Soil salinity related to physical soil characteristics and irrigation management in four Mediterranean irrigation districts

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Abstract

Irrigated agriculture is threatened by soil salinity in numerous arid and semiarid areas of the Mediterranean basin. The objective of this work was to quantify soil salinity through electromagnetic induction (EMI) techniques and relate it to the physical characteristics and irrigation management of four Mediterranean irrigation districts located in Morocco, Spain, Tunisia and Turkey. The volume and salinity of the main water inputs (irrigation and precipitation) and outputs (crop evapotranspiration and drainage) were measured or estimated in each district. Soil salinity (EC<sub>e</sub>) maps were obtained through electromagnetic induction surveys (EC<sub>a</sub> readings) and district-specific EC<sub>a</sub>-EC<sub>e</sub> calibrations. Gravimetric soil water content (WC) and soil saturation percentage (SP) were also measured in the soil calibration samples. The EC<sub>a</sub>-EC<sub>e</sub> calibration equations were highly significant (P < 0.001) in all districts. EC<sub>a</sub> was not significantly correlated (P > 0.1) with WC, and was only significantly correlated (P < 0.1) with soil texture (estimated by SP) in Spain. Hence, EC<sub>a</sub> mainly depended upon EC<sub>e</sub>, so that the maps developed could be used effectively to assess soil salinity and its spatial variability. The surface-weighted average EC<sub>e</sub> values were low to moderate, and ranked the districts in the order: Tunisia (3.4 dS m<sup>-1</sup>) > Morocco (2.2 dS m<sup>-1</sup>) > Spain (1.4 dS m<sup>-1</sup>) > Turkey (0.45 dS m<sup>-1</sup>). Soil salinity was mainly affected by irrigation water salinity and irrigation efficiency. Drainage water salinity at the exit of each district was mostly affected by soil salinity and irrigation efficiency, with values very high in Tunisia (9.0 dS m<sup>-1</sup>), high in Spain (4.6 dS m<sup>-1</sup>), moderate in Morocco (estimated at 2.6 dS m<sup>-1</sup>), and low in Turkey (1.4 dS m<sup>-1</sup>). Salt loads in drainage waters, calculated from their salinity (EC<sub>dw</sub>) and volume (Q), were highest in Tunisia (very high Q and very high EC<sub>dw</sub>), intermediate in Turkey (extremely high Q and low EC<sub>dw</sub>) and lowest in Spain (very low Q and high EC<sub>dw</sub>) (there were no Q data for Morocco). Reduction of these high drainage volumes through sound irrigation management would be the most efficient way to control the off-site salt-pollution caused by these Mediterranean irrigation districts.

Keywords:
Electromagnetic induction (EMI), Mediterranean agriculture, irrigation management, irrigation water salinity, drainage water salinity, salt load
1. Introduction

Irrigation is vital for agricultural production in arid and semi-arid areas with scarce or irregular precipitation, but its misuse may cause negative effects on the quality of soils (Lal and Stewart, 1990) and waters (Aragüés and Tanji, 2003). A serious threat to sustainable irrigated agricultural production is secondary salinization since estimates indicate that, globally, 20% of irrigated land suffers salinization induced by the build-up of salts caused by irrigation (Wood et al., 2000).

Salt accumulation in Mediterranean soils is a natural process favored by the ecological conditions of the region, governed first and foremost by the water balance of the area (Zalidis et al., 2002). Human activities, particularly irrigation in relatively flat arable lands, may profoundly modify this water balance and may cause salt accumulation under limited drainage conditions, so accelerating land degradation in semiarid Mediterranean environments. According to FAO estimates gathered by the terrastat database, the salt-affected areas in the Mediterranean basin amount to 27.3 million ha, with about 7.3 million ha in the four countries studied (Morocco, Spain, Tunisia and Turkey).

A proper knowledge of the effects of irrigation on the spatial and temporal variability of salt-affected soils is essential to assess the magnitude and trends of this soil quality problem and its effects on water quality. In the Mediterranean basin, soil and climate variability, combined with small-sized farms, results in a wide range of different soil and water management practices. Since geographical information systems (GIS) facilitate the processing of large data collections (Çetin and Diker, 2003), the real challenge in such situations is the appropriate and accurate acquisition of spatial and temporal salinity data. Because such data collection through conventional soil sampling and laboratory analysis is not affordable for large areas, assessment of the spatial and temporal variability of soil salinity in complex Mediterranean landscapes requires the development of alternative, dependable and low-cost methodologies aimed at providing information about the status of soil salinity as affected by different soil, crop and irrigation management practices.

Electromagnetic induction (EMI) instruments have been used for three decades to perform bulk apparent soil electrical conductivity ($EC_a$) measurements (Rhoades et al., 1999). These cost-effective, non-invasive EMI techniques are well suited to assess the temporal and spatial variability of soil properties such as salinity (Johnston et al., 1997; Lesch et al., 1992; Rhoades et al., 1999; Triantafilis et al., 2000; Urdanoz and Aragüés, 2010; Wittler et al., 2006), water content (Brevik et al., 2006; Kachanoski et al., 1988), soil
texture and depth-to-clay mapping (Doolittle et al., 1994; Saey et al., 2009), and in applications to precision
agriculture (Corwin and Plant, 2005; Sudduth et al., 2001). Estimations of these soil properties from ECa
measurements are more suitable in areas with a single dominant soil factor, when variations in ECa response
can be directly related to changes in the dominant property (Friedman 2005). Hence, EMI instruments are
feasible tools for the appraisal of soil salinity at the irrigation district level if properly calibrated to provide low
uncertainty in the predictive equations.

The objective of this work was to quantify soil salinity through EMI techniques and relate it to physical
caracteristics and irrigation management in four semiarid Mediterranean irrigation districts located in
Morocco, Spain, Tunisia and Turkey. To achieve this, the following sub-objectives were envisaged: (1)
analysis of EMI-soil salinity calibration equations, (2) assessment of normal and inverted EMI profiles to
delineate potential shallow water table areas, (3) development of soil salinity maps from EMI surveys by
integrating geographic information systems, and (4) establishment of relationships between soil salinity,
physical characteristics and irrigation management.

2. Materials and Methods

2.1. General characteristics of the study areas

The names of the four Mediterranean irrigation districts studied are given in Table 1. For the purpose
of simplicity, the names of the corresponding countries will be used in this work. Table 1 summarizes some
relevant physical and management characteristics of the study areas.

Irrigation volumes (I) were provided by the respective Water User Associations or were measured in
gauging stations constructed at the inlets and, if needed, outlets of the study areas. Precipitation (P) was
measured in meteorological stations located within each district, and reference evapotranspiration (ETo) was
calculated with the FAO Penman-Monteith method (Allen et al., 1998) using the data gathered in these
meteorological stations. Crop evapotranspiration (ETc) was calculated as \( ET_c = ET_o K_c \), where \( K_c \) are crop
coefficients taken from local information or the literature (Allen et al., 1998). Drainage was measured in
gauging stations constructed at both the inlets and outlets of each catchment to determine the net drainage
flow (Q) within each district and drainage water salinity (electrical conductivity, EC) was measured daily in
water samples taken in these stations with automatic water samplers. Irrigation water EC was also measured
in samples taken periodically. The ECs given in Table 1 are discharge-weighted average values for the given irrigation seasons.

From the inputs and outputs of water shown in Table 1, the following indexes were calculated:

Leaching Fraction (LF), the percentage of irrigation (I) and precipitation (P) that percolates below the crop root zone:

$$\text{LF} = 100 \left( \frac{I + P - ET_c}{I + P} \right)$$  \hspace{1cm} (1)$$

Drainage Fraction (DF), the percentage of irrigation (I) and precipitation (P) that exits the study area as drainage (Q):

$$\text{DF} = 100 \left( \frac{Q}{I + P} \right)$$  \hspace{1cm} (2)$$

Irrigation Efficiency (IE), the percentage of irrigation (I) that is evapotranspired by crops (ET$_c$) discounting the effective precipitation (P$_{ef}$):

$$\text{IE} = 100 \left( \frac{ET_c - P_{ef}}{I} \right)$$  \hspace{1cm} (3)$$

Irrigation Concentration Factor (ICF), the ratio of drainage water salinity (EC$_{drainage\text{ water}}$) to irrigation water salinity (EC$_{irrigation\text{ water}}$):

$$\text{ICF} = \frac{\text{EC}_{\text{drainage\text{ water}}}}{\text{EC}_{\text{irrigation\text{ water}}}}$$  \hspace{1cm} (4)$$

Based on local information, the effective precipitation included in the IE index was taken as 75% of P in Morocco, Spain and Tunisia (Cuenca, 1989), and 43% of P in Turkey (Brouwer and Heibloem, 1986). Some information is missing in Table 1 for Morocco because some farmers use the drainage waters for irrigation and the flows at the exit of the irrigation district are negligible.

A short summary of some relevant characteristics of each study area follows.

**Morocco**: the 2600 ha Beni Amir irrigation district is located in the Tadla irrigation scheme (Oum Er Rbia River basin, 250 km south-east of Rabat, Morocco; latitude: 32° 20’ N; longitude: 6° 40’ W). The area has a Mediterranean climate characterized by annual average values of 350 mm (precipitation), 18.9 ºC (air temperature) and 1796 mm (ET$_{o}$). Irrigation started in 1938 using surface waters from the Ahmed El Hansali dam in the Oum Er Rbia River and groundwaters pumped from a large aquifer system. Drainage waters are
also used by some farmers for irrigation purposes. The area consists of syncline depressions covered by heterogeneous mio-plio-quaternary deposits. This depression is constituted by a heterogeneous wavy bedding of conglomerates, white marls and lacustrine limestones surmounted by a red clay formation. The Oum Er Rbia River flows through a valley filled by homogeneous and fine-texture deposits. The predominant soil classes are iso-humic, clay to clay-silty and deep to moderately deep soils, and calci-magnesic, highly calcareous and shallow soils.

Spain: the 505 ha Lerma gully basin is located in the Bardenas II irrigation scheme (middle Ebro River basin, Zaragoza, Spain; latitude: 42° 3’ 34.84” N; longitude: 1° 8’ 2.86” W). The basin is located on the remains of glacis over Miocene marls high in limestone, gypsum and evaporitic salts that are the substrate of the basin. The glacis have a colluvium covering of variable thickness (1 to 2 m) over the underlying marls. The soils (orthent and fluvent entisols) are shallow in the erosional slopes and deeper close to the gullies present in the basin, with a silty-clay-loam texture, and with salts derived from rock weathering. The soils over the glacis have a 2-3% gentle slope, good internal drainage due to its loamy texture and stoniness (up to 60%), are non saline, and show calcic and cambic horizons. The infiltration waters percolate through these soils, meet the underlying marls and dissolve and transport the salts towards the gullies. Irrigation in the area began in 2006 and the irrigated area in 2008 was 60% of the catchment area. The irrigation water is taken from the Bardenas Canal.

Tunisia: the 2905 ha Kalaât Landalous irrigation district is located in the lowest part of Mejreda River basin (latitude: 6° 37’ and 37° 2’ N; longitude: 10° 5’ and 10° 10’ E). The drainage outlet of this district is below sea level, and drainage waters are discharged to the Mediterranean Sea through a pumping station. The administrative limits of the study area are the Mediterranean Sea (east), the Mejreda River (north-west) and the drainage emissary of Henchir Tobias (south). The district is equipped with irrigation and drainage networks. The irrigation water is taken from the Mejreda River. The soils have a fine texture, ranging from silty-clay to clayey-silt. Most soils have ECe values above 2 dS m⁻¹, and may reach values up to 8-10 dS m⁻¹ near to the south-east sebkha (playa lake). Shallow water tables of about 1.4 m depth are present in the lower parts of the district, with very high salinity values that make them unsuitable for irrigation or other municipal and industrial uses.

Turkey: the Akarsu Irrigation District is located between 36° 57’ 32” and 36° 50’ 43” N latitudes and 35° 40’ 22” and 35° 28’ 42” E longitudes in Lower Seyhan Plain (LSP), named after the River Seyhan, in the Eastern part of the Mediterranean region, Turkey. The LSP covers a gross area of 213200 ha, of which 174088 ha are suitable for irrigation. The soils in the 9495 ha Akarsu Irrigation District are largely alluvial
deposits of the Old River Terraces and Bajadas (Dinc et al., 1991) with high clay contents, varying from 51 to 77%, that are predominantly swelling smectites. The soils generally have A and C horizons and, upon drying, 1-cm wide and 1-m deep cracks may develop. The area has been irrigated for over 40 years with appropriate irrigation and drainage infrastructures. The irrigation water is diverted from the Seyhan River. Presently, there are no soil salinity and sodicity problems in the district, and the main constraints to high crop yields are shallow groundwater and excess irrigation volumes. Irrigation efficiency in the area is very low, and irrigation management needs to be improved to prevent excess irrigation and thereby to decrease drainage discharge.

The hydrographic boundaries of the studied catchments were established in previous works or were delineated using a 20 x 20 m Digital Elevation Model (DEM) and the ArcHydro application (ArcGIS 9.1, ESRI Inc., Redlands, CA, USA). This application defines the stream lines from the DEM and, after selecting the drainage outlets, automatically generates the corresponding catchment boundaries by linking together the pixels draining towards each outlet.

2.2. EMI sensor readings

Manual ECa readings were taken with a Geonics EM38 sensor (Geonics Inc., Mississauga, ON, Canada) in all study areas except Spain, where automatic readings with the Dualem 1S sensor (Dualem Inc., Milton, ON, Canada) were taken using a mobile, geo-referenced EMI vehicle (Urdanoz et al., 2008). The Geonics EM38 has two coplanar transmitter and receiver coils, 1 m apart. The coils may be positioned parallel (H-H orientation) or perpendicular (V-V orientation) to the earth’s surface. The Dualem 1S has three coils: one vertical transmitter coil and two receiver coils: vertical (coplanar, 1 m apart from the transmitter) and horizontal (perpendicular, 1.1 m apart from the transmitter) which provide for two simultaneous ECa readings (V-V and V-H, respectively). The depths of exploration for a 70% cumulative response in the V-V mode (i.e., ECa-v readings) are 1.55 m for the Geonics and Dualem, whereas they are 0.75 m for the Geonics H-H and 0.50 m for the Dualem V-H modes (Abdu et al., 2007). Depending on soil profile characteristics, these H-H and V-H readings could be somewhat different, but in practical terms both may be considered similar. For the purpose of simplicity, in this work the H-H and V-H readings will be referred as ECa-h, and the V-V readings as ECa-v.

The total number of ECa readings taken in each study area ranged from 149 in Morocco to 556 in Spain. Table 2 gives some basic statistics of these readings. The EMI surveys were generally carried out two
to three days after irrigation, so that soil water contents would be as uniform and close to field capacity as possible. Soil temperatures were recorded at each surveying time to convert the readings to a reference temperature of 25 °C. The ECa readings were interpolated into a 15 x 15 m regular grid by ordinary kriging (Goovaerts, 1997) using public domain SGeMS software (Remy, 2004) to facilitate further geographic and statistical analyses. All the ECa values are given in dS m\(^{-1}\) at 25°C.

Potential shallow water table areas were delineated through the EC\(_{a,h}/EC_{a,v}\) ratios obtained from the EMI readings in each study area. Uniform (0.9 < EC\(_{a,h}/EC_{a,v}\) < 1.1) and normal (EC\(_{a,h}/EC_{a,v}\) < 0.9) ECa profiles indicate a net downward flux of water and salts, whereas inverted profiles (EC\(_{a,h}/EC_{a,v}\) > 1.1) are or can be related to a net upward flux of water and salts arising from shallow water tables (Rhoades et al., 1999).

2.3. EMI sensor calibration

A total of 18 to 34 evenly distributed calibration sites were selected with EMI readings along the full ECa interval in each district. The EMI sensors were calibrated against soil salinity (electrical conductivity of the soil saturation extract, ECe) two to three days after irrigation by taking soil samples beneath the sensors immediately following the EMI readings at each site. The soil samples were taken, when permitted, at 0.3 m increments to a depth of 0.9 m in Morocco and Tunisia, 1.2 m in Spain and 2.0 m in Turkey. ECe, saturation percentage (SP) and, except in Turkey, gravimetric soil water content (WC) were measured by standard methods (United States Salinity Laboratory Staff, 1954). Table 3 gives some basic statistics for these measurements. From the EC\(_{a,h}\) and EC\(_{a,v}\) readings and the soil profile average ECe values measured in each calibration site, the linear regressions between ECe and ECa were established in each study area (Table 4).

The relative effects of soil profile ECe, texture (quantified through SP as given by Slavich and Petterson, 1993) and WC on EC\(_{a,h}\) were assessed through a multiple linear regression (MLR) analysis between the standardized ECe, SP and WC independent variables and the standardized EC\(_{a,h}\) dependent variable (Table 5). The results obtained using EC\(_{a,v}\) as the dependent variable were qualitatively similar and are not shown.

2.4. Soil salinity maps
The interpolated ECa values were transformed to ECe by means of the site-specific ECa-ECe calibration equations. For simplicity, the ECe values estimated from ECa-h and ECa-v will be referred as ECe-h and ECe-v, respectively. The ECe-h maps of each study area (Fig. 1) were obtained using ArcGIS 9.1. The ECe-v maps showed higher values than the ECe-h maps, but their spatial patterns were similar and, therefore, they are not presented. From these maps, the percentage of the total irrigated areas falling into different ECe-h intervals and the surface-weighted ECe-h were calculated in each study area (Table 6).

3. Results and Discussion

3.1. General characteristics of the study areas

The study areas varied in irrigated area between a minimum of about 300 ha in Spain and a maximum of about 9500 ha in Turkey, amounting in all cases to more than 60% of the total catchment areas. Winter cereals were predominant in Morocco and Tunisia, and maize in Spain and Turkey. Surface irrigation was the main system, except in Spain and Tunisia where sprinkler irrigation was predominant. Irrigation efficiency (IE) was lowest in the surface-irrigated districts (IE ≤ 52% in Morocco and Turkey) and highest in the Spanish pressurized irrigation district (IE = 70%). The Tunisian pressurized irrigation district appeared to have the lowest average IE (39%), although a significant fraction of the area only had supplementary irrigation and calculating IE on a monthly basis increased the average value to 69%.

Important differences were obtained in the main water inputs (I and P) and outputs (ETc and Q) between the study areas and, consequently, between the leaching fraction (LF, minimum of 28% in Spain and maximum of 52% in Turkey) and the drainage fraction (DF, minimum of 13% in Spain and maximum of 48% in Turkey).

Irrigation water salinity was very low in Spain and Turkey (ECiw = 0.4 dS m⁻¹), moderate in Morocco (ECiw = 2.6 dS m⁻¹) and high in Tunisia (ECiw = 3.6 dS m⁻¹). Cropping patterns responded to these irrigation salinity levels, so that maize, very sensitive to salinity, was dominant in Spain and Turkey whereas winter crops and forages, tolerant to salinity, were significant in Tunisia.
Drainage water salinity was low to moderate in Turkey ($EC_{dw} = 1.4 \, dS \, m^{-1}$), high in Spain ($EC_{dw} = 4.6 \, dS \, m^{-1}$) and very high in Tunisia ($EC_{dw} = 9.0 \, dS \, m^{-1}$). In Morocco, an average $EC_{dw}$ could not be recorded because most drainage waters either deep-percolated or were used by farmers to irrigate winter crops. In addition the drainage ditch was used to purge the main irrigation canal when needed. For these reasons, the volume and salinity of drainage waters in Morocco are not reported in Table 1. Nevertheless, drainage water samples collected in some points along the drainage ditch in Morocco had an $EC_{dw}$ of around 2.6 dS m$^{-1}$.

The irrigation concentration factor (ICF, ratio of $EC_{dw}$ to $EC_{iw}$) reflects the evapo-concentration effect due to ET (i.e., the inverse of LF) and the weathering effect due to mineral dissolution (i.e., leaching of salts arising from weathered minerals occurring in the soil profile or deposited below) (Aragüés and Tanji, 2003). The ICF was highest in Spain (11.5) due to a low 28% LF and the presence of saline marls that are the substrate of the basin. Even though some soils were salt-affected, the lowest ICF was found in Tunisia (2.5) due to a high (48%) LF. An unexpected and relatively high ICF of 3.5 was obtained in Turkey, even though LF (52%) and DF (48%) were high and soil salinity was low, suggesting that other undetermined sources of salts, most likely transported from the neighboring areas that increased the salinity of shallow groundwater, were present in this catchment. These ICF values should be treated with caution because the hydrogeology in these study areas is not well known and, as the example in Turkey shows, the $EC_{dw}$ could be influenced by the interception of groundwaters of variable salinity that will affect ICF.

### 3.2. EMI sensor readings

Table 2 summarizes some basic statistics of the $EC_{a-h}$ and $EC_{a-v}$ readings taken in each district. The $EC_a$ values were quite different between areas, with maximum values in Tunisia and minimum values in Spain and Morocco. The mean $EC_a$ values were also lowest in Morocco and Spain, and highest in Tunisia, with CV between 40% (Tunisia) and 100% (Spain). The medians were close to the means in Morocco and Turkey (i.e., the $EC_a$ distributions were not-skewed) and lower than the means in Spain and Tunisia (i.e., the $EC_a$ distributions were right-skewed).

The mean $EC_{a-h}$ readings were lower than the mean $EC_{a-v}$ readings, and most of the $EC_a$ profiles (i.e., $EC_{a-h}/EC_{a-v}$) were uniform or normal. These results suggest that the soils were generally subject to salt-leaching. Spain was the only exception, where 19% of the profiles were inverted. Most of these inverted profiles were close to gullies, and since they may be related to a net upward flux of water and salts (Rhoades...
et al., 1999), these areas should be further surveyed to determine whether shallow water tables are being
developed. The lack of inverted ECa profiles in Tunisia was apparently inconsistent, since shallow water
tables were present in the lower south-east areas of the district. However, these water tables were highly
saline due to sea water intrusion, so that ECa-v would be higher than ECa-h (i.e., normal instead of inverted
profiles) because of the larger depth of exploration of the V-V readings that will penetrate deeper in these
highly saline water tables. In these cases, ECa profiles would not be suitable to characterize the flux of water
and salts in the soil profile.

3.3. EMI sensor calibration

Table 3 shows for each district the number of sampling points for EMI calibration, the number of total
soil samples analyzed, and some basic statistics for soil profile average gravimetric water content (WC),
saturation percentage (SP) and saturation extract EC (ECe). WC was not measured in Turkey, but previous
information shows that WC at field capacity is very high (close to 35%) due to the presence and redundancy
of swelling smectite clay minerals. Since the calibration surveys were usually performed two to three days
after irrigation, this value of 35% will be representative of actual soil water contents at the time of
measurement. In the other study areas, mean WC varied between 16% (Spain) and 25% (Tunisia). These
values were in agreement with mean SP values, maximum in Turkey (99%) and minimum in Spain (41%).
Soil texture was not measured, but the SP values indicate that the textural grades vary between heavy clays
in Turkey and loam to silty-clay-loam in Spain (Slavich and Petterson, 1993). Based on the CV of the mean
SP and WC values, soil textures and soil water contents of the samples taken were considered relatively
uniform (CV values below 25%).

Soil salinity (ECe) was quite variable within and between districts, with maximum values close to 15
dS m⁻¹, minimum values below 1 dS m⁻¹, and CV values between 37% (Morocco) and 105% (Spain).
Although the mean ECe for the relatively low number of sampling points may not be representative of actual
soil salinity in the study areas, the ranking will be (Table 3): Tunisia > Spain > Morocco > Turkey. Except in
Morocco, the means were higher than the medians, showing that the ECe distributions were skewed to the
right. These skewed distributions were a consequence of the sampling strategy and the physical and
management characteristics of the districts.
The EC$_{a}$-EC$_{e}$ calibration equations were highly significant (P < 0.001) in all the study areas, with $R^2$ values close to or above 0.8 (Table 4). The $R^2$ values were generally lower for EC$_{a-v}$ than for EC$_{a-h}$, an expected result since the depth of exploration in the V-V dipole configuration (i.e., EC$_{a-v}$) is higher than the depth of soil sampling. The regression coefficients (“a” values in Table 4) were relatively similar in Morocco, Spain and Tunisia, and much lower in Turkey. The intercepts (“b” values in Table 4) were not significantly different from zero (P > 0.05) in all the study areas except in Tunisia. These results show that the calibration equations are site-specific and must be developed for the particular soils of interest.

Many studies have shown that EC$_{a}$ is generally influenced by EC$_{e}$ but, depending on soil characteristics, may also be affected by WC, texture, bulk density and temperature (Corwin and Lesch, 2005; Hanson and Kaita, 1997; McKenzie et al., 1989; Urdanoz and Aragüés, 2010). The relative effects of EC$_{a}$, WC and SP (texture) on EC$_{a}$ were determined through a multiple linear regression (MLR) analysis of the corresponding standardized variables (Table 5). EC$_{a-h}$ was significantly correlated (P < 0.001) with EC$_{e-h}$ in all the study areas, with coefficients varying between 1.01 (Tunisia) and 0.23 (Morocco). EC$_{a-h}$ was not significantly correlated (P > 0.1) with WC because the sampling strategy (soil samples taken at or close to field capacity) provided a relatively low CV of this variable (Table 3). In contrast, EC$_{a}$ and WC have been found to be positively correlated in other studies (Hanson and Kaita, 1997; Rhoades et al., 1999; Wittler et al., 2006), although excess soil moisture may also reduce EC$_{a}$ due to a dilution of the electrolytes present in the soil solution (McKenzie et al. 1989). Soil texture (SP) was positively and significantly correlated with EC$_{a}$ in Spain (P < 0.1) and Turkey (P < 0.01), in agreement with previous works (Brevik et al., 2006; Doolittle et al., 1994). In contrast, soil texture was not significantly correlated (P > 0.1) with EC$_{a-h}$ in Morocco and Tunisia. Wittler et al. (2006) also found that the soil textural class was not a significant explanatory variable. Thus, the effects of soil water content and soil texture on EC$_{a}$ were site-specific and should be determined in each study area.

The MLR analysis showed that the EC$_{a-h}$ coefficients (“a” in Table 5) were much higher than the SP coefficients (“c” in Table 5) in all districts except Turkey, although the Turkish case was not comparable to the other study areas because WC could not be included in the MLR analysis. These results indicate that EC$_{a-h}$ was mostly affected by EC$_{e-h}$, so that the EC$_{e-h}$ maps obtained from the interpolated EC$_{a-h}$ values and the site-specific EC$_{a-h}$ vs. EC$_{e-h}$ calibration equations could be used effectively to assess soil salinity and its spatial variability in these irrigation districts.

3.4. Soil salinity maps and relationships with characteristics of the study areas
The EC<sub>e-h</sub> maps (Fig. 1) indicate that the spatial variability of soil salinity was relatively low in Morocco, Spain and Turkey and relatively high in Tunisia. The differences in EC<sub>e-h</sub> observed in Morocco between the central-northern and the southern areas were attributed to the nature of the soils and different geology. In Morocco, 84% of the total irrigated area was within the 1.7 to 2.6 dS m<sup>-1</sup> EC<sub>e-h</sub> interval (Table 6). The variability in Spain was attributed to the differential geomorphology, with uniform and low EC<sub>e-h</sub> soils located over the glacis and more irregular and higher EC<sub>e-h</sub> soils located in areas with shallower saline marls close to some gullies in the south of the study area. In Spain, 86% of total irrigated area had EC<sub>e-h</sub> values below 2.0 dS m<sup>-1</sup> (Table 6). In Tunisia, the high EC<sub>e-h</sub> soils observed in the south-east area were mainly due to sea water intrusion derived from its low elevation and proximity to the sea, whereas the high EC<sub>e-h</sub> soils present in the north-east were attributed to typical high irrigation efficiencies in drip-irrigated forages and vegetable crops. The high soil salinity variability in Tunisia is also reflected by the high percentages of total irrigated area in each EC<sub>e-h</sub> interval (Table 6). The variability in Turkey could most likely be attributed to the wide range of different irrigation systems, the changes of cropping patterns taking place during the irrigation season and the observed spatial variability of groundwater depths with varying salinity. In Turkey, 86% of total irrigated area had EC<sub>e-h</sub> values below 0.54 dS m<sup>-1</sup> (Table 6).

The surface-weighted average EC<sub>e-h</sub> values (EC<sub>e-h-swa</sub> in Table 6) varied between 3.4 dS m<sup>-1</sup> in Tunisia and 0.45 dS m<sup>-1</sup> in Turkey, with intermediate values in the other districts. Based on these values and the salinity tolerance (Maas and Hoffman, 1977) of the most important crops grown in each study area, average expected yield decreases would only be significant for vegetables cropped in Tunisia, and would be irrelevant in the remaining districts. The EC<sub>e-h-swa</sub> ranking for the study areas was Tunisia > Morocco > Spain > Turkey. This ranking was similar to the ranking given by the measured mean EC<sub>e</sub> values (Table 3) in Tunisia and Turkey, but was different in Morocco and Spain, showing that salinity values based on a limited number of soil samples could deviate from salinity estimates that more precisely take into account its irrigation-district spatial variability.

A comparison of soil salinity with the general characteristics of the districts (Table 1) showed that it was positively correlated ($R^2 = 0.878; P < 0.06$) with irrigation water salinity (EC<sub>iw</sub>). The addition of IE (irrigation efficiency) in an MLR analysis increased the coefficient of determination to 0.995 (significant at $P < 0.05$):

$$EC_{e-h-swa} \text{ (dS m}^{-1} \text{)} = -1.7 + 0.68 \text{ EC}_{iw} \text{ (dS m}^{-1} \text{)} + 0.04 \text{ IE (％)}$$

(5)

The inclusion in the MLR analysis of leaching (LF) and/or drainage (DF) fractions did not increase its significance. Although the low number of studied districts was insufficient to obtain sound conclusions, this
relationship consistently showed that soil salinity in these districts was mostly affected by irrigation salinity, followed by the efficiency of irrigation. Leaching and/or drainage fractions were not correlated with soil salinity, probably because they were obtained from hydrological variables (I and Q) with some measurement uncertainties in certain districts as Morocco and Tunisia.

Drainage water salinity ($EC_{dw}$) measured at the exit of each irrigation district (Table 1) was positively correlated with soil salinity ($R^2 = 0.72$) and irrigation efficiency ($R^2 = 0.67$), although they were only significant at $P < 0.4$. The MLR of $EC_{dw}$ on both variables was significant at $P < 0.2$:

$$EC_{dw} \text{ (dS m}^{-1}\text{)} = -8.2 + 1.55 EC_{e-h-swa} \text{ (dS m}^{-1}\text{)} + 0.16 \text{ IE } (\%) \quad (6)$$

The highest $EC_{dw}$ values measured in Tunisia (9.0 dS m$^{-1}$) and Spain (4.6 dS m$^{-1}$) were also a consequence of the shallow and saline water tables present in some areas in Tunisia and of the saline marls that form the substrate of the basin in Spain. Hence, besides soil salinity and irrigation efficiency, hydrogeology and geomorphology also played an important role in the salinity of drainage waters in these districts.

In terms of salt loads in irrigation return flows (IRF), both salinity ($EC_{dw}$) and volume (Q) of drainage waters must be quantified. The Tunisian district had the highest IRF salt load due to both high $EC_{dw}$ and Q values, whereas the Spanish district, despite its relatively high $EC_{dw}$, had the lowest IRF-salt load due to its low Q (118 mm). Although $EC_{dw}$ in the Turkish district was three times lower than in Spain, its IRF salt load was almost twice that of Spain due to its very high Q (780 mm). The quantification of these figures is essential to assess off-site salt pollution induced by irrigated agriculture, since salt load rather than salt concentration is the critical variable to quantify salinity build-up in the receiving water bodies (Aragüés and Tanji, 2003). Whereas salinity of irrigation return flows depends to a large extent on the sources of salts in irrigation waters, soils and geologic materials that cannot be significantly minimized through human intervention, the volume of irrigation return flows may be properly controlled through efficient water management at the delivery, conveyance, distribution and field-application levels. Our results show that a better water management to alleviate off-site salt-pollution problems should be implemented in Tunisia and Turkey, the two districts with higher IRF salt loads.

4. Conclusions
The EMI surveys performed in each irrigation district studied provided mean ECₐ values that were lowest in Morocco and Spain, intermediate in Turkey and highest in Tunisia. With the exception of Spain, where 19% of the ECₐ profiles were inverted, the rest of the profiles were uniform or normal, suggesting that the soils were subject to a net downward flux of water and salts. However, the shallow and saline water tables present in some low-lying areas in Tunisia were not detected by this profile analysis, showing the limitations and site-specific results of this assessment.

ECₐ was significantly correlated (P < 0.001) with ECₑ, but not with soil water content and soil texture at this probability level. Hence, the ECₑ maps obtained in each district from the interpolated ECₐ values and the ECₐ-ECₑ calibrations were a sensible approach for the assessment of salinity at the irrigation district scale. Soil salinity and its spatial variability was relatively low in all districts except Tunisia, where some low-lying areas in the south-east were affected by sea water intrusion and shallow water tables that raised soil salinity to EC values above 5 dS m⁻¹. The ranking of districts based on the surface-weighted average ECₑ values calculated from these maps, and on the mean ECₑ values measured in 18 to 34 soil samples taken in each district was different for Morocco and Spain, showing that salinity values based on a limited number of soil samples could deviate from salinity estimates that take into account more precisely its spatial variability.

Irrigation district soil salinity consistently depended on irrigation water salinity and irrigation efficiency (IE), but not on the rest of the analyzed variables. Furthermore, drainage water salinity (ECₐₑ) measured at the exit of each district consistently depended on soil salinity and irrigation efficiency (IE). Thus, IE was a significant variable negatively affecting soil and drainage water salinity concentrations.

However, since salt loads in irrigation return flows are a function of both the salinity (ECₐₑ) and the volume (Q) of drainage waters, and this volume depends to a large extent on the district irrigation efficiency, the lowest salt loads were obtained in Spain (high ECₐₑ but very low Q), intermediate in Turkey (low ECₐₑ but very high Q) and highest in Tunisia (very high ECₐₑ and high Q) while no Q data was available for Morocco. Therefore, the reduction of these high drainage volumes in Tunisia and Turkey through sound irrigation management and higher irrigation efficiencies will be the most efficient strategy to control the off-site salt-pollution induced by these Mediterranean irrigation districts.

Acknowledgments
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References


Table 1. General characteristics of the irrigation districts studied in each Mediterranean country.

<table>
<thead>
<tr>
<th>Name of irrigation district</th>
<th>MOROCCO</th>
<th>SPAIN</th>
<th>TUNISIA</th>
<th>TURKEY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irrigation season year</td>
<td>Beni Amir</td>
<td>Lerma</td>
<td>Kalaât Landalous</td>
<td>Akarsu</td>
</tr>
<tr>
<td>Catchment area (ha)</td>
<td>2600</td>
<td>505</td>
<td>2905</td>
<td>9495</td>
</tr>
<tr>
<td>Irrigated area (ha)</td>
<td>2084</td>
<td>302</td>
<td>2312</td>
<td>9495</td>
</tr>
<tr>
<td>Irrigation systems (% of total)</td>
<td>SU (100%)</td>
<td>SP (90%), DR (10%)</td>
<td>SP (65%), DR (35%)</td>
<td>SU (74%), DR (20%), SP (6%)</td>
</tr>
<tr>
<td>Main irrigated crops (% of total)</td>
<td>WC (40%), AL (34%), OL (15%), OT (11%)</td>
<td>MA (49%), WC (25%), VE (21%), OT (5%)</td>
<td>WC (37%), VE (33%), FO (29%), OT (1%)</td>
<td>MA (41%), CI (29%), WC (18%), OT (12%)</td>
</tr>
<tr>
<td>Irrigation (I, mm)</td>
<td>773</td>
<td>529</td>
<td>1187</td>
<td>1105</td>
</tr>
<tr>
<td>Precipitation (P, mm)</td>
<td>519</td>
<td>361</td>
<td>676</td>
<td>524</td>
</tr>
<tr>
<td>Reference ET (ET₀, mm)</td>
<td>1432</td>
<td>1069</td>
<td>1412</td>
<td>1128</td>
</tr>
<tr>
<td>Crop ET (ETc, mm)</td>
<td>793</td>
<td>642</td>
<td>975</td>
<td>779</td>
</tr>
<tr>
<td>Surface drainage (Q, mm)</td>
<td>--</td>
<td>118</td>
<td>411</td>
<td>780</td>
</tr>
<tr>
<td>Leaching fraction (LF, %)</td>
<td>39</td>
<td>28</td>
<td>48</td>
<td>52</td>
</tr>
<tr>
<td>Drainage fraction (DF, %)</td>
<td>--</td>
<td>13</td>
<td>22</td>
<td>48</td>
</tr>
<tr>
<td>Irrigation efficiency (IE, %)</td>
<td>52</td>
<td>70</td>
<td>39</td>
<td>50</td>
</tr>
<tr>
<td>EC irrigation water (dS m⁻¹)</td>
<td>2.6⁵</td>
<td>0.4</td>
<td>3.6</td>
<td>0.4</td>
</tr>
<tr>
<td>EC drainage water (dS m⁻¹)</td>
<td>--</td>
<td>4.6</td>
<td>9.0</td>
<td>1.4</td>
</tr>
</tbody>
</table>

²DR: drip; SP: sprinkler; SU: surface
³AL: alfalfa; CI: citrus; FO: forages; FT: fruit trees; MA: maize; OL: olive; OT: others; VE: vegetables;
⁴WC: winter cereals
⁵Volume-weighted average of the three sources of irrigation water: canal water, drainage water and groundwater
Table 2. Basic statistics of EMI soil apparent ECₐ readings (ECₐ-h, horizontal; ECₐ-v, vertical) taken in each Mediterranean irrigation district. N = number of ECₐ readings. The percent of total uniform, normal and inverted ECₐ profiles are also given.

<table>
<thead>
<tr>
<th>MOROCCO</th>
<th>SPAIN</th>
<th>TUNISIA</th>
<th>TURKEY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ECₐₕ</td>
<td>ECₐ₋</td>
<td>ECₐₕ</td>
</tr>
<tr>
<td>N</td>
<td>149</td>
<td>556</td>
<td>200</td>
</tr>
<tr>
<td>Maximum</td>
<td>1.06</td>
<td>1.31</td>
<td>3.47</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.01</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>Mean</td>
<td>0.42</td>
<td>0.49</td>
<td>0.41</td>
</tr>
<tr>
<td>CV (%)</td>
<td>43</td>
<td>45</td>
<td>108</td>
</tr>
<tr>
<td>Median</td>
<td>0.42</td>
<td>0.49</td>
<td>0.20</td>
</tr>
</tbody>
</table>

ECₐ profiles (% of total)

| Uniformᵃ | 19 | 73 | 1 | 1 |
| Normalᵇ  | 76 | 8  | 99 | 99 |
| Invertedᶜ | 5 | 19 | 0 | 0 |

ᵃ0.9 < ECₐₕ/ECₐ₋ < 1.1
ᵇECₐₕ/ECₐ₋ < 0.9
ᶜECₐₕ/ECₐ₋ > 1.1
Table 3. Number of sampling points for EMI sensor calibration, number of total samples and basic statistics of soil-profile average gravimetric water content (WC), saturation percentage (SP) and saturation extract EC (ECe) in each Mediterranean irrigation district.

<table>
<thead>
<tr>
<th></th>
<th>MOROCCO</th>
<th>SPAIN</th>
<th>TUNISIA</th>
<th>TURKEY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WC (%)</td>
<td>SP (%)</td>
<td>ECe (dS m⁻¹)</td>
<td>WC (%)</td>
</tr>
<tr>
<td>Nº of sampling points</td>
<td>29</td>
<td>34</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>Nº of total samples</td>
<td>87</td>
<td>108</td>
<td>54</td>
<td>120</td>
</tr>
<tr>
<td>Max</td>
<td>40.2</td>
<td>57</td>
<td>24.2</td>
<td>58</td>
</tr>
<tr>
<td>Min</td>
<td>9.0</td>
<td>29</td>
<td>0.59</td>
<td>9.1</td>
</tr>
<tr>
<td>Mean</td>
<td>21.5</td>
<td>44</td>
<td>1.9</td>
<td>15.9</td>
</tr>
<tr>
<td>CV (%)</td>
<td>15</td>
<td>17</td>
<td>37</td>
<td>24</td>
</tr>
<tr>
<td>Median</td>
<td>21.6</td>
<td>44</td>
<td>2.0</td>
<td>15.5</td>
</tr>
</tbody>
</table>

⁻Estimates based on soil water content measured at field capacity in four soil samples.
Table 4. EMI sensor calibration performed in each Mediterranean irrigation district: number of calibration points (N) and linear regression equations of soil-profile average saturation extract EC (ECₑ) against EMI soil apparent EC (ECₐ-h, horizontal; ECₐ-v, vertical).

<table>
<thead>
<tr>
<th></th>
<th>MOROCCO</th>
<th></th>
<th>SPAIN</th>
<th></th>
<th>TUNISIA</th>
<th></th>
<th>TURKEY</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ECₑ (dS m⁻¹) = a ECₐ (dS m⁻¹) + b</td>
<td>N</td>
<td>a</td>
<td>b</td>
<td>N</td>
<td>a</td>
<td>b</td>
<td>N</td>
</tr>
<tr>
<td>ECₐ-h</td>
<td></td>
<td>29</td>
<td>3.97</td>
<td>0.57</td>
<td>0.89</td>
<td>34</td>
<td>3.90</td>
<td>0.44</td>
</tr>
<tr>
<td>ECₐ-v</td>
<td></td>
<td>29</td>
<td>3.00</td>
<td>0.15</td>
<td>0.92</td>
<td>34</td>
<td>3.22</td>
<td>0.01</td>
</tr>
</tbody>
</table>
Table 5. Effects of soil salinity (EC_{e-h}), gravimetric water content (WC) and saturation percentage (SP) on EMI soil apparent EC_{a-h} in each Mediterranean irrigation district: number of sampling points (N) and multiple linear regression equations of standardized EC_{a-h} against standardized soil profile EC_{e-h}, WC and SP. Numbers in parenthesis are probability (P) values.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>R² adj.</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOROCCO</td>
<td>29</td>
<td>0.23 (0.000)**</td>
<td>0.00 (0.46)ns</td>
<td>0.00 (0.70)ns</td>
<td>0.95 (0.000)***</td>
</tr>
<tr>
<td>SPAIN</td>
<td>34</td>
<td>0.77 (0.000)**</td>
<td>0.11 (0.202)ns</td>
<td>0.17 (0.084)*</td>
<td>0.90 (0.000)***</td>
</tr>
<tr>
<td>TUNISIA</td>
<td>18</td>
<td>1.01 (0.000)**</td>
<td>-0.12 (0.399)ns</td>
<td>0.03 (0.779)ns</td>
<td>0.88 (0.000)***</td>
</tr>
<tr>
<td>TURKEY</td>
<td>20</td>
<td>0.69 (0.000)**</td>
<td>-</td>
<td>0.33 (0.003)**</td>
<td>0.86 (0.000)***</td>
</tr>
</tbody>
</table>

***,**,* Significant at P < 0.001, 0.01 and 0.1, respectively; ns Not significant at P > 0.1
Table 6. Percent of total irrigated area (TIA) in each EC$_{e-h}$ interval estimated from the EC$_{e-h}$ maps obtained in each Mediterranean irrigation district. The surface-weighted average EC$_{e-h}$ values (EC$_{e-h-swa}$) are also given.

<table>
<thead>
<tr>
<th>MOROCCO</th>
<th>SPAIN</th>
<th>TUNISIA</th>
<th>TURKEY</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC$_{e-h}$ interval (dS m$^{-1}$)</td>
<td>TIA (%)</td>
<td>EC$_{e-h}$ interval (dS m$^{-1}$)</td>
<td>TIA (%)</td>
</tr>
<tr>
<td>0-1.7</td>
<td>7.2</td>
<td>0-1.0</td>
<td>54.3</td>
</tr>
<tr>
<td>1.7-2.0</td>
<td>16.5</td>
<td>1.0-2.5</td>
<td>31.8</td>
</tr>
<tr>
<td>2.0-2.3</td>
<td>27.2</td>
<td>2.5-4.0</td>
<td>9.2</td>
</tr>
<tr>
<td>2.3-2.6</td>
<td>40.8</td>
<td>4.0-5.5</td>
<td>3.0</td>
</tr>
<tr>
<td>&gt; 2.6</td>
<td>8.3</td>
<td>&gt; 5.5</td>
<td>1.8</td>
</tr>
<tr>
<td>EC$_{e-h-swa}$</td>
<td>2.2</td>
<td>EC$_{e-h-swa}$</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Fig. 1. Soil salinity ($\text{EC}_{e-h}$) maps obtained in each Mediterranean irrigation district from the interpolated $\text{EC}_{e-h}$ values and the site-specific EMI sensor calibrations. Black points indicate the locations of the EMI survey.