculture resilience as climate change impacts intensify. The present study addresses from a multidisciplinary perspective, the local and regional impacts of the progressive incorporation of DSW to irrigated agriculture, so its conclusions are particularly relevant to farmers, irrigation districts and regional water managers for decision making. The following general conclusions can be drawn:

- The joint agronomic impact was favourable, and increasingly relevant with greater sensitivity of the crop to irrigation water salinity. The progressive incorporation of DSW implied a decrease in the salinity of irrigation water, which led to improvements in crop productivity and reductions in irrigation requirements. On the contrary, it also entailed additional fertilisation costs due to the low mineralisation of DSW. Since the improvement in crop productivity decreased or even disappeared as the salinity of the irrigation water decreased, the positive joint agronomic effect was somewhat mitigated when the proportion of DSW exceeded 50 %.
- The environmental impact was significant and unfavourable. The progressive incorporation of DSW implied a proportional increase in the environmental load per unit area for all crops. However, due to the agronomic benefits of DSW, this increase was buffered when the environmental load was considered per unit mass, being very small (outdoor vegetables) or even beneficial (woody crops) in the combined source scenario. This low sustainability is not an intrinsic problem of DSW supply, but rather of the energy system supporting the activity of SWDPs, and which could be mitigated by using renewable energies.
- The economic impact offered heterogeneous results per crop group, as it integrates the economic valuation of the joint agronomic impact (positive) together with the effect of DSW incorporation on the cost of irrigation water (negative). This was clearly favourable in the case of non-citrus trees, and unfavourable for outdoor vegetables, whilst in citrus and almond trees the impacts were very low. In all cases, the combined source scenario (50 %DSW) was more profitable than the single source scenario (100 %DSW). The case study presented confirmed that 100 %DSW use in agriculture results in considerably higher operational costs than for other water supply options, thus jeopardising the economic feasibility of most crops.
- The combined source scenario was more recommendable than the single source scenario from the different perspectives considered in the study, since: (1) the favourable agronomic impacts were saturated for proportions of DSW above 50 %; (2) the unfavourable environmental impacts increased almost linearly with the proportion of DSW; and (3) the economic impact was always better for 50 % DSW than for 100 %DSW. Therefore, all the perspectives considered highlight the benefits of the integrated planning and management of DSW with other available water resources.
- The agronomic and environmental indicators presented a somewhat uniform behaviour for all the crop groups in the study area, which facilitates regional management and planning decisions in these fields. However, the crop groups showed different patterns in the economic indicator, resulting in a heterogeneous economic effect in the irrigation districts of the study area since they present high

variability in the predominant crops. This aspect hinders the adoption of general economic strategies such as subsidies to the DSW price, which would be more effective if applied considering the crops being grown.
- In the study area, developing a combined use scenario of DSW seems only feasible by maintaining the TSWT supply, as it represents 55.5 % of the irrigation water allocations recognised by the official water planning in the study area. Our results stress the need to promote combined water source management, properly evaluating water blending options for each irrigation district or farming case, which should be modelled and analysed in detail to optimise DSW use.

Our research should be considered as a first approximation to the questions under study and is reliable enough for assessing the general behaviour of the selected impact indicators. However, it should be interpreted with caution as it does involve general scenarios that are representative of the wide diversity in the study area rather than specific cases. Nevertheless, the methodology applied can prove useful for assessing the feasibility of DSW integration to support agriculture in other regions worldwide, where the construction of desalination plants is being considered as a means to increase the availability of irrigation water.

CRediT authorship contribution statement

Conceptualization, V. Martínez-Alvarez, JF. Maestre-Valero, B. Gallego-Elvira; Data curation, A. Imbernón-Mulero, M. Soto-García, JF. Maestre-Valero; Formal analysis, A. Imbernón-Mulero, M. Soto-García, V. Martínez-Alvarez; Funding acquisition, B. Gallego-Elvira, JF Maestre-Valero; Investigation, all authors; Methodology, V. Martínez-Alvarez, A. Imbernón-Mulero, B. Gallego-Elvira; Visualization, V. Martínez-Alvarez, A. Imbernón-Mulero, B. Gallego-Elvira; Project administration, Jose Maestre-Valero; Writing – original draft, V. Martínez-Alvarez; Writing – review & editing: all authors. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A

Table A1
Parameters a and b of the production function, and soil saturation extract electric conductivity producing a 100 % yield decrease ($maxEC_s$) for the selected crops.

Crop	*a* (EC_s threshold, dS/m)	*b* (slope, %)	$maxEC_s$ (dS/m)
Artichoke	6.1	11.5	14.8
Broccoli	2.8	9.2	14.0
Lettuce	1.3	13	9.0
Melon	1.0	8.4	12.9
Lemon	1.5	12.8	9.3
Mandarin	1.7	13.1	8.0
Orange	1.7	13.1	8.0
Apricot	1.6	24	5.8
Peach	1.7	21	6.5
Almond	1.5	19	6.8

Appendix B

Table B1
Environmental impact indicators value by unit mass rather than by unit area, per crop group and scenario. The variation with respect to the reference scenario is also shown in brackets.

Crop group	Impact indicator	0 %DSW scenario	50 %DSW scenario	100 %DSW scenario
Outdoor vegetables	EUP (kg PO_{4eq}/kg)	$16.9 \bullet 10^{-4}$	$19.8 \bullet 10^{-4}$ (+17.2 %)	$22.9 \bullet 10^{-4}$ (+35.9 %)
	GWP (kg CO_{2eq}/kg)	$49.8 \bullet 10^{-2}$	$68.6 \bullet 10^{-2}$ (+37.8 %)	$78.8 \bullet 10^{-2}$ (+58.3 %)
Citrus trees	EUP (kg PO_{4eq}/kg)	$9.3 \bullet 10^{-4}$	$9.8 \bullet 10^{-4}$ (+5.0 %)	$11.1 \bullet 10^{-4}$ (+19.3 %)
	GWP (kg CO_{2eq}/kg)	$33.0 \bullet 10^{-2}$	$38.7 \bullet 10^{-2}$ (+17.1 %)	$46.8 \bullet 10^{-2}$ (+41.7 %)
Non-citrus trees	EUP (kg PO_{4eq}/kg)	$11.6 \bullet 10^{-4}$	$10.6 \bullet 10^{-4}$ (−8.9 %)	$11.9 \bullet 10^{-4}$ (+2.3 %)
	GWP (kg CO_{2eq}/kg)	$37.70 \bullet 10^{-2}$	$39.3 \bullet 10^{-2}$ (+4.3 %)	$47.4 \bullet 10^{-2}$ (+25.6 %)
Almond trees	EUP (kg PO_{4eq}/kg)	$56.3 \bullet 10^{-4}$	$50.9 \bullet 10^{-4}$ (−9.6 %)	$54.0 \bullet 10^{-4}$ (−4.1 %)
	GWP (kg CO_{2eq}/kg)	$34.0 \bullet 10^{-2}$	$46.0 \bullet 10^{-2}$ (+8.9 %)	$72.0 \bullet 10^{-2}$ (+28.4 %)

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