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_e) maps were obtained through electromagnetic induction surveys (EC_a readings) and district-specific EC_a-EC_e calibrations. Gravimetric soil water content (WC) and soil saturation percentage (SP) were also measured in the soil calibration samples. The EC_a-EC_e calibration equations were highly significant ($P < 0.001$) in all districts. EC_a 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_a mainly depended upon EC_e, so that the maps developed could be used effectively to assess soil salinity and its spatial variability. The surface-weighted average EC_e values were low to moderate, and ranked the districts in the order: Tunisia (3.4 dS m^{-1}) > Morocco (2.2 dS m^{-1}) > Spain (1.4 dS m^{-1}) > Turkey (0.45 dS m^{-1}). 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^{-1}), high in Spain (4.6 dS m^{-1}), moderate in Morocco (estimated at 2.6 dS m^{-1}), and low in Turkey (1.4 dS m^{-1}). Salt loads in drainage waters, calculated from their salinity (EC_{dw}) and volume (Q), were highest in Tunisia (very high Q and very high EC_{dw}), intermediate in Turkey (extremely high Q and low EC_{dw}) and lowest in Spain (very low Q and high EC_{dw}) (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 EC_a measurements are more suitable in areas with a single dominant soil factor, when variations in EC_a 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 characteristics 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 (ET_o) was calculated with the FAO Penman-Monteith method (Allen et al., 1998) using the data gathered in these meteorological stations. Crop evapotranspiration (ET_c) 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:

$$LF = 100\,\frac{(I + P - ETc)}{(I + P)} \tag{1}$$

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

$$DF = 100\,\frac{Q}{(I + P)} \tag{2}$$

Irrigation Efficiency (IE), the percentage of irrigation (I) that is evapotranspired by crops (ET_c) discounting the effective precipitation (P_{ef}):

$$IE = 100\,\frac{(ET_c - P_{ef})}{I} \tag{3}$$

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

$$ICF = \frac{EC_{drainage\ water}}{EC_{irrigation\ water}} \tag{4}$$

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: 32º 20’ N; longitude: 6º 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 (ETo). 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: 42º 3' 34.84'' N; longitude: 1º 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 EC_e 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 EC_a 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 EC_a readings (V-V and V-H, respectively). The depths of exploration for a 70% cumulative response in the V-V mode (i.e., $EC_{a\text{-}v}$ 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 $EC_{a\text{-}h}$, and the V-V readings as $EC_{a\text{-}v}$.

The total number of EC_a 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 ºC. The EC_a 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 EC_a values are given in dS m^{-1} at 25ºC.

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 ($EC_{a-h}/EC_{a-v} < 0.9$) EC_a 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 EC_a interval in each district. The EMI sensors were calibrated against soil salinity (electrical conductivity of the soil saturation extract, EC_e) 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. EC_e, 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 EC_e values measured in each calibration site, the linear regressions between EC_e and EC_a were established in each study area (Table 4).

The relative effects of soil profile EC_e, 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 EC_e, 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 EC_a values were transformed to EC_e by means of the site-specific EC_a-EC_e calibration equations. For simplicity, the EC_e values estimated from EC_{a-h} and EC_{a-v} will be referred as EC_{e-h} and EC_{e-v}, respectively. The EC_{e-h} maps of each study area (Fig. 1) were obtained using ArcGIS 9.1. The EC_{e-v} maps showed higher values than the EC_{e-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 EC_{e-h} intervals and the surface-weighted EC_{e-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 (ET_c 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 (EC_{iw} = 0.4 dS m^{-1}), moderate in Morocco (EC_{iw} = 2.6 dS m^{-1}) and high in Tunisia (EC_{iw} = 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 EC_a 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 EC_{a-v} would be higher than EC_{a-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, EC_a 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 (EC_e). 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 (EC_e) 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 EC_e 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 EC_e 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 $EC_{a\text{-}v}$ than for $EC_{a\text{-}h}$, an expected result since the depth of exploration in the V-V dipole configuration (i.e., $EC_{a\text{-}v}$) 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_e, WC and SP (texture) on EC_a were determined through a multiple linear regression (MLR) analysis of the corresponding standardized variables (Table 5). $EC_{a\text{-}h}$ was significantly correlated ($P < 0.001$) with $EC_{e\text{-}h}$ in all the study areas, with coefficients varying between 1.01 (Tunisia) and 0.23 (Morocco). $EC_{a\text{-}h}$ 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 $EC_{a\text{-}h}$ 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 $EC_{a\text{-}h}$ 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 $EC_{e\text{-}h}$ 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 $EC_{a\text{-}h}$ was mostly affected by $EC_{e\text{-}h}$, so that the $EC_{e\text{-}h}$ maps obtained from the interpolated $EC_{a\text{-}h}$ values and the site-specific $EC_{a\text{-}h}$ vs. $EC_{e\text{-}h}$ 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 $EC_{e\text{-}h}$ 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 $EC_{e\text{-}h}$ 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^{-1} $EC_{e\text{-}h}$ interval (Table 6). The variability in Spain was attributed to the differential geomorphology, with uniform and low $EC_{e\text{-}h}$ soils located over the glacis and more irregular and higher $EC_{e\text{-}h}$ 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 $EC_{e\text{-}h}$ values below 2.0 dS m^{-1} (Table 6). In Tunisia, the high $EC_{e\text{-}h}$ 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 $EC_{e\text{-}h}$ 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 $EC_{e\text{-}h}$ 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 $EC_{e\text{-}h}$ values below 0.54 dS m^{-1} (Table 6).

The surface-weighted average $EC_{e\text{-}h}$ values ($EC_{e\text{-}h\text{-}swa}$ in Table 6) varied between 3.4 dS m^{-1} in Tunisia and 0.45 dS m^{-1} 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 $EC_{e\text{-}h\text{-}swa}$ ranking for the study areas was Tunisia > Morocco > Spain > Turkey. This ranking was similar to the ranking given by the measured mean EC_e 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_{iw}). The addition of IE (irrigation efficiency) in an MLR analysis increased the coefficient of determination to 0.995 (significant at $P < 0.05$):

$$EC_{e\text{-}h\text{-}swa}\ (\text{dS m}^{-1}) = -1.7 + 0.68\ EC_{iw}\ (\text{dS m}^{-1}) + 0.04\ \text{IE}\ (\%) \quad (5)$$

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 $P < 0.2$:

$$EC_{dw}\ (\mathrm{dS\ m^{-1}}) = -8.2 + 1.55\ EC_{e\text{-}h\text{-}swa}\ (\mathrm{dS\ m^{-1}}) + 0.16\ IE\ (\%);\ R^2 = 0.92 \qquad (6)$$

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 EC_a values that were lowest in Morocco and Spain, intermediate in Turkey and highest in Tunisia. With the exception of Spain, where 19% of the EC_a 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.

EC_a was significantly correlated ($P < 0.001$) with EC_e, but not with soil water content and soil texture at this probability level. Hence, the EC_e maps obtained in each district from the interpolated EC_a values and the EC_a-EC_e 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 EC_e values calculated from these maps, and on the mean EC_e 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 (EC_{dw}) 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 (EC_{dw}) 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 EC_{dw} but very low Q), intermediate in Turkey (low EC_{dw} but very high Q) and highest in Tunisia (very high EC_{dw} 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.

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

	MOROCCO	SPAIN	TUNISIA	TURKEY
Name of irrigation district	Beni Amir	Lerma	Kalaât Landalous	Akarsu
Irrigation season year	2009	2008	2009	2008
Catchment area (ha)	2600	505	2905	9495
Irrigated area (ha)	2084	302	2312	9495
Irrigation systems (% of total)[a]	SU (100%)	SP (90%), DR (10%)	SP (65%), DR (35%)	SU (74%), DR (20%), SP (6%)
Main irrigated crops (% of total)[b]	WC (40%), AL (34%), OL (15%), OT (11%)	MA (49%), WC (25%), VE (21%), OT (5%)	WC (37%), VE (33%), FO (29%), OT (1%)	MA (41%), CI (29%), WC (18%), OT (12%)
Irrigation (I, mm)	773	529	1187	1105
Precipitation (P, mm)	519	361	676	524
Reference ET (ET_o, mm)	1432	1069	1412	1128
Crop ET (ET_c, mm)	793	642	975	779
Surface drainage (Q, mm)	--	118	411	780
Leaching fraction (LF, %)	39	28	48	52
Drainage fraction (DF, %)	--	13	22	48
Irrigation efficiency (IE, %)	52	70	39	50
EC irrigation water (dS m^{-1})	2.6[c]	0.4	3.6	0.4
EC drainage water (dS m^{-1})	--	4.6	9.0	1.4
Irrig.conc. factor (ICF)	--	11.5	2.5	3.5

[a] DR: drip; SP: sprinkler; SU: surface

[b] AL: alfalfa; CI: citrus; FO: forages; FT: fruit trees; MA: maize; OL: olive; OT: others; VE: vegetables; WC: winter cereals

[c] Volume-weighted average of the three sources of irrigation water: canal water, drainage water and groundwater

Table 2. Basic statistics of EMI soil apparent EC_a readings (EC_{a-h}, horizontal; EC_{a-v}, vertical) taken in each Mediterranean irrigation district. N = number of EC_a readings. The percent of total uniform, normal and inverted EC_a profiles are also given.

	MOROCCO		SPAIN		TUNISIA		TURKEY	
	EC_{a-h}	EC_{a-v}	EC_{a-h}	EC_{a-v}	EC_{a-h}	EC_{a-v}	EC_{a-h}	EC_{a-v}
	---------------------------------- dS m^{-1} at 25ºC ----------------------------------							
N	149		556		200		162	
Maximum	1.06	1.31	3.47	4.36	4.65	5.78	2.94	3.33
Minimum	0.01	0.03	0.05	0.00	0.66	0.91	0.13	0.26
Mean	0.42	0.49	0.41	0.62	1.51	1.93	0.78	1.06
CV (%)	43	45	108	106	39	40	52	45
Median	0.42	0.49	0.20	0.34	1.36	1.71	0.74	0.99
	EC_a profiles (% of total)							
Uniform[a]	19		73		1		1	
Normal[b]	76		8		99		99	
Inverted[c]	5		19		0		0	

[a] $0.9 < EC_{a-h}/EC_{a-v} < 1.1$

[b] $EC_{a-h}/EC_{a-v} < 0.9$

[c] $EC_{a-h}/EC_{a-v} > 1.1$

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 (EC_e) in each Mediterranean irrigation district.

	MOROCCO			SPAIN			TUNISIA			TURKEY		
	WC (%)	SP (%)	EC_e (dS m^{-1})	WC (%)	SP (%)	EC_e (dS m^{-1})	WC (%)	SP (%)	EC_e (dS m^{-1})	WC (%)	SP (%)	EC_e (dS m^{-1})
Nº of sampling points		29			34			18			20	
Nº of total samples		87			108			54			120	
Max	40.2	57	3.3	24.2	58	15.3	36.9	97	14.3	--	126	0.75
Min	9.0	29	0.59	9.1	26	0.54	16.9	38	0.65	--	56	0.29
Mean	21.5	44	1.9	15.9	41	3.8	25.3	58	5.7	34.6[a]	99	0.49
CV (%)	15	17	37	24	21	105	21	23	74	5[a]	24	24
Median	21.6	44	2.0	15.5	40	1.8	24.1	56	4.6	--	106	0.46

[a] 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 (EC_e) against EMI soil apparent EC (EC_{a-h}, horizontal; EC_{a-v}, vertical).

	EC_e (dS m^{-1}) = a EC_a (dS m^{-1}) + b															
	MOROCCO				SPAIN				TUNISIA				TURKEY			
	N	a	b	R^2	N	a	b	R^2	N	a	b	R^2	N	a	b	R^2
EC_{a-h}	29	3.97	0.57	0.89	34	3.90	0.44	0.86	18	3.4	-2.1	0.89	20	0.30	0.17	0.86
EC_{a-v}	29	3.00	0.15	0.92	34	3.22	0.01	0.79	--	--	--	--	17	0.47	-0.01	0.79

Table 5. Effects of soil salinity ($EC_{e\text{-}h}$), gravimetric water content (WC) and saturation percentage (SP) on EMI soil apparent $EC_{a\text{-}h}$ in each Mediterranean irrigation district: number of sampling points (N) and multiple linear regression equations of standardized $EC_{a\text{-}h}$ against standardized soil profile $EC_{e\text{-}h}$, WC and SP. Numbers in parenthesis are probability (P) values.

	$EC_{a\text{-}h}$ (dS m^{-1}) = a $EC_{e\text{-}h}$ (dS m^{-1}) + b WC (%) + c SP (%)				
	N	a	b	c	R^2 adj.
MOROCCO	29	0.23 (0.000)***	0.00 (0.46)^{ns}	0.00 (0.70)^{ns}	0.95 (0.000)***
SPAIN	34	0.77 (0.000)***	0.11 (0.202)^{ns}	0.17 (0.084)*	0.90 (0.000)***
TUNISIA	18	1.01 (0.000)***	-0.12 (0.399)^{ns}	0.03 (0.779) ^{ns}	0.88 (0.000)***
TURKEY	20	0.69 (0.000)***	-	0.33 (0.003)**	0.86 (0.000)***

***,**,* 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.

MOROCCO		SPAIN		TUNISIA		TURKEY	
EC_{e-h} interval ($dS\ m^{-1}$)	TIA (%)	EC_{e-h} interval ($dS\ m^{-1}$)	TIA (%)	EC_{e-h} interval ($dS\ m^{-1}$)	TIA (%)	EC_{e-h} interval ($dS\ m^{-1}$)	TIA (%)
0-1.7	7.2	0-1.0	54.3	0-2.5	29.5	0.0-0.33	14.1
1.7-2.0	16.5	1.0-2.5	31.8	2.5-3.5	34.4	0.33-0.40	17.0
2.0-2.3	27.2	2.5-4.0	9.2	3.5-4.5	16.4	0.40-0.47	18.0
2.3-2.6	40.8	4.0-5.5	3.0	4.5-5.5	11.0	0.47-0.54	37.0
> 2.6	8.3	> 5.5	1.8	> 5.5	9.1	>0.54	13.9
$EC_{e-h-swa}$	2.2	$EC_{e-h-swa}$	1.4	$EC_{e-h-swa}$	3.4	$EC_{e-h-swa}$	0.45

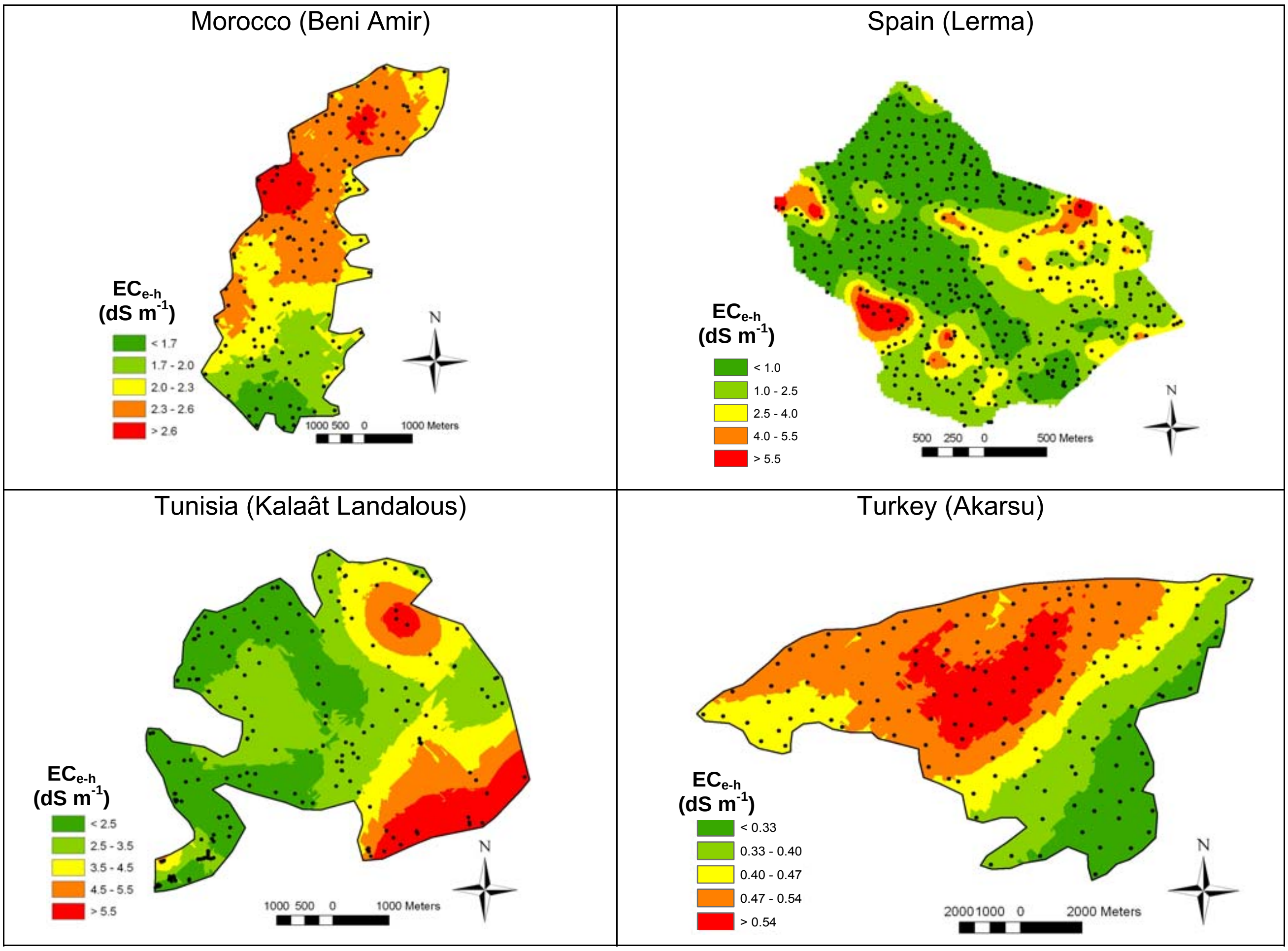

Fig. 1. Soil salinity ($EC_{e\text{-}h}$) maps obtained in each Mediterranean irrigation district from the interpolated $EC_{a\text{-}h}$ values and the site-specific EMI sensor calibrations. Black points indicate the locations of the EMI survey.