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Best management irrigation practices assessed by a GIS-based decision tool for reducing salinization risks in olive orchards

Juan M. Peragón[a], Francisco J. Pérez-Latorre[a], Antonio Delgado[b,*], Tibor Tóth[c]

[a] Área Mecánica de Fluidos, Campus Científico Tecnológico Linares, Universidad de Jaén, Cinturón Sur s/n, 23700 Linares, Spain
[b] Departamento de Ciencias Agroforestales, ETSIA, Universidad de Sevilla, Ctra. Utrera km 1, 41013 Sevilla, Spain
[c] Institute for Soil Sciences and Agricultural Chemistry, Centre for Agricultural Research, Hungarian Academy of Sciences, H-1022 Budapest, Herman Ottó út 15, Hungary

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ABSTRACT

Sustainable irrigation should rely on the efficient use of water while avoiding soil degradation. To this end, decision tools for assessing best management practices are necessary. There is, however, little evidence of efficient tools to assess best irrigation practices at regional scale taking into account water quality to avoid soil degradation and negative impacts on crop yields. The objective of this work was the performance of a GIS-based decision tool to assess best irrigation management practices aimed at reducing the negative effect of salts in irrigation water in olive orchards. The approach in this tool involved first the blending of two sources of available waters, surface and underground, and when necessary, the application of leaching fractions (LF). We tested this tool in the province of Jaen (south Spain) as representative area of olive cultivation in Mediterranean environments.

In 82.4% of the study area, the use of one of both water sources with electrical conductivity (ECw) below the defined threshold (1.8 dS m^{-1}) was possible without blending. Water blending for achieving optimal irrigation water quality was possible in 16% of the irrigated land. In other 9.8% of the irrigated land, leaching fraction was required to achieve the defined salinity threshold. In the area where water blending was possible, this strategy resulted in the best irrigation water efficiency (IWE) estimated for the province. With water blending and LF when necessary, the annual gross income in the province can be increased by 80 mill €.

The proposed GIS-base decision tool is easy to update for different crops and regions. It is able to transform and combine geographical data and value judgments for decision making in irrigation at a regional scale with a view of achieving the most efficient irrigation water use while avoiding negative effects on crop and soil due to water salinity.

1. Introduction

Water is the most critical resource for sustainable agricultural development worldwide (Chartzoulakis and Bertaki, 2015). Agriculture consumes more water than any other human activity (Pimentel et al., 1997; Hosseinzade et al., 2017), and the efficient and sustainable use of water is nowadays the main challenge of irrigated agriculture (Araus, 2004; Levidow et al., 2014). A sustainable use of water resources in irrigation must take into account not only crop water requirements but also the quality of irrigation water in order to predict and overcome negative impacts mainly ascribed to water salt content (Ghassemi et al., 1995; Paz et al., 2004; Houk et al., 2006). In this regard, soil salinization ascribed to irrigation is the main constraint for irrigation agriculture sustainability in many regions of the World, affecting more than 34 Mha (Letey et al., 2011; Mateo-Sagasta and Burke, 2011; Mora et al., 2017). Only in Europe, around 4 Mha have a moderate to high soil salinization by irrigation, mostly in the Mediterranean countries where this problem affects 25% of irrigated agricultural land (Paz et al., 2004; Daliakopoulos et al., 2016).

The main strategy used to prevent the harmful effects of excessive accumulation of soluble salts in soils due to irrigation is to promote drainage in the root zone in order to leach the excess of soluble salts that could constrain crop yield. The fraction of applied water required to maintain soil salt content below a given threshold is named “leaching fraction” (LF), which increases with increased crop sensitivity to salinity (U.S. Salinity Laboratory Staff, 1954; Rhoades, 1974). This extra volume of water percolates below the root zone displacing at least in part the salts accumulated therein (Pastor et al., 2002; Orgaz and Fereres, 2004; Raine et al., 2007; Mesa-Jurado et al., 2010). In the long term, the amount of salts displaced by leaching must be equal to or

* Corresponding author.
E-mail addresses: jpjuarez@ujaen.es (J.M. Peragón), fjperez@ujaen.es (F.J. Pérez-Latorre), adelgado@us.es (A. Delgado), tibor@rissac.hu (T. Tóth).

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higher than the salts applied with the irrigation water to avoid their accumulation at dangerous levels in soil. This salt balance is the crucial issue in achieving sustainability in irrigated agriculture (Corwin et al., 2007; Letey et al., 2011). However, it implies a decreased water application efficiency since a significant fraction of applied water must be lost through drainage. In areas where different source of water with different quality are available, their combined use may allow an improvement in irrigation water quality through dilution (Qureshi et al., 2004). This leads to a decreased LF requirement and consequently an increased efficiency in irrigation water application. In practice, this means more water available for irrigation while maintaining yield and soil quality. This strategy is feasible by combining surface and underground water with different salt concentrations in areas where both water sources coincide (Mahfuzur et al., 2014; Prendergast et al., 1994; Singh, 2014).

In recent decades, irrigated land has increased steadily, frequently involving the use of poor quality irrigation water (Singh, 2016). This consequently increases the area with risk of soil salinization. This occurred particularly in arid regions of the world, where agricultural production is strongly dependent on irrigation (Ashour and Al-Najar, 2012; Hosseinzade et al., 2017). In the Mediterranean basin, many new irrigated olive orchards were planted in the last decades (Fereres, 1998; Fereres and González-Dugo, 2009; Vega et al., 2001; Vega and Pastor, 2005; Wiesman et al., 2004). This is explained because olive is one of the most important crops in this region (10.4 Mha, 98% of the world's olive cultivated area; FAO, 2016), with lower water demand than other crops, and which allows a profitable deficit irrigation with low water availability (Peragón et al., 2015). A representative example of this expanded irrigation land in the Mediterranean basin sometimes relying on poor quality irrigation water is the province of Jaen (south Spain). This is the most representative area of olive cultivation in Spain, with near a quarter of the total national orchard surface, and amounting to 5.5% of the total surface in the world (Peragón et al., 2015, 2016). This area has arid and semi-arid zones (Junta de Andalucía, 2011; AEMET, 2011), with scarcity and irregular distribution of rainfall throughout the agricultural year constraining yields in olive orchards (Melgar et al., 2009). The water authority assigns an irrigation rate of 1.500 $m^3\,ha^{-1}$ per year, which in practice means deficit irrigation in this crop (Pastor et al., 2002). Therefore, LF to avoid soil salinization may pose in practice a reduction in available water for olives negatively affecting yields in the short-term.

The efficient management of limited water resources for agriculture in Mediterranean basin requires complex decision-making processes at regional scales (Araus, 2004). This implies the management of large datasets and the spatial analysis of the information, which can be achieved with geographic information systems (GIS) (Chowdary et al., 2003; Malczewski, 2006). GIS allows geospatial analysis integrating different sources of information making maps and providing complex outputs of the model results (Singh, 2016; Pereira et al., 2018). GIS have proved practical tools for assessing the quality of irrigation water and the risk of salinization at the regional level by providing maps of water quality and salinization risks in many regions of the world such as west Asia (Simsek and Gunduz, 2007; Arslan, 2012), Argentine Pampas (Romanelli et al., 2012), and Spain (Paz et al., 2004). In the province of Jaen, Peragón et al. (2015) recently described how the use of GIS was useful for providing salinization risk maps. In addition, GIS-based tools were useful in calculating LF and water blending from different sources in the same province (Peragón et al., 2016). However, for developing a GIS-based decision tool for the assessment of best irrigation management practices a next step is required beyond the release of risk maps. This means the definition of targets to be achieved with the use of the decision tool. To this end, the GIS-based tool should be implemented with a model able to combine and process geographical data in order to provide different solutions to achieve the defined target (Chowdary et al., 2003). In this case, the target is a salinity threshold in irrigation water below which no substantial yield decrease or soil salinization can be expected. These solutions involve, first water blending and second, if necessary, LF estimation to compensate the effect of water salinity on soil and crops if the threshold is surpassed. In addition, an analysis of solutions provided is required to assess the efficiency in using irrigation water. This means an assessment of the economic implications of these irrigation management practices for farmers and policy makers. In this regard, the objective of the present work was to study the suitability of a GIS-based decision tool in assessing the best management practices to avoid salinization effects due to irrigation, not only in terms of potential effects on crops and soils, but also in terms of water saving, efficiency, and economical balance at regional scale.

2. Materials and methods

2.1. Study area

The study was carried out in the province of Jaén (southern Spain), which is the most representative area of olive production in Spain. It covers an area of 13.489 km^2, which accounts for 15.4% and 2.7% of the Andalusian region and Spanish territory, respectively. The province has a mountainous geography with heights above 900 m in the north, south, and east of the province. The valley formed by the Guadalquivir River and its tributaries, especially the Guadalimar and Guadiana Minor rivers, offers a relatively flat topography in the central zone, with heights lower than 450 m. Overall, 25% of the province is below 450 m.a.s.l.; 20% is between 450 and 600; 31% between 600 and 900; 20.5% between 900 and 1.500; and 3.51% is above 1,500 m.a.s.l. Most of the territory, 97% of the total area of the province, corresponds to the administrative area of the Guadalquivir River Basin, and the rest of the area (3%) to the Segura River Basin. Between both areas, there is a small endorheic basin of only 130 km^2. There are two different sources of ground water aquifers: carbonated aquifers and detrital aquifers. On the one hand, carbonate aquifers from limestone materials poses less salt concentration than detrital aquifers. Aquifers in the province cover around 8.030 km^2. These water sources are mostly located in the eastern part of the province, in the areas known as Sierras de Cazorla Segura and the Villas and Quesada-Castril, accounting for 61% of the area covered by aquifers (4.900 km^2) (IGME, 2010).

The olive orchard is the main crop in this province, and irrigated orchards amounts to a surface of 2.903 km^2, mainly within the basin of the Guadalquivir River (MAGRAMA, 2015). Olive orchards are mainly irrigated by a drip system with deficient water supplies (MAGRAMA, 2012). Even with these water limitations, olive tree has proved to be the best cultivation alternative in the area, it being a key element for the sustainability of irrigated land in the province, which provides maximum social and economic profitability per cubic meter of water (Pastor et al., 2002).

In this province, olive orchards are predominantly of the Picual variety (CESPJ, 2011), which is considered one of the most tolerant varieties to salinity (Benlloch et al., 1994). For this variety, salinity in irrigation water may constraint yields at electrical conductivity (EC) higher than 1.8 $dS\,m^{-1}$. Above this threshold, yield decrease may be expected. Reduced yields of olive orchard of 10%, 25% and 50% are expectable at EC values of 2.6, 3.7 y 5.6 $dS\,m^{-1}$, respectively (Maas and Hoffman, 1977; Fipps, 1996).

2.2. Data set

The authority of the Guadalquivir basin (Confederación Hidrográfica del Guadalquivir, 2014) provided the monthly average electrical conductivity data of irrigation water (ECw) for the years 1994–2013. This information comes from 66 surface water stations, and 136 groundwater stations. The underground stations corresponded to 26 hydrogeological units delimited territorially according to the National Institute of Geology and Mining of Spain (IGME, 2010). Water quality parameters, in particular salt concentration, are described elsewhere (Peragón et al., 2015). Estimation of the water blending rate and leaching requirement (leaching fraction; LF) were done according to previous results by Peragón et al. (2016).

In the province of Jaén, drip irrigation system is installed in around 90% of irrigated olive orchards (Peragón et al., 2016). For this system, annual fixed irrigation cost was set at 692.74 € ha^{-1} (Alarcón, 2016), based on the average irrigation cost in Spain. This cost includes: average amortization of the investment to install a drip irrigation system, average maintenance of irrigation system, and maintenance costs and average annual cost of installed electrical power (Aquavir, 2005; AEMO, 2010; CESPJ, 2011). Calculation of the irrigation cost was done for an annual water supply of 1.500 $m^3\,ha^{-1}$, which is the irrigation rate allowed in the area. The economic data for olive production in the province of Jaén according to the described irrigation typology were estimated according to Alarcón (2016) and COI (2015). Average income for growers were 2197.20 € ha^{-1} based on mean olive fruit production, oil concentration in olive, and oil production (AEMO, 2010; CESPJ, 2011).

2.3. Model

A methodological framework was defined for the management of water resources in the province of Jaén (Fig. 1). This model integrates the required information for a geostatistical analysis involving spatial analysis and management. After that, georeferencing of the different layers of information was performed using the gvSIG program (www.gvsig.org) (Peragón et al., 2015, 2016). The model includes the definition of a target of EC in irrigation water to avoid negative effects (1.8 $dS\,m^{-1}$). On this ground, information was processed, required strategies defined (water blending, or LF), and maps where each strategy should be applied released as a result. Thus, released maps define, for each area considered, the best management option for irrigation water according to premises in the model.

Areas with different salinity range were defined based on the expectable yield decrease for both surface and underground water. Upper limits in the considered ranges were: 1.8, 2.6, 3.7 and 5.6 $dS\,m^{-1}$; an additional range above the latter value was also considered. The three later values corresponded to the threshold values for a relative yield reduction in the production of the olive orchard of 10, 25 and 50% respectively (Ayers and Westcot, 1985; Fipps, 1996; Hoffman and Shalhevet, 2007). For both sources of water, surface and underground, the following premises were applied to define alternative solutions in the model:

a) Zones with water salinity lower than the threshold value of 1.8 $dS\,m^{-1}$, where it is not necessary any action since there is not any expectable yield reduction due to salinity in water.
b) Zones with water salinity higher than the threshold value of 1.8 $dS\,m^{-1}$, which were divided into two categories: (i) those where both sources of water cannot be blended and consequently yield reduction is expectable; differentiation according to the threshold values of 2.6, 3.7 and 5.6 $dS\,m^{-1}$ was done in order to predict reductions of the relative yield of the olive orchard of 10, 25 and 50%, respectively, and (ii) areas where water blending is feasible to achieve an ECw of 1.8 $dS\,m^{-1}$ and consequently LF is not required.
c) Areas with water salinity above 1.8 $dS\,m^{-1}$ where water blending is not applicable (those defined in point (i) above), and also where the blending can be applied but the result obtained is higher than the threshold of 1.8 $dS\,m^{-1}$. In these cases, leaching fraction (LF) is required to reduce risks. LF requirement was estimated to avoid a yield reduction in olive higher than 10%.

2.4. GIS calculations

The classifications in the limitations for the use of irrigation water in olive and the definition of thresholds for irrigation water are based on data published by Ayers and Westcot (1985), Maas and Hoffman (1977) and Benlloch et al. (1994), Rhoades (1982) and Rhoades and Loveday (1990).

The optimum proportions of both sources of water were calculated where their blending was possible, i.e. in those sub-basins with surface and underground water availability. By mathematical algorithms of rasterization ("rasterize vector layer" and "cut raster layer with polygon layer"), and later vectorization ("vectorize raster layer"), the GIS Sextant module reduces the thematic map of EC in surface water to the region where there is an overlap with aquifers. Then, using the "mapping calculator" algorithm of the GIS, the proportion of each water source in water mixture was calculated. This calculation was done according to the tolerance limit of olive to salinity mentioned above, i.e., for ECw of 1.8 $dS\,m^{-1}$. This calculation was applied to areas of surface waters below defined values that coincide with areas of underground water with values higher than the established thresholds or vice versa. After integrating all the variables in the model with their geospatial attributes, through queries involving both thematic and spatial components, we obtained the maps that meet the criteria for efficient use of irrigation water according to the three premises defined above. In practice this means that, where it was not possible to use a source of water with less than 1.8 $dS\,m^{-1}$, we applied first water blending; if this alternative was not feasible to achieve the defined threshold, LF was applied.

Finally, to compare the water use strategies described above, we calculated the irrigation water efficiency (IWE) as ratio of the potential olive yield (kg ha^{-1}) to the irrigation rate ($m^3\,ha^{-1}$). In addition, an analysis of the income according to the harvest value and the cost of irrigation was performed according to sources mentioned above in the description of the dataset.

3. Results

3.1. Irrigated areas without water blending

Approximately in 82% of the land which can be potentially irrigated with surface water (11111 km^2), it can be used water with electrical conductivity (ECw) below the threshold of 1.8 $dS\,m^{-1}$, meanwhile 85% of the land potentially irrigated with groundwater (6855 km^2) was supplied with water below that limit (Table 1; Fig. 2). A yield reduction of 10%, i.e., ECw ranging from 1.8 to 2.6 $dS\,m^{-1}$, was expectable in 4.6% of the area supplied with surface water (617 km^2), and in 2.7% (218 km^2) of the area supplied with underground water (Table 1, Fig. 2). The land potentially irrigated with water with EC ranging from 2.6 to 3.7 $dS\,m^{-1}$, where a yield decrease between 10 and 25% may be expectable as result, amounted to 10.7% (1457 km^2) and 11.9% (957 km^2) of the land with surface and underground water supplies, respectively. The area irrigable with water ranging from 3.7 to 5.6 $dS\,m^{-1}$ was not accountable, and that irrigated with water with EC higher than 5.6 $dS\,m^{-1}$ only represented 2.3% (304 km^2) of the area supplied with surface water. Thus, irrigated areas with EC between 1.8 and 5.6 $dS\,m^{-1}$, where yield reduction up to 50% was possible, accounted for ca 15% of the land supplied with surface and underground water supplies (2074 km^2 and 1176 km^2, respectively, Table 2).

In 17.7 and 13.0% of the land potentially irrigated with surface water, ECw was higher than 1.8 and 2.6 $dS\,m^{-1}$, respectively (Table 2; Fig. 3). ECw values greater than 3.7 were observed in 2.9% of the area potentially irrigated with surface water. For groundwater, ECw above 1.8, and 2.6 $dS\,m^{-1}$ was observed in 14.6 and 11.9% of the surface potentially irrigated with this water source, respectively (Table 2; Fig. 3). For this source, the area potentially irrigated with water with EC higher than 3.7 was negligible (Table 2, Fig. 3).

3.2. Application of water blending strategy

Sub-basins with surface water supply coincident with aquifers

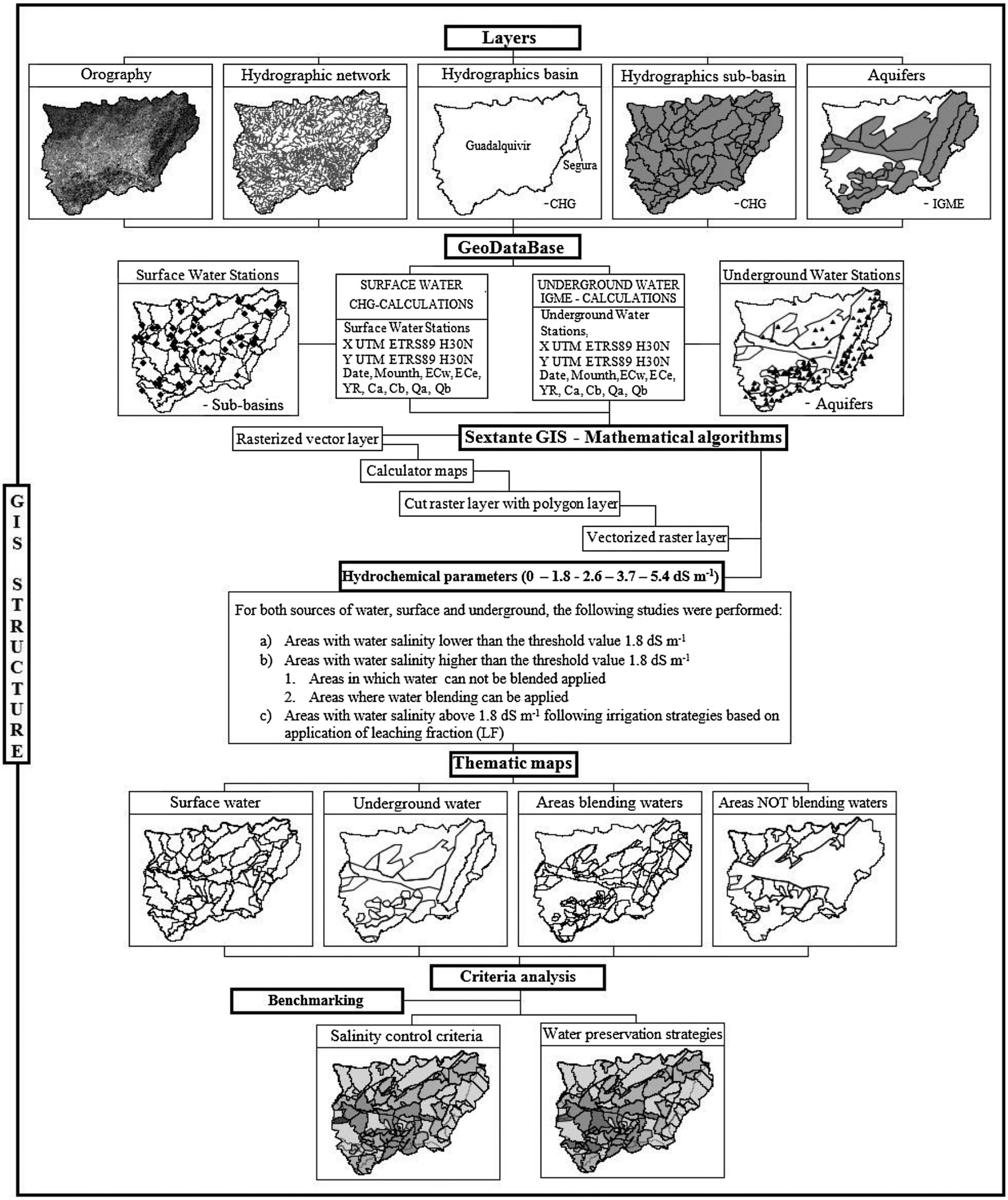

Fig. 1. Model: Methodological framework. ECw, electrical conductivity in irrigation water; ECe, electrical conductivity in the saturation extract of the soil; YR, relative yield; Ca, proportion of surface water in the water blending; Cb, proportio of undergournd water in blending; Qa, amount of surface water; Qb, amount of underground water.

accounted for 8030 km^2. It was possible the use of surface water with ECw lower than 1.8 dS m^{-1} in 11111 km^2. This accounted for 82.4% of the total area irrigable with surface water. Thus, in this area it was not necessary any measure to improve irrigation water quality. Only in 1130 km^2 of the remaining 2378 km^2 irrigable with surface water it was feasible water blending with underground water. With this blending, it was possible to maintain an EC in irrigation water lower than 1.8 dS m^{-1} in 1056 km^2 by using different surface to underground water ratios (Table 3; Fig. 4). On the other hand, when underground water had ECw higher than 1.8 dS m^{-1}, it was possible the obtaining of irrigation water below this threshold by blending with surface water in 1102 km^2 (Table 3; Fig. 4). The defined ECw threshold was unfeasible

Table 1
Area irrigated with surface and underground irrigation water according to their electrical conductivity in the province of Jaen. Surface water is divided in two categories: that overlapping with underground water, and that not overlapping with underground water.

Electrical Conductivity	Surface Water						Underground Water	
	A		B		C			
$dS\,m^{-1}$	km^2					% Area	km^2	% Area
0–1.8	11111	=	6900	+	4211	82.4	6855	85.4
1.8–2.6	617	=	191	+	426	4.6	218	2.7
2.6–3.7	1457	=	751	+	706	10.7	957	11.9
3.7–5.6	–	=	–	+	–	–	–	–
> 5.6	304	=	188	+	116	2.3	–	–
Total	13489	=	8030	+	5459	100	8030	100

A, All the surface irrigated with surface water.
B, Area where surface water overlap with underground water.
C, Area where surface water do not overlap with underground.
% Area is referred to that area potentially irrigated with each source of water (over 13489 km^2 in surface water, and 8030 km^2 in underground water).

with water blending in 74 km^2 of the area with overlap of both sources of water (Table 3).

3.3. Application of leaching fraction (LF)

In sub-basins with ECw higher than the defined threshold value where it is not possible to mix water, i.e. not coincident aquifers (1248 km^2; Table 4) as well as where water blending is impractical for achieving defined thresholds for ECw (74 km^2; Table 4) the leaching fraction criteria was applied. The model provided different leaching fractions for the defined yield loss threshold (10%), which was achievable in all the targeted area defined above (1322 km^2; Table 4, Fig. 5).

3.4. Irrigable areas with different approaches

There was not any expectable negative effect ascribed to water salinity, i.e. ECw < 1.8 $dS\,m^{-1}$, in 6.900 km^2 of the area irrigable indifferently with superficial or underground water (overlap of both sources), and in 4211 km^2 of the area irrigable with surface water where it do not overlap with underground (Table 5). When the EC of both sources of water was lower than 1.8 $dS\,m^{-1}$, it was not necessary water blending or LF. Only in 2158 km^2 (16% of the total irrigable land), and 1322 km^2 (9.8%), it was required water blending and LF, respectively, according to the defined premises in the model (Table 5).

If we define a different approach, which is the preservation of water without any action to preserve soils or yields (no water blending and no LF as defined in the model), land or irrigation rates for areas with LF can be increased. In fact, this is the current irrigation strategy in the province of Jaen. With this premise of water preservation, 11111 km^2 (82.4%) was irrigable with water with EC till 1.8 $dS\,m^{-1}$, as estimated for the yield preservation approach defined above in the GIS-based model. However, 762 km^2 (5.7%) were potentially irrigated with water ranging from 1.8 to 2.6 $dS\,m^{-1}$, and consequently with an expectable yield decrease up to 10%, and 1616 km^2 (10.9%) with water ranging from 2.6 to 3.7 $dS\,m^{-1}$, thus potentially promoting a yield decrease of up to 25% (Table 6).

3.5. Benchmarking

Overall, with the yield preservation strategy defined in the model, the cost of irrigation in the irrigable land of the province of Jaen was € 943 million, meanwhile the value of the production was € 2936 million (Table 5). In this case, the ratio of olive yield to volume of water used (IWE) was 8.66. Above the ECw threshold of 1.8 $dS\,m^{-1}$ defined in the model, LF was applied. This means that production decreased with increased volume of water used for salt leaching. As a result, IWE decreased to 7.09 (Table 5). With this LF requirement, it is assumed that irrigation costs increased by 10% with a decrease in production of the same percentage (10%).

With the premise of water preservation without any action, the value of crop production and the irrigation cost in the irrigable land decreased to 2859 and 935 million €, respectively (Table 6). Regarding IWE, it varied according to the source of water used. For the threshold value 1.8 $dS\,m^{-1}$, IWE was 8.66, meanwhile for ECw thresholds of 2.6 and 3.7, it decreased to 7.80 and 6.50, respectively, due to yield losses (Table 6).

On a regional basis, yield preservation approach defined in our GIS-

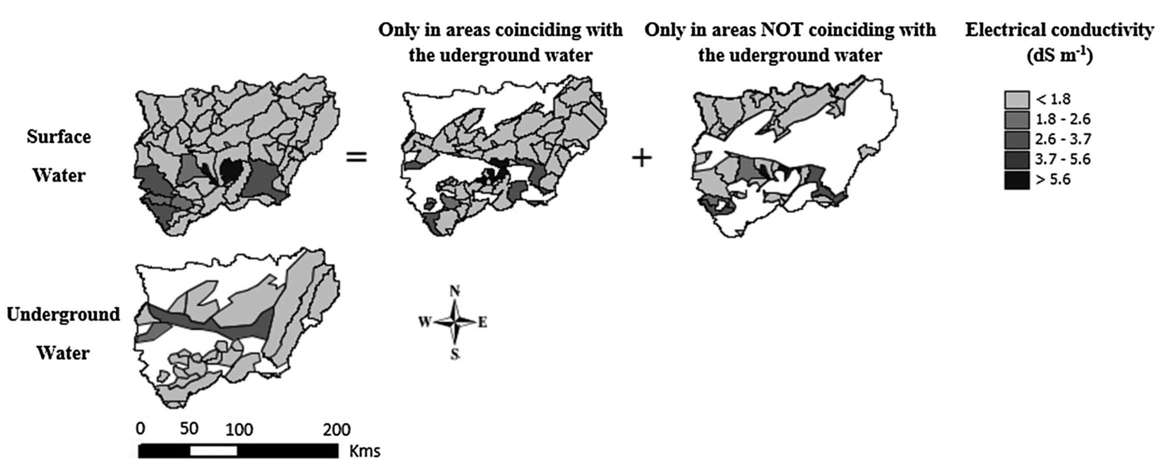

Fig. 2. Electrical conductivity in the irrigation water (in $dS\,m^{-1}$).

Table 2
Areas irrigated with different water sources in the province of Jaen with water salinity expressed in electrical conductivity (dS m^{-1}) above and below different threshold values for different effect on olive crop.

		< 1,8		≥1,8		< 2.6		≥2.6		< 3.7		≥3.7		< 5.6		≥5.6	
		km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
Surface Water	A	11111	82.4	2378	17.7	12181	90.3	1760	13.0	13102	97.1	387	2.9	13176	97.6	304	2.3
	B	6900	51.2	1130	8.4	7543	55.9	939	6.9	7842	58.1	188	1.4	7842	58.1	188	1,4
	C	4211	31.2	1248	9.3	4638	34.4	821	6.1	5260	39.0	199	1.5	5334	39.5	116	0.9
Underground Water		6855	85.4	1176	14.6	7073	88.1	957	11.9	8030	100.0	–	–	8030	100.0	–	–

A, All the surface irrigated with surface water.
B, Area where surface water overlap with underground water.
C, Area where surface water do not overlap with underground.
% Area is referred to that area potentially irrigated with each source of water (13489 km2 in surface water, and 8030 km2 in underground water).
Below 1.8 dS m^{-1}, no yield reduction can be expected; above 5.6 dS m^{-1} yield decrease above 50% can be expected.

based decision tool implied an increased irrigation cost of 8 million €; however, it was expectable an increase in the value of the harvest of near 80 million € (Tables 5 and 6). It should be remarked that this increased gross income was mostly obtained in the 2158 km^2 where water blending is possible when compared with the water preservation strategy without any action.

4. Discussion

The proposed GIS-based decision tool was useful in managing hydrochemical information of irrigation water intended to create maps of qualities and irrigable surfaces which each source of water (surface and underground). Similar results were obtained in other geographical areas with analogous water quality criteria (e.g. Romanelli et al., 2012 for Argentine Pampas). However, in contrast with previous literature on the use of GIS in predicting soil salinization risks, our model applied decision criteria for defining the best management option with the premise of yield preservation and soil protection. The information released is not only a risk map. Our GIS-based tool was useful to estimate where the blending of both water sources is possible to calculate LF requirements to achieve the minimum yield loss defined in the model. Our approach is similar to that used by Chowdary et al. (2003) for providing best solutions for each zone of an irrigated land for groundwater preservation. The proposed GIS-based tool was useful for using irrigation water efficiently in order to avoid constraints ascribed to water salinity. Alternatively, the model can handle the information by applying different decision criteria, e.g. with a water preservation approach (i.e. without blending or LF) instead the yield preservation approach. Although the water preservation approach lead to less sustainability in the agricultural land (salinization will occur), its implementation in the model allow us to compare IWE with different approaches and the potential economic implications of different irrigation strategies. The approach based in yield preservation by avoiding salt accumulation in soil by water blending or LF led to an increased IWE in the areas affected by irrigation with saline water. This was achieved by decreasing LF requirements with blending or by increasing potential crop yield in the cases that LF had to be applied. Although area affected by water blending amounted to 16% of the total irrigable area of the province of Jaen, the economic impact in this affected area was significant. Water blending was an effective strategy to maintain IWE in the highest value (8.66) in 2158 km^2. Without any control measure, IWE would diminish in this area due to the reduction in crop yield. Thus, in these affected areas, economic implications of water quality and best management options for irrigation are truly relevant. Water blending implies an expected cost in the infrastructure required for this strategy. However, the economic study revealed that this investment can be affordable at least partially with expected benefits in affected areas.

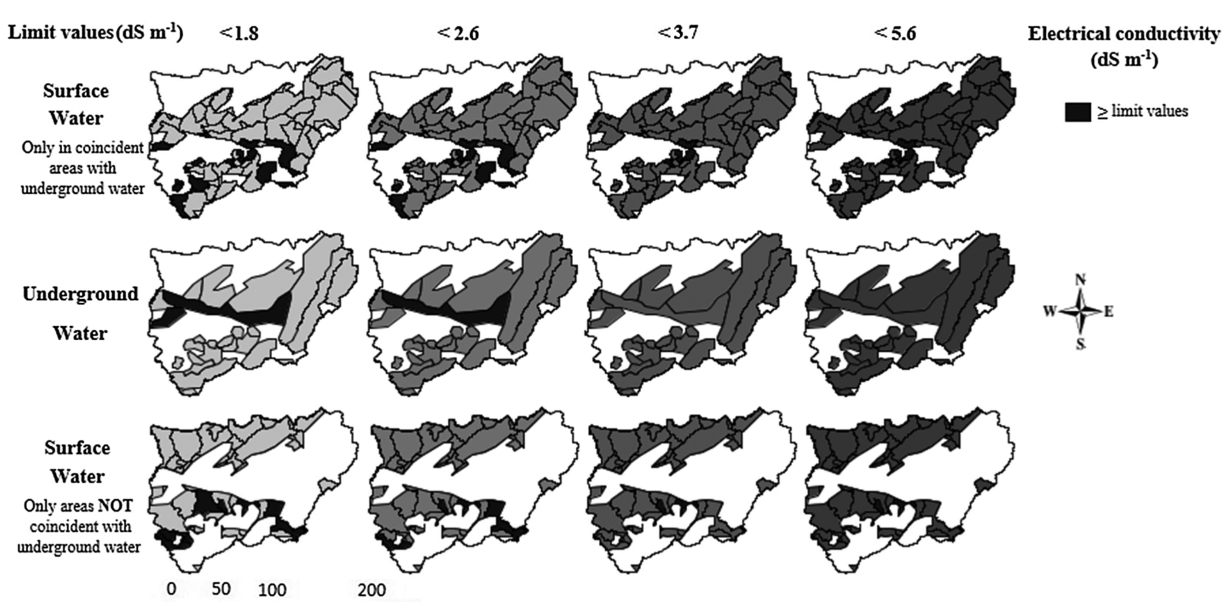

Fig. 3. Areas with water salinity lower and higher than the threshold value 1.8 dS m^{-1}. Above this threshold, different thresholds according to the effect on olive yield are described (2.6, 3.7, and 5.6 dS m^{-1}). Areas in black are those in which the values are greater than the specified limits for each map.

Table 3
Proportion of surface water in water blending and area where this proportion is feasible to achieve an electrical conductivity in irrigation water of 1.8 dS m^{-1} after water blending.

Proportion of surface water in irrigation water %	Surface water area with ECw > 1.8 dS m^{-1} water where blending with underground water is possible[a] km^2	% Area	Underground water area with ECw > 1.8 dS m^{-1} water where blending with underground water is possible[a] km^2	% Area
< 10	129	11.4	203	17.3
10–20	48	4.3	–	–
20–30	210	18.6	319	27.1
30–40	98	8.7	236	20.1
40–50	407	36.0	72	6.1
50–60	–	–	37	3.1
60–70	128	11.4	199	16.9
70–80	3	0.2	3	0.3
80–90	33	2.9	33	2.8
90–100	–	–	–	–
Total area where blending can be applied obtaining an ECw < 1.8 dS m^{-1}	1056	93.5	1102	93.7
Total area where water blending is impractical[b]	74	6.5	74	6.3
Total area	1130	100	1176	100

% Area is referred to the area studied potentially irrigated with this water source.
[a] Water blending is possible, but not required to achieve the threshold value.
[b] Area where water blending is impractical is that with overlap of both water sources where it is not possible to achieve an electrical conductivity of 1.8 dS m^{-1} after blending.

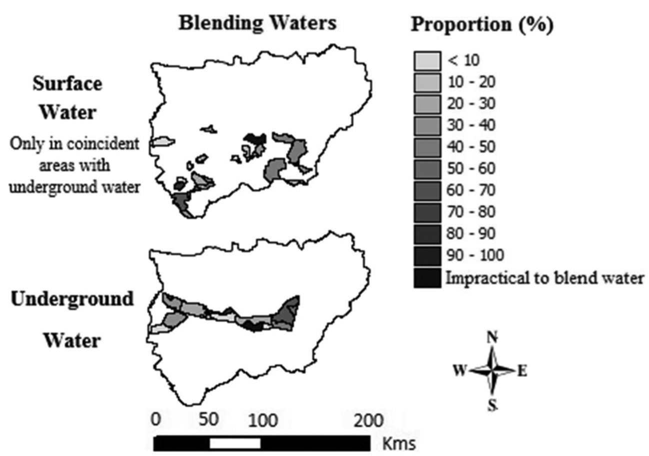

Fig. 4. Proportion of surface water and area where this proportion is feasible to achieve an electrical conductivity in irrigation water of 1.8 dS m^{-1} after water blending.

Table 4
Areas with water salinity above 1.8 dS m^{-1} where different leaching fraction (LF) are required to avoid salt accumulation in root zone.

Risk in the use of water	Leaching Fraction	A km^2		B		C	Area %
Low	< 5	–	+	1143	=	1143	86.5
	5–10	74	+	–	=	74	5.6
Medium	10–15	–	+	–	=	–	–
	15–20	–	+	–	=	–	–
	20–25	–	+	82	=	82	6.2
	25–30	–	+	–	=	–	–
High	> 30		+	23	=	23	1.7
	Total area affected	74	+	1248	=	1322	100

A = Areas with overlap of both water sources where it is impractical to blend water because it is not possible to achieve a final electrical conductivity of 1.8 dS m^{-1}.
B = Areas where there is not overlap of both sources of water, surface and underground.
C = Sum of A and B.
% Area is referred to the area accounting for cases A and B.

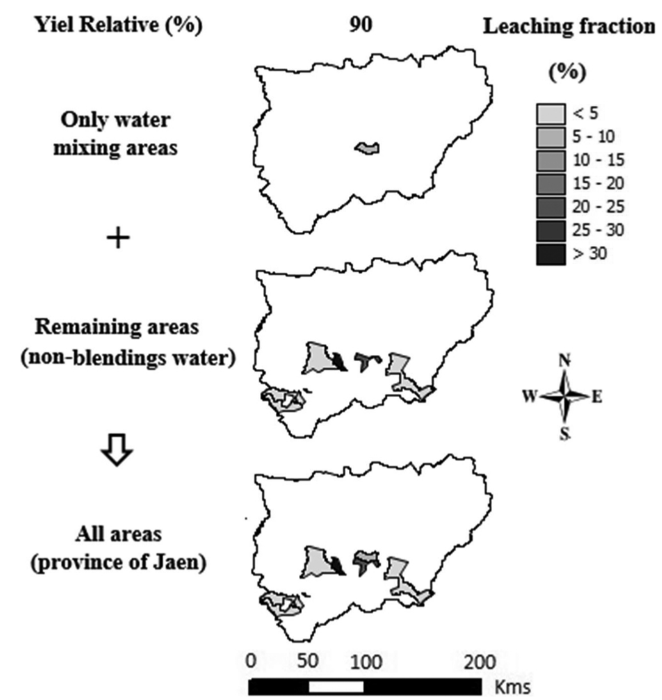

Fig. 5. Areas with water salinity above 1.8 dS m^{-1} where different leaching fraction (LF) should be applied to avoid yield reduction in olive.

The proposed tool can facilitate the analysis and processing of data, allowing the visualization of the geographic information and offering all the functionalities of manipulation of the geographic data. This can be used in the planning and decision making processes (Peragón et al., 2015, 2016). With these capabilities, GIS can be considered as a decision support system involving the integration of spatially referenced data in a problem solving environment (Cowen, 1988). However, the proposed GIS-based tool was effective in defining the best management options for irrigation and represented the next step to previous models. These previous models were only able to make a geospatial analysis of water quality and constraints derived from its use, such as models proposed by Peragón et al. (2015, 2016); for the same area and crop. Thus, the proposed tool is able to transform and combine geographical data and value judgments to obtain information for decision making. It provides procedures for structuring decision problems, and designing, evaluating and prioritizing alternative decisions. Thus, it can be considered an example of GIS-based multicriteria decision analysis (Feick and Hall, 2004; Malczewski, 2006).

The GIS-based decision tool proposed here is able to define best management options for salinity control in each area after defining the target to be achieved, which in a first step is an irrigation water below a given ECw value. This is very relevant in the arid regions such as the area of study where water availability is scarce. In the province of Jaen, with an assigned limit of 1500 m^3 ha^{-1}, deficit irrigation is only possible (Pastor et al., 2002). Mixing both sources of water up to the threshold of water salinity in the irrigation that is established as tolerance limit for olive orchard (1.8 dS m^{-1}) will allow a reasonable control of water salinity effects while increasing water availability to crop by decreasing LF. It should be highlighted that high LF requirements cannot be considered suitable which such a low water irrigation rates (Peragón et al., 2016) and alternative strategies such as water blending can contribute to the sustainability of olive production in these areas. Usually, the GIS techniques have been used as a tool for storing, analyzing, and displaying spatial information in an efficient

Table 5
Benchmarking of irrigation water based on salinity control criteria (yield preservation).

	Area km^2	% Area %	Irrigation Cost Mill €	Production Cost Mill €	IWE
Surface (A) or Underground Water (ECw < 1.8 dS m^{-1})	6900	51.2	478	1516	8.66
Surface Water (B) (ECw < 1.8 dS m^{-1})	4211	31.2	292	925	8.66
Blending water for surface water with EC > 1.8 dS m^{-1}	1056	7.8	73	232	8.66
Blending water for underground water with EC > 1.8 dS m^{-1}	1102	8.2	76	242	8.66
Leaching Fraction (A)	74	0.5	5	16	7.09
Leaching Fraction (B)	1248	9.3	95	247	7.09
Total potentially irrigable area	13489	100	943	2936	–

A, Area where surface water overlap with underground water; B, Area where surface water do not overlap with underground.
ECw, electrical conductivity in water; IWE, irrigation water efficiency = kg of olive produced per cost m^3 of water used for olive groves irrigation.
Sum of all water use strategy is greater than the total potentially irrigable area since 1102 km^2 of underground water with EC > 1.8 dS m^{-1} overlaps with surface water with EC < 1.8 dS m^{-1}.
Economic data for the olive grove in the province of Jaén (Alarcón, 2016): Irrigation cost: 692.74 € ha^{-1}. Fixed cost of irrigation for 1500 m^3 ha^{-1}, Production value: 2197.2 € ha^{-1}, for a production of 6000 kg ha^{-1} of olives (equivalent to 1280 kg ha^{-1} olive oil).
Leaching fraction for relative yield of 90%, which means an increase in irrigation cost (+10%) and a decrease in production (−10%).
% Area is referred to the area potentially irrigated with both surfaces of water, surface and underground water (13489 km^2).

Table 6
Benchmarking of irrigation without blending based on water preservation strategies (no leaching fraction applied).

	Area km^2	% Area %	Irrigation cost Mill €	Production value Mill €	IWE
Surface (A) or Underground Water (Ecw < 1,8 dS m^{-1})	6900	51.2	478	1516	8.66
Surface Water (B) (ECw < 1.8 dS m^{-1})	4211	31.2	292	925	8.66
Surface Water (ECw = 1,8–2,6 dS m^{-1})	617	4.6	43	122	7.80
Surface Water (ECw = 2,6–3,7 dS m^{-1})	659	4.9	46	109	6.50
Underground Water (ECw = 1,8–2,6 dS m^{-1})	145	1.1	10	29	7.80
Underground Water (ECw = 2,6–3,7 dS m^{-1})	957	7.0	66	158	6.50
Total	13489	100	935	2859	–

A, Area where surface water overlap with underground water; B, Area where surface water do not overlap with underground.
ECw, electrical conductivity in water; IWE: is the average irrigation water efficiency: kg of olive produced per cost m^3 of water used for olive groves irrigation.
Economic data for the olive grove in the province of Jaén (Alarcón, 2016): Irrigation cost: 692.74 € ha^{-1}. Fixed cost of irrigation for 1500 m^3 ha^{-1},Production value: 2197.2 € ha^{-1}, for a production of 6000 kg ha^{-1} of olives (equivalent to 1280 kg ha^{-1} olive oil).
Surface and/or Underground Water (to 1.8 ds m^{-1}): no yield decrease is assumed.
Surface and/or Underground Water (1.8–2.6 dS m^{-1}): 10% yield decrease is assumed.
Surface and/or Underground Water (2.6–3.7 dS m^{-1}): 25% yield decrease is assumed.
Area and% Area is referred to the area potentially irrigated with both sources of water, surface and underground (13489 km^2).

manner for water resources management (Singh, 2016). We demonstrated here that spatial information can be successfully processed for providing best solutions in each zone of an irrigated land with an economic analysis at regional scale. This spatial and economic analysis of control measures for avoiding salinization risks related to irrigation water quality was never described in literature. However, this is a relevant issue not only with a view of analyzing potential economic benefits. Frequently, in the implementation of changes in irrigating schemes, social benefits prevail and large public investments are required. In this regard, GIS-based tools can help governmental policymakers in taking decisions (Neji and Turki, 2015).

This type of GIS-based tools is also able to adapt decisions to fast changes in water composition as previously proved by Peragón et al. (2016). The GIS-based decision tool proposed was developed for olive crop in the province of Jaen in Spain. This is a representative example of crop and environment with increasing risk of soil salinization by irrigation. However, this tool can be easily extrapolated to other regions and crops and it can be an useful tool for helping stakeholders to take decisions on irrigation management at regional scales.

5. Conclusions

The proposed GIS-based is able to transform and combine geographical data and value judgments for decision making. This was useful in defining best irrigation practices to avoid salinization risks in the different areas of the irrigated land studied. In those areas where water blending was possible, this strategy allowed the best irrigation water efficiency. Without blending and leaching fraction, this efficiency decreased with increased salt concentration in water due to yield reductions. With water blending and leaching fraction when necessary, the annual gross income in the province can be increased by 80 mill €. Further research is however required to check the long-term efficiency of this tool in avoiding soil salinization and for implementations of more complete GIS-based decision tools providing accurate irrigation rates for different crops.

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