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Irriblend-DSW: A decision support tool for the optimal blending of desalinated and conventional irrigation waters in dry regions

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ABSTRACT

Desalinated sea water (DSW) is increasingly being used as an alternative source of irrigation in dry coastal areas. Owing to its high price and singular composition, it is often blended with other water resources to curb costs. Although this is a common practice, limited resources are available to manage the increased agro-economic complexity required to balance several water sources with heterogeneous quality, price, and availability restrictions. To support the management of fertigation with DSW, in this study, we present an open-source decision support tool (DST), Irriblend-DSW. The DST has been designed to identify potentially profitable fertigation options for different water and fertiliser availability scenarios. To demonstrate the key features of the tool, we applied it to two actual case study scenarios in south-eastern Spain, where severe water scarcity led to massive seawater desalination for agricultural supply. The information provided by the DST enabled the assessment of the viability of different water blending options and the selection of an optimal combination of water and fertilisers. The simulation results showed that the fertigation costs of the studied crops, hydroponic lettuce, and greenhouse tomato substantially increased with the integration of DSW. The DST output showed how water price rises, and how additional types and amounts of fertilisers are required when more DSW is used. However, because the salinity of the blend is also reduced with the use of DSW, the yield outcome improves and, thus, to some extent, compensates for the increased cost. In fact, despite higher costs, the studied crops were found to be very profitable when the optimised solutions computed by the DST were selected. Moreover, the optimum fertigation solutions not only reduced costs but also decreased nutrient leaching in areas of severely polluted aquifers.

1. Introduction

Freshwater resources are scarce and cannot meet current or future demands of irrigated agriculture. Therefore, non-conventional resources are becoming indispensable in many parts of the world (Scheierling and Tréguer, 2018). In water-stressed coastal regions, seawater desalination can provide unlimited irrigation supply without being climate-dependent, thereby fostering long-term food security and socio-economic stability (Burn et al., 2015). Furthermore, in water-limited areas that have long resorted to marginal low-quality waters (Bortolini et al., 2018), the low salinity of desalinated seawater (DSW) allows reversing prior problematic trends of soil salinisation and groundwater contamination (Kaner et al., 2017; Raveh and Ben-Gal, 2018). Overall, DSW is an attractive solution to alleviate irrigation water shortages, but its high price and potential increases in fertilisation costs may reduce farming profitability and hinder adoption.

The high energy consumption of seawater desalination makes DSW more expensive than other resources (Zarzo and Prats, 2018). Moreover, its singular chemical composition could cause agronomic risks, such as phytotoxicity, soil alkalinisation, and an increase in fertilisation costs (Ben-Gal et al., 2009; Kim et al., 2020; Yermiyahu et al., 2007). The increase in fertilisation costs is because DSW lacks certain essential nutrients for plant growth, such as Ca, Mg, and S, which are generally abundant in conventional irrigation waters in many arid regions and, thus, taken for granted by farmers (Ben-Gal et al., 2009). In addition to the need for increased amounts of fertiliser, the management of a higher variety of fertilisers could in some cases also require intensive upgrading of the irrigation system head (Martinez-Alvarez et al., 2020). In order to reduce water and fertigation costs, DSW can be used in combination with cheaper water sources with a higher mineral content (Ben-Gal

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et al., 2009; Martinez-Alvarez et al., 2020). Recent studies have demonstrated this aspect and presented new economically feasible irrigation management options based on DSW blended with locally available brackish water for greenhouse crops in Spain (Reca et al., 2018), Maltese vineyards (Aparicio et al., 2019), and several salt-sensitive crops in Israel's Arava Valley (Kaner et al., 2017).

The integration of DSW into irrigated agriculture is increasing; however, limited resources are available to assist with the management of multiple water sources with heterogeneous quality, price, and availability restrictions. One of the first suitable resources in this direction was AnswerApp (Kaner et al., 2017), which is an online application that combines a biological–physical model for crop response to salinity with economic calculations. This application indicates the potential profitability of irrigation of various crops as a function of water salinity but does not provide options for water blending and fertilisation optimisation. To the best of our knowledge, the first resource to specifically compute the optimal irrigation blend of DSW with other sources was the GARUM software (Reca et al., 2018). This is a useful decision support tool (DST) which helps farmers optimise the water mixture and usage when different sources of nonuniform quality water are available for the irrigation of greenhouse crops in semiarid regions. The main drawback of this method is that fertilisation is included in fixed costs and not as part of the optimisation algorithm. Several fertigation simulators and applications can be found in the literature for managing the application of fertilisers in soil and soilless crops (Barradas et al., 2012; Perez-Castro et al., 2017). However, few of these resources offer the possibility of calculating the optimal combination of fertilisers to meet the nutritional needs at a minimum cost (Bueno-Delgado et al., 2016), and none have integrated the combined management of DSW with other sources (Martinez-Alvarez et al., 2020).

Building on previous knowledge from GARUM developers, the main aim of the DST presented herein, Irriblend-DSW, is to help users form more effective decisions to maximise profits in crop production with a mix of conventional waters (e.g. surface, underground, and brackish) and DSW. A remarkable novelty of our DST is that apart from computing the optimum (most profitable) water blend, it provides the optimal selection and amount of commercial fertiliser required for that water combination, given that the irrigation water is already a nutrient carrier. The benefits of this approach are two-fold: it optimises the fertilisation cost and prevents over-fertilisation and leaching of nutrients. Another notable aspect of our DST is that it follows the current practice for the effective design and delivery of DSTs to improve the otherwise low uptake by potential users (Gallardo et al., 2020; Rose et al., 2016). Thus, our tool is free, open-source, and easily accessible on the cloud from a web browser and does not require software installation. It is ready to be used by end-users with visual and interactive input and output files in common formats. In addition, the code is open and accessible in a free repository hosting service for researchers and advanced users and is prepared for further development.

The main objectives of this study are (i) to describe the main features and structure of Irriblend-DSW and (ii) to demonstrate its use with two case studies of high-return hydroponic crops in south-eastern (SE) Spain and discuss its practicality for fertigation management in water-limited areas. In the following sections, we first provide an overview and description of the modules of the DST and present the case studies. Then, we analyse and discuss the results of the two case studies and finally conclude the article and indicate the strengths and weaknesses of the presented tool as well as its future work prospects.

2. Materials and methods

2.1. Irriblend-DSW overview

Irriblend-DSW is a DST designed to optimise soilless crop fertigation profitability when irrigated with a mix of DSW and conventional water. The tool computes the optimal blend of DSW with the available conventional water and selects the best combination of commercial fertilisers considering the composition of the water blend. Therefore, the following information is required by the DST: the available water sources (quality, price, quantity restrictions), available commercial fertilisers (composition and price), nutritional needs and salinity threshold of the crop, and indicators of potential profit under optimal conditions (without water stress, salinity damage, or phytosanitary issues). The tool uses this information to calculate the most profitable water blend and the required amount of each selected fertiliser. The potential profitability for each possible water blend and the amount of each commercial fertiliser used to optimise costs are also provided and compared with the optimum.

2.2. Programme structure and modules

The DST is coded in Python 3 and uses freely available scientific libraries. The programme was implemented in Google Colaboratory (GC), which is an excellent environment for collaborative research. GC is a free Jupyter Notebook environment that runs entirely on the cloud and requires no installation. It serves as an interactive code interface, a data visualisation tool, and a markdown editor, which can be used by research collaborators as well as end-users. The DST code and the user guide are freely available at GitHub along with the input and output data of the two examples corresponding to the case studies presented in this article (please see research data statement). The user guide explains how Irriblend-DSW can be easily implemented from a web browser without any setup or installation. The only requirement is to have a free Google account to enable access to the GC. The input and output files are all stored in the Google Drive (Gdrive) of the user account. Due to the possible hurdles of data requirements and formats, all the inputs required to run this DST are stored in one spreadsheet. Users can use the sample input files provided to test the DST and as a template for their runs. The DST is structured into four interconnected parts with specific functionalities, as described in the following subsections. Fig. 1 shows the outline and data flow of the DST.

2.2.1. Input data import

This module reads and imports all the input data from one spreadsheet (Fig. 1). Running the DST requires the following specific information:

- Ideal solutions for crop fertigation. The ideal solution must be provided in mmol/l along with the electrical conductivity (EC) limit in dS/m for the simulation. The EC limit is the maximum electrical conductivity in the fertigation solution (mix of water and fertilisers) allowed by the user for simulation purposes. This value should be substantially above the crop tolerance to allow the simulation of yield loss under salinity stress.
- Water sources: composition, price, and availability. The composition of each water source must be provided in mg/l, the EC in dS/m, the price in €/m^3, and the availability as a percentage. A value of 100% means that there are no restrictions on the availability of that water source. The programme can run simulations using two or three water sources.
- Commercial fertilisers: composition and price. The composition of each available commercial fertiliser must be provided in mmol/g, density in g/cm^3, and price in €/kg. The programme can handle up to 30 fertilisers.
- Crop info: productivity and profitability indicators. The following indicators are to be provided assuming a crop without limitations of water and nutrients and free of climate and phytosanitary stress:
  - o Water productivity (kg yield/m^3 water used for fertigation).
  - o Land productivity (kg yield/m^2 of crop surface).
  - o Crop market price (€/kg).
  - o Crop salinity threshold ("a", dS/m) above which there is yield loss and salinity yield reduction factor ("b"). These parameters "a" and

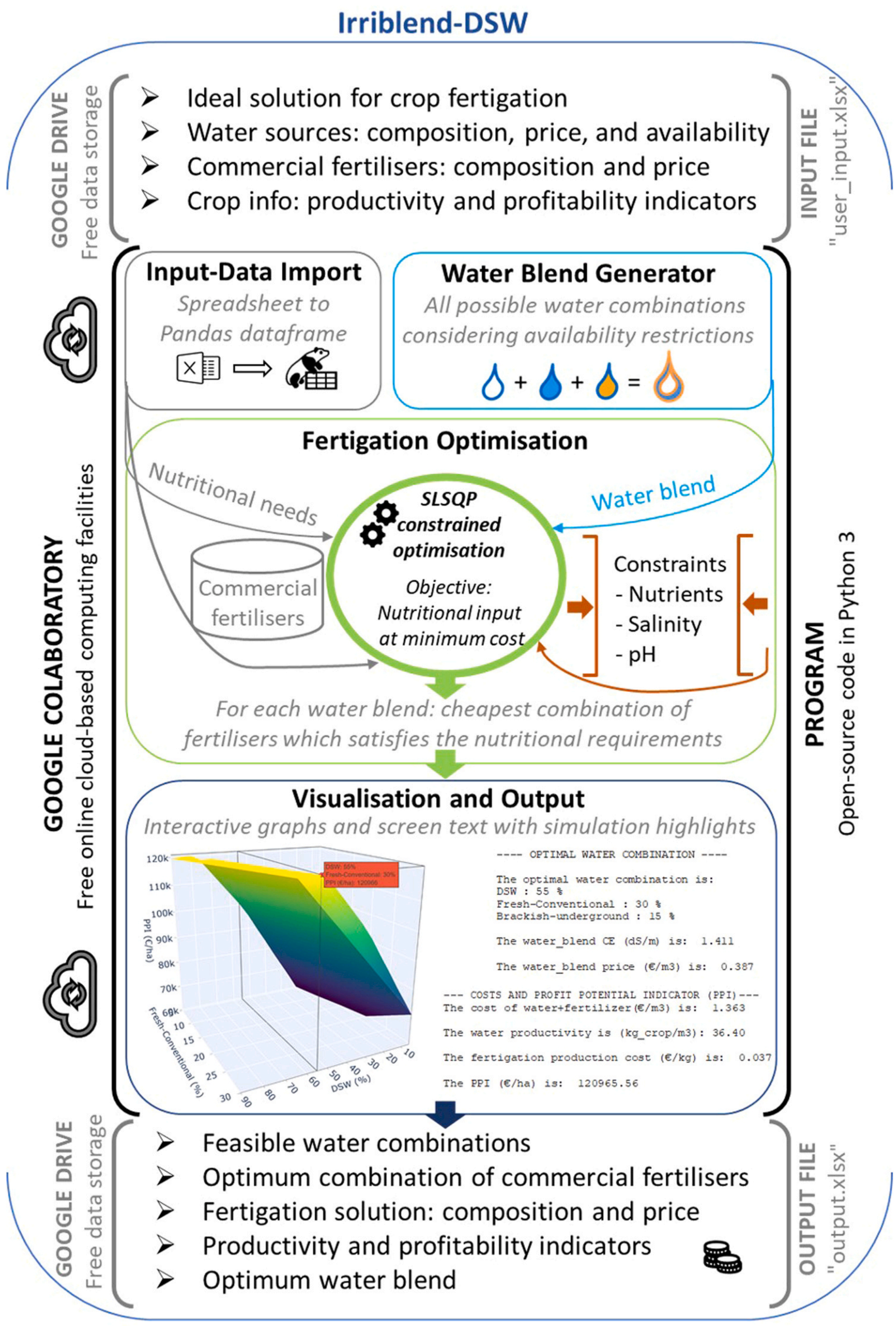

Fig. 1. Schematic representation and flow chart of Irriblend-DSW.

"b" are based on the formula of FAO 61 (FAO, 2002), in which yield is reduced linearly over the crop salinity threshold: Relative yield = 100 - b(ECr - a), where ECr is the EC in the root zone in the soilless culture in dS/m.

2.2.2. *Water blend generator*

The water blend generator simulates all possible water blends from two or three water sources in 5% steps, considering the availability restrictions given by the user. For example, if there are three water sources, wA, wB, and wC with availabilities of 100%, 100%, and 20%, then a possible water blend could be wA: 35%, wB: 50%, and wC: 15%. The sum of wA, wB, and wC is always 100%, and in this example, wC is either less than or equal to 20%. The blend is a linear average of the composition and conductivity, in which each water source is given the corresponding percentage weight. The fertigation optimisation algorithm (2.2.3) determines—for each water blend generated—whether nutritional needs can be fulfilled using the irrigation water, given the specified restrictions and constraints.

2.2.3. *Fertigation optimisation*

Given the chemical composition of the water blend and the ideal fertigation solution, the programme calculates the nutrients that must be added to the already nutrient-loaded irrigation water to satisfy the uptake for the crop. Thereafter, the type and quantity of commercial fertilisers, from the database that can provide the nutrients needed at the minimum cost were calculated. For this purpose, the optimisation algorithm runs the *optimisation* function of the Python *scipy* library for constrained minimisation with the sequential least squares programming (SLSQP) to minimise the cost function, under the assumption of the following set of constraints:

- EC < EC limit.
- Exact nutritional needs amounts of NO_3^-, NH_4^+, $H_2PO_4^-$, K^+, and HCO_3^-.
- Amounts of Ca^{+2}, Mg^{+2}, SO_4^{2-}, Cl^-, and Na^+, equal to or above needs.

2.2.4. *Visualisation and output*

The last module visualises and stores the results. Five sections of results are presented in the output file.

- Feasible water combinations: All the water combinations having a solution (i.e. those that provide the target fertigation solution with the given set of commercial fertilisers under the user's restrictions) are stored. For these combinations, the EC (dS/m) and price (€/m^3) are provided.
- Optimum combination of commercial fertilisers: For each feasible water combination, the optimum (cheapest) combination of commercial fertilisers is provided. The amount of each fertiliser is given in g/l.
- Fertigation solution: The fertigation solution (ions in mmol/l) for each feasible water combination is provided along with the final EC (dS/m) in the solution and the price (€/m^3).
- Productivity and profitability indicators: For each water combination, the profit potential indicator (€/ha), water productivity (kg yield/m^3), and production cost (€/kg yield) are given. The profit potential indicator (PPI) is the yield benefit (production [kg] × market price [€/kg]) minus the fertigation cost (cost of water plus fertiliser).
- Optimum water blend: This indicates the water blend that provides the maximum PPI.

2.3. *Case studies*

Both case studies to demonstrate the features of Irriblend-DSW correspond to high-return hydroponic crops in water-limited areas of SE Spain. Specifically, Case 1 is set in the Segura River Basin (SRB) and Case 2 is set in the eastern part of the Andalusian Mediterranean Basins (AMB) where irrigated agriculture is concentrated (Fig. 2). Substantial seawater desalination for agricultural supply has been implemented in these areas due to the exacerbated water shortage that threatens their strategic, highly profitable agricultural production. The water deficit directly impacting irrigated agriculture is over 400 Mm^3/year in the SRB (CHS, 2015) and over 160 Mm^3/year in AMB (CMAOT, 2015). This deficit is partly alleviated by DSW agricultural supply, which amounts to 126 Mm^3 in the SRB and to 34 Mm^3 in the AMB (Fig. 2, acuaMed, 2019; Martinez-Alvarez et al., 2019). We describe each case and the data used to evaluate the DST in detail in the subsequent sections.

2.3.1. *Case 1: soilless lettuce in the SRB*

A lettuce crop in the "Campo de Cartagena" irrigation district (Fig. 2) was selected for the case study because it is the principal winter vegetable crop grown in the SRB. More than 500,000 t of lettuce was exported in 2019, generating a revenue of 475 million (FEPEX, 2020). In particular, we present a case of the lettuce variety Little Gem grown with the hydroponic nutrient film technique (NFT) in which the nutrient solution flows through channels where plants have their bare root systems. The NFT system has been reported to provide higher yields and water productivity and is more eco-friendly than the traditional soil cultivation (Maestre-Valero et al., 2018).

Tables 1–4 show the input data used to run the DST for each section indicated in epigraph 2.2.1 respectively: (i) nutrient solution for fertigation, (ii) water sources, (iii) commercial fertilisers, and (iv) productivity and profitability indicators. The input data used in this case study were obtained mainly from a recent study conducted by our research team, in which a comprehensive inventory was built with data from two commercial farms using NFT systems to grow lettuce in the SRB (Maestre-Valero et al., 2018; Martinez-Mate et al., 2018). The traditional water supply in the area is surface water from the Segura Basin or the Tagus-Segura external water transfer. This conventional fresh water supply is of high quality (EC < 1 dS/m, with approximately 100 mg/L of Ca and 40 mg/L of Mg) and has a low cost (0.16 €/m^3); however, its

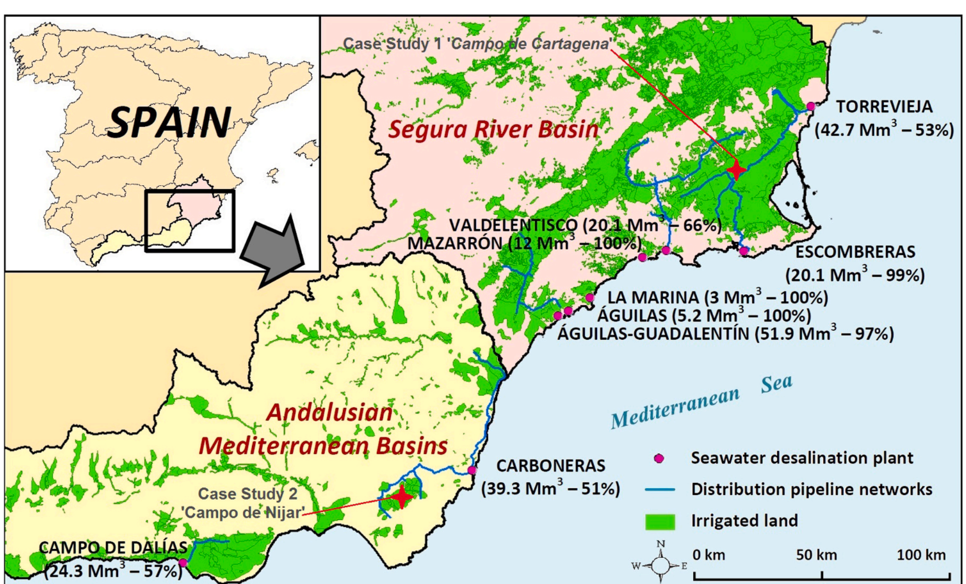

Fig. 2. Location of the Segura River Basin, the Andalusian Mediterranean Basins, "Campo de Cartagena" and "Campo de Níjar". All seawater desalination plants indicated on the map dedicate their production totally or partially to irrigation. The figures are the total production in 2018 (Mm^3) and the corresponding percentage (%) of agricultural supply.

Table 1
Fertigation nutrient solution for case study crops: nutrient film technique (NFT) lettuce and greenhouse (GH) tomato.

Crop	Nutrient solution (mmol/l)								Source
	NO_3^-	$H_2PO_4^-$	SO_4^{2-}	HCO_3^-	NH_4^+	K^+	Ca^{2+}	Mg^{2+}	
NFT lettuce	11	1	2.5	0.5	1	7.4	4.4	1.2	Maestre-Valero et al. (2018)
GH tomato	10.3	1.5	1.8	0.5	1.3	4.8	5	1.5	Rodriguez et al. (2014)

Table 2
Mean values of price, electrical conductivity, and chemical composition of water sources for case studies.

	Type:	Fresh	Desalinated	Brackish	Desalinated	Brackish
	Origin:	Tagus-Segura	Escombreras plant	Underground Segura Basin	Carboneras plant	underground Níjar
Price	€/m^3	0.16	0.60	0.06	0.60	0.18
Conductivity	dS/m	0.86	0.54	5.7	0.55	4.6
Ca^{2+}	mg/L	97.0	20.0	381.4	14.4	208.3
Mg^{2+}	mg/L	40.0	2.4	265.8	4.1	181.5
Na^+	mg/L	41.0	88.0	831	91.6	564.9
K^+	mg/L	2.2	4.0	16.6	9.2	14.9
NH_4^+	mg/L	0.16	0.02	1.7	0	0.1
Cl^-	mg/L	59.0	140.0	1352	148.9	1116.2
SO_4^{2-}	mg/L	233.0	4.0	1432.4	14.5	458.2
HCO_3^-	mg/L	180.0	68.2	68.2	58.7	303.3
NO_3^-	mg/L	1.7	0.1	60.6	0.5	20.55
$H_2PO_4^-/PO_4^{3-}$	mg/L	0.1	0.1	0.3	0.1	0

Table 3
Purity and price of fertilisers used in the simulations.

		Fertiliser purity (%)					Price €/kg
		N	P	K	Ca	Mg	
Phosphoric acid (85%)	H_3PO_4	–	22.7	–	–	–	0.58
Nitric acid (59%)	HNO_3	12.5	–	–	–	–	0.43
Calcium nitrate	$5Ca(NO_3)_2$ $10H_20$ NH_4 NO_3	15.5	–	–	19.0	–	0.46
Magnesium nitrate	$Mg(NO_3)_2$ 6H20	11.0	–	–	–	9.5	0.58
Potassium nitrate	KNO_3	13.0	–	38.7	–	–	1.03
Ammonic nitrate	NH_4NO_3	33.5	–	–	–	–	0.34
Ammonium sulphate	$(NH_4)_2SO_4$	21.0	–	–	–	–	0.23
Potassium sulphate	K_2SO_4	–	–	43.2	–	–	0.68
Magnesium sulphate	$MgSO_4$ $7H_2O$	–	–	–	–	9.6	0.32
Monoammonium phosphate	$NH_4H_2PO_4$	12.0	26.7	–	–	–	1.03
Monopotassium phosphate	KH_2PO_4	–	22.9	28.0	–	–	1.38
Calcium chloride	$CaCl_2$ $2H_2O$	–	–	–	27.2	–	0.20

Average values from fertiliser suppliers in southeast Spain (Maestre-Valero et al., 2018; Martinez-Alvarez et al., 2020).

Table 4
Productivity and profitability indicators of case study crops: nutrient film technique (NFT) lettuce and greenhouse (GH) tomato.

Indicator	NFT lettuce[a]	GH tomato[b]
Water productivity (kg yield/m^3 water used for fertigation)	36.4	19.5
Land productivity (kg yield/m^2 of crop surface)	23.6	7.1
Crop market price (€/kg)	0.55	0.54
Crop salinity threshold (dS/m) above which there is yield loss	3.0	3.2
Percent yield loss per dS/m above crop salinity threshold (%/dS/m)	13.0	9.0

Data are expressed per year (9 cycles) for NFT lettuce and per cycle (5 months) for GH tomato.

[a] Maestre-Valero et al. (2018) and Martinez-Mate et al. (2018).

[b] Rodriguez et al. (2014) and Magan et al. (2008).

availability for agriculture has drastically decreased over the last decade (Pellicer-Martinez and Miguel Martinez-Paz, 2018). This is the main reason for the increased use of DSW, which is often mixed with low-quality underground water to reduce costs. In our simulations, we used three water sources (Table 2): water transferred by the Tagus-Segura aqueduct, DSW from the Escombreras desalination plant (Fig. 2), and brackish underground water (AQUALOGY, 2016). It should be noted that the quality and price of the DSW from the Escombreras plant is similar to the rest of the desalination plants in the area shown in Fig. 2 (Martinez-Alvarez et al., 2020). In accordance with the current availability situation, supply restrictions were imposed only for the Tagus-Segura water, with a limitation of 30% in the blend.

2.3.2. *Case 2: greenhouse tomato in Almeria*

In the eastern part of the AMB there are more than 32,000 ha of horticultural greenhouses, which generate over 3.5 M t vegetables and 2 B € each year (Cajamar, 2019). The greenhouse (GH) tomato is the most important vegetable, representing 20% of the total GH area in the region. Half of the production is exported mainly to European markets (Cajamar, 2019). There are different varieties of GH tomato grown in soil and soilless cultures and with short and long production cycles. Our case study corresponds to hydroponic tomato cultivar Ramyle (variety with a long post-harvest life), which can be grown in autumn or spring short (5 months) cycles in the study area.

The case study was conducted in the “Campo de Níjar” GH district (Fig. 2), where there is currently no surface water available for irrigation. The continuous over-withdrawal of irrigation water from the aquifer resulted in a severe drop in the groundwater level. Furthermore, excessive return flows from irrigation have led to severe aquifer salinisation and pollution (Sanchez et al., 2015a). The high salinity of the irrigation water has led to notably reduced crop yields and has limited crop production in the area to only the most salt-tolerant crops, such as tomato and watermelon (Sanchez et al., 2015b). The aquifer was the only source available until the Carboneras desalination plant started supplying water for irrigation in this district in 2005. However, the usage of DSW has been lower than expected, mainly because of farmers' concerns about its high price and the need for additional fertilisation (Aznar-Sanchez et al., 2017). Our case study represents the current situation in which farmers have access to two independent water distribution networks, one supplying low-quality underground water (Underground Níjar in Table 2) at a low rate (0.18 €/m^3) and DSW from the Carboneras plant at a higher rate (0.6 €/m^3). The farmers must then make proper water usage and mixing decisions to obtain the desired water quality.

Tables 1–4 show the input data used to run the DST. These data were obtained from recent studies conducted in the study area, in which the ideal nutrient solution for soilless GH cultivar Ramyle tomato was defined (Rodriguez et al., 2014); the water sources were characterised (Reca et al., 2018; Valera et al., 2017); productivity and profitability indicators of the crop were assessed (Rodriguez et al., 2014; Sanchez et al., 2015a); and the salinity threshold and yield loss were observed (Magan et al., 2008).

3. Results

Table 5 presents the main data outputs of the optimum water blend computed by DST for both case studies.

Table 5
Water combination, selected fertilisers, nutrient solution, and profitability indicators for the optimum water blend computed by the DST for both case studies.

Optimum water blend				
	Case 1 – lettuce		Case 2 – tomato	
Water combination				
Price: 0.38 €/m^3; Conductivity: 1.41 dS/m			Price: 0.45 €/m^3; Conductivity: 1.9 dS/m	
Resource	Amount (%)	Availability (%)	Amount (%)	Availability (%)
Fresh	30	up to 30	0	up to 0
Desalinated	55	up to 100	65	up to 100
Brackish	15	up to 100	35	up to 100
Fertilisers				
Cost: 0.98 €/m^3			Cost: 0.81 €/m^3	
Fertiliser		Dose (g/l)		Dose (g/l)
Phosphoric acid (85%)		0.1152		0.1729
Nitric acid (59%)		0.1359		0.0391
Calcium nitrate		0.4265		0.6372
Potassium nitrate		0.4688		0.2642
Ammonium nitrate		0.047		0.0527
Potassium sulphate		0.2285		0.1611
Nutrient solution				
Price: 1.36 €/m^3; Conductivity: 2.90 dS/m			Price: 1.26 €/m^3; Conductivity: 3.09 dS/m	
Ion Concentration (mmol/l)			Concentration (mmol/l)	
NO_3^-		11		10.3
$H_2PO_4^-$		1		1.5
SO_4^{2-}		4.3		2.7
HCO_3^-		0.5		0.5
NH_4^+		1		1.3
K^+		7.4		4.7
Ca^{2+}		4.4		5
Mg^{2+}		2.2		2.7
Costs and profit potential indicator (PPI)				
Water productivity (kg/m^3)		36.40		19.50
Fertigation cost (€/kg)		0.037		0.065
PPI (€/ha)		120,965.56		33,742.11

3.1. Case 1

Considering the crop needs, the fertiliser and water types available, and the restrictions imposed, the DST calculated that the optimum water blend consisted of 30% fresh water (Tagus-Segura), 55% of DSW, and 15% brackish underground water (Fig. 3). This water blend had an EC of 1.41 dS/m, and the cost per m^3 was 0.38 €. The optimal (cheapest) combination of fertilisers and final (closest to user input considering the imposed restraints) fertigation solution are shown in Table 5. The EC of the computed fertigation solution (2.9 dS/m) was just below the salinity threshold of the crop (3 dS/m) and therefore the water and land productivity potential is reached. The cost of the fertigation solution (water + fertiliser) was 1.36 €/m^3, which implies a fertigation production cost of 0.037 €/kg. The optimal solution found by the DST leaves a PPI of 120.9×10^3 €/ha/year (corresponding to nine crop cycles), which shows that this crop can be very profitable (17.7×10^3 €/ha/year) with good management of water resources and fertilisers.

In this simulation (Output-file-case1, Appendix A), out of 93 water combinations in 5% steps for each water source, there were 87 feasible solutions (i.e. the fertigation optimisation algorithm found a solution under the set of constraints for the given available water and fertilisers). Only 42 surpassed the profitability threshold, which is the sum of investment and operational costs, excluding the cost of water and fertilisers (103.2×10^3 €/ha/year, Maestre-Valero et al., 2018). Looking at the fertiliser selection for each water blend, only phosphoric and nitric acids, potassium and ammonium nitrates, and potassium sulphate are required for blends containing up to 40% DSW. However, the simulation shows that apart from these fertilisers, calcium nitrate is required for blends with more than 40% of DSW to compensate for the lack of Ca in the DSW, and magnesium nitrate is also needed when the proportion of DSW exceeds 70%.

3.2. Case 2

For the given input data (crop needs, fertiliser, and water types and restrictions), the DST calculated the optimum water blend to be 65% of DSW and 35% of brackish underground water (Fig. 4). This water blend had an EC of 1.98 dS/m, and the cost per m^3 was 0.45 €. The economically optimal combination of fertilisers and final fertigation solution are shown in Table 5. The EC of the computed fertigation solution (3.09 dS/m) was just below the salinity threshold of the crop (3.2 dS/m) and therefore the water and land productivity potential can be reached (as in case study 1). In this case, the use of 35% of low-cost brackish water substantially reduces the costs by 0.15 €/m^3 compared with that by using only DSW, without (simulated) yield losses. The final cost of the fertigation solution (water + fertiliser) was 1.26 €/m^3, which implies a fertigation production cost of 0.065 €/kg. The optimal solution proposed by the DST has a PPI of 33.7×10^3 €/ha/cycle, which after discounting the rest of the costs leaves a reasonably good net profit of 6.4×10^3 €/ha/cycle.

The simulation output (Output-file-case2, Appendix A) shows 10 feasible solutions. All of them surpassed the profitability threshold (investment plus operational costs excluding the cost of water and fertilisers: 27.3×10^3 €/ha), but a sharp decrease in PPI was observed with percentual increases in brackish water (Fig. 4). The fertilisers required in the blend of up to 50% of DSW were mainly nitric and phosphoric acids, and potassium and ammonium nitrates. However, if DSW dominates, potassium sulphate is required, and the amount of calcium nitrate increases linearly with the percentage of DSW in the blend.

4. Discussion

The results of the Irriblend-DSW simulations offered valuable information for the fertigation management of the demonstrative case studies

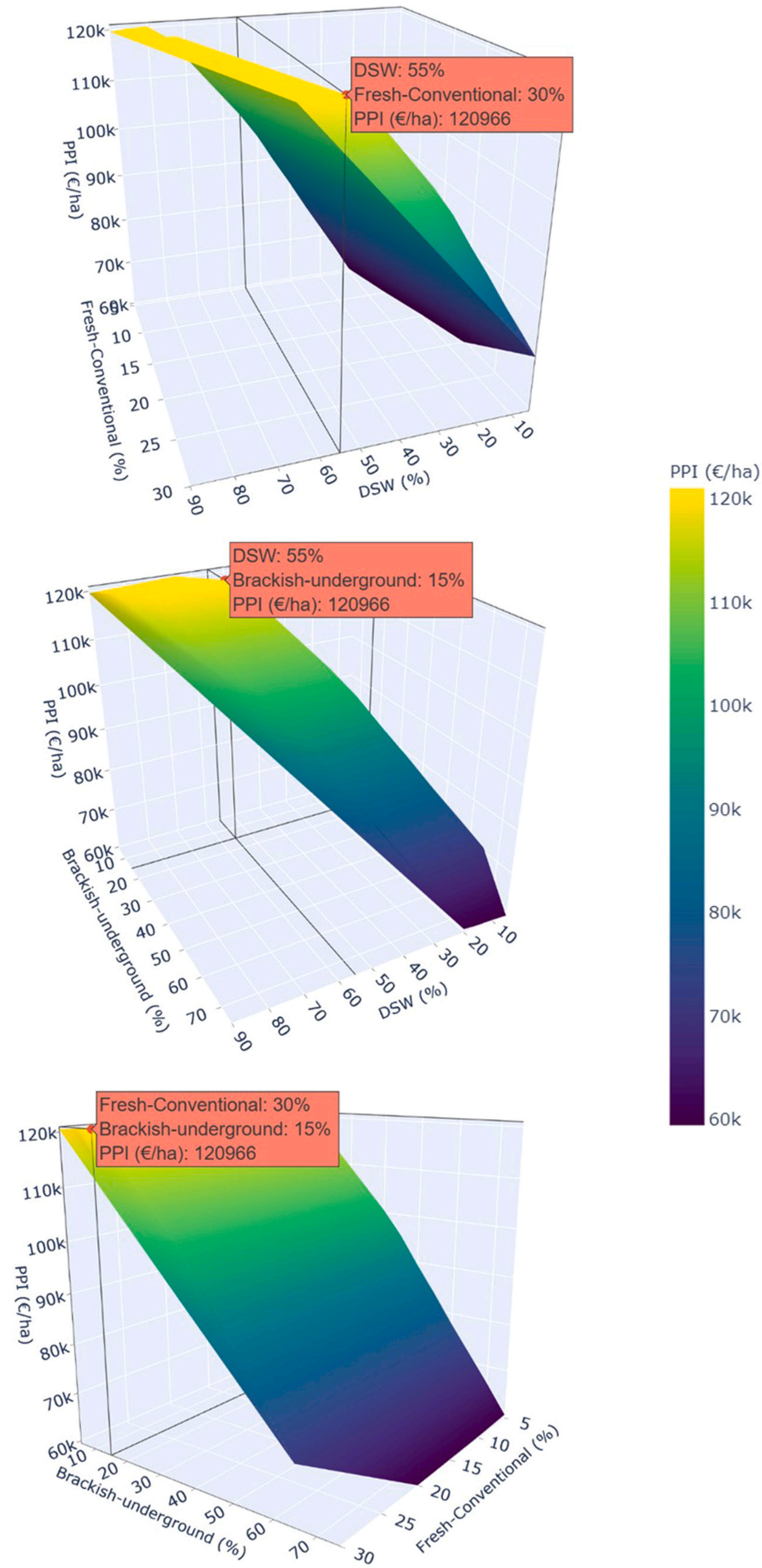

Fig. 3. Image of the 3D interactive plots showing the profit potential indicator (PPI) vs. the percentages in the water blend of the water sources (fresh, brackish, and desalinated sea water (DSW)) for case study 1. The optimal blend is highlighted in red in the hover label. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

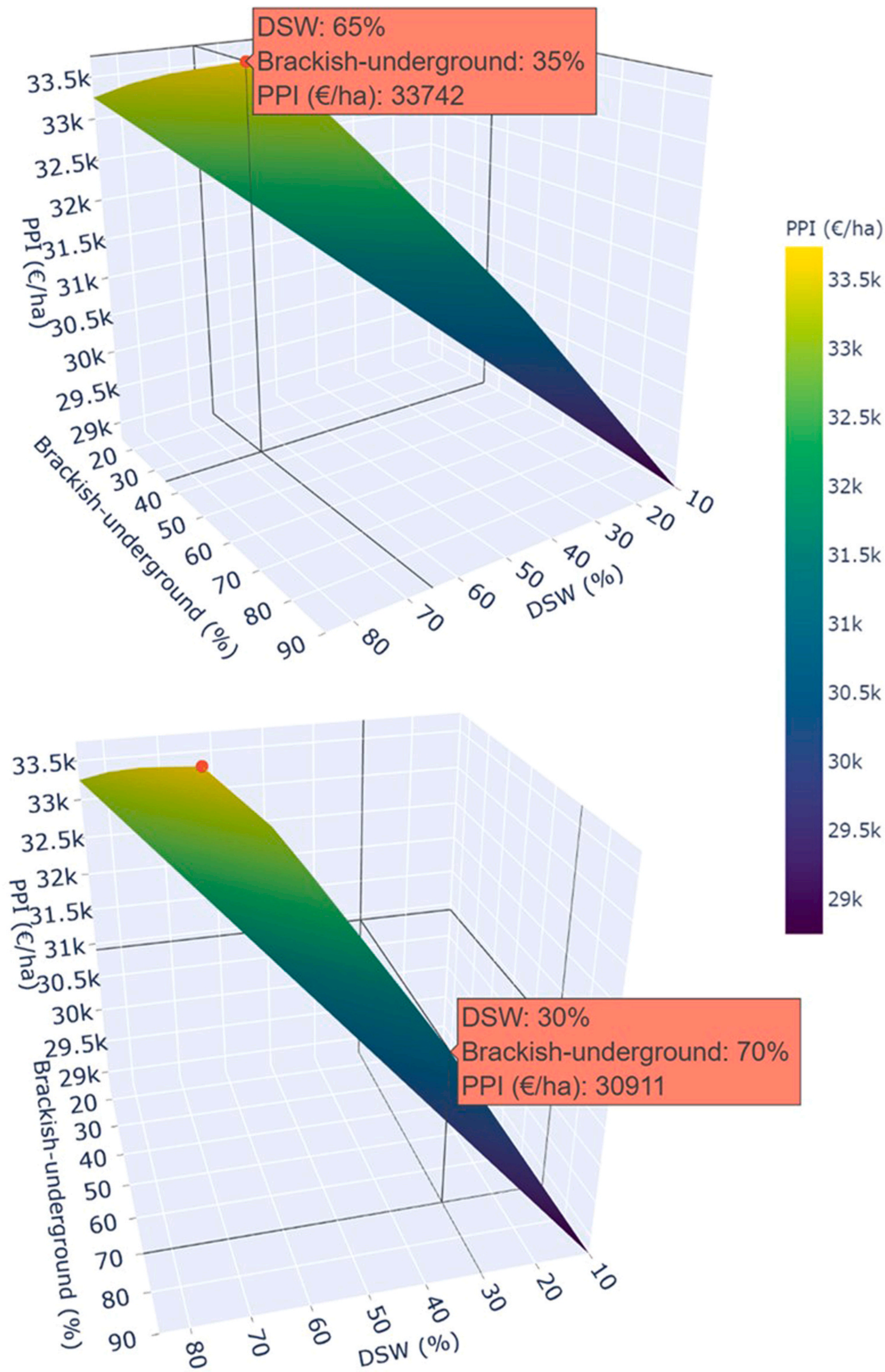

Fig. 4. Image of the 3D interactive plot showing the profit potential indicator (PPI) vs. the percentages in the water blend of the two water sources (brackish and desalinated sea water (DSW)) for case study 2. The optimal blend is highlighted in red in the hover label. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

presented, in which DSW and conventional waters with different quality, price, and availability are used. Once the requirements and available resources for the production systems were characterised, the DST could identify which combinations of water and fertiliser could be viable from a technical and economic perspective.

Both case studies involve intensive production systems with great land and water productivity (Table 4), but with substantial investment and operational costs (much higher than traditional systems). The DST provides the value of PPI (money left when subtracting the cost of fertigation from the crop revenue) for all technically feasible combinations, but only those with a PPI above the profitability threshold (investment plus operational costs excluding the cost of water and fertilisers) would be economically feasible. For the NFT lettuce case, the DST showed that only half of the technically viable options were likely to be profitable, whereas for the GH tomato, all the solutions were above the profitability threshold. However, the real contribution of the DST is not merely filtering out unfeasible options from an economic perspective but also to offer information on how to optimise the use of available resources and maximise profits.

Navigating the interactive plots (Figs. 3 and 4, Supplementary Videos 1 and 2), it can be seen that in both cases, increasing the amount of low-quality water (brackish) over the optimum percentage drastically reduces the PPI. In fact, the EC of the optimal solutions was close to the crop salinity threshold, since maximal addition of cheaper brackish water substantially reduces costs without (simulated) yield loss. In the NFT lettuce case, this limit was 35% of brackish water in the blend, as percentages over it rendered the crop non-profitable. This implies that, because the availability of conventional fresh water is becoming very scarce, without the supply of DSW, production would not be viable. In the case of GH tomato, although all solutions surpassed the profitability threshold, the DST showed that adding more than 65% of brackish water in the blend causes the EC to increase above the salinity threshold, which can result in a decrease in net profit over 2×10^3 €/ha/cycle. It is important to note here that, for the calculations, we used the mean GH tomato market price (0.54 €/kg) in the 2017–18 season. For a crop market price below 0.45 €/kg (as in the 2015–16 season), we would have found combinations with the PPI below the profitability threshold among the technically viable ones as in the case of NFT lettuce.

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Information about fertiliser selection and cost for each water blend derived from these simulations was relevant for fertigation management. In both cases, the data showed that the amount and type of fertiliser required increased as the percentage of DSW increased in the water blend. However, this cost increase is lower than that owing to the DSW cost. The increase in fertiliser cost was approximately 0.06 €/m^3 for both the NFT lettuce and the GH tomato when moving from 35% to 85% of DSW in the water blend, whereas the increase in water cost was over 0.22 €/m^3 in the said percentage range. Therefore, notwithstanding that fertilisation programmes and even systems require adaptation to DSW, the fertiliser cost overrun derived from the integration of DSW did not seem to pose a major threat to profitability. However, it is important to bear in mind that even if minimising the fertiliser input had a less relevant impact on costs, it is key to preventing leaching nutrients and preserving the over-polluted aquifers in the region.

5. Conclusion

We have presented Irriblend-DSW, a user-friendly freely available DST designed to guide water managers make correct decisions to maximise profits in soilless crop fertigation when blending conventional waters with DSW. Additionally, we have demonstrated its use with two case studies of hydroponic crops in SE Spain, in which the DST showed fluctuations in fertigation costs for different water combinations and identified which of these are potentially profitable.

Our results demonstrate that the intensive horticultural crops analysed in this study can be very profitable despite the increase in fertigation costs caused by the integration of DSW, provided there is adequate management of water resources and fertilisers. The plots displayed by the DST allow us to see at a glance the economic impact of the different water blending options, thereby enabling selection of the optimal blend. The increase in cost was mainly due to the high cost of DSW, and marginally due to additional fertilisers needed to compensate for the lack of certain nutrients in DSW. In both cases, we observed evidence of significant economic benefit of mixing DSW with moderate amounts of low-cost brackish water. The latter should only be done up to the crop EC threshold, as beyond that limit, the yield loss cannot be compensated by the decrease in cost due to the use of cheaper water.

The current version of the DST is open-source, coded in Python (a language widely used for scientific research), implemented in GC, and shared in GitHub to enhance collaborative research. The programme has a modular structure ready for upgrades and further development. One key aspect to be improved in future versions is the modelling of the salinity impact on yield with new modules that could link the DST with biological–physical models similar to AnswerApp. Another current limitation of the DST is that it is only implemented for soilless fertigation. One of the priorities for future versions of this tool is to enable simulations with traditional crops in soil. Moreover, we have not addressed the potential phytotoxicity issues from the use of DSW and underground brackish water in this study; this could also be implemented to improve the tool. Overall, we envision future versions of Irriblend-DSW which, in connection with crop models and other irrigation tools, provide high-quality data to enhance the assessment capability of water management advisers from farms and irrigation communities in the private and public sectors.

Declaration of Competing Interest

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

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Research Data

The code and user guide of Irriblend-DSW are freely available at https://github.com/irriblend-dsw/irriblend-dsw-v1 along with the input and output data of the two examples corresponding to the case studies described in Section 2.3.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2021.107012.

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