Multivariate analysis of soil salination-desalination in a semi-arid irrigated district of Spain

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ABSTRACT

15 Long-term studies of the changes in soil salinity are scarce and most overlook individual ions. Here, we assess changes in soil ionic contents using 42 soils repeatedly sampled during three campaigns over 24 years in a semi-arid irrigated district. Multivariate analysis (MVA) was used to evaluate the spatial distribution of ions and the temporal changes at comparable soil depths in relation to environmental and
20 management factors. In general, the position of the soil in the landscape governed the spatial distribution of the salinity, while the temporal variations were related to irrigation, with incidences depending on the location in the district. Many soils on the slopes and foothills became salinated during the first years due to land leveling, but salination eventually tapered off after sprinkler utilization. At high and middle
25 elevations, most soils were slightly saline in the first campaign but underwent desalination during the study period. At lower elevations, an initial desalination was followed by a pronounced salination, which was attributed to a water table rise with generalized irrigation in the basin. Whereas univariate salinity assessment might lead to conclusions that are over-simplistic at the landscape scale, MVA detects singular

behaviors of groups of soils or single cases and has enormous potential coupled with GIS assessment of soil salinity data.

Keywords: Irrigation, salt-affected soils, soil salinity, soil sodicity.

Abbreviations: ECe, electrical conductivity of the saturation extract; GIS, geographic information system; MVA, multivariate analysis; PCA, principal components analysis; RDA, redundancy analysis; SAR, sodium adsorption ratio.

1. Introduction

Soil salinity and sodicity are the two major concerns in irrigated agriculture in dry regions of the world, and they are increasing worldwide due to poor management of water and soil resources (Shahid, 2013). Periodic information on the status of soil salinity and sodicity in irrigation districts can suggest management practices and corrective measures to improve the profitability and sustainability of irrigated agriculture (Young, 1991; Rhoades et al., 1997; Herrero et al., 2011).

Temporal monitoring of soil salinity is mainly based on the comparison of point-size data for several years (regular observations and sampling in the same point) or on the comparison of soil salination maps developed in different years (Rhoades et al., 1997; Rukhovich et al., 2013). The standard method for appraising agricultural salinity is to measure the electrical conductivity of a saturated soil paste extract (ECe – dS m^{-1}) following the United States Salinity Laboratory Staff (1954) approach. This extract can be used to determine the pH and the ionic composition of the soil solution. Focus is set on the concentration of undesirable ions, e.g., high contents of chloride (Cl^-) which causes toxicity in plants. Attention is also paid to the relationships between ions, e.g., the ratio of sodium (Na^+) to calcium (Ca^{2+}) and magnesium (Mg^{2+}), as expressed by the sodium adsorption ratio (SAR), which has long been the standard measure of potential sodication hazard for irrigated soils (United States Salinity Laboratory Staff, 1954). In recent decades, soil salinity and sodicity has been indirectly monitored through its expression on vegetative cover using remote sensing (Metternicht and Zinck, 2009; Domínguez-Beisiegel et al., 2016) or proximal sensors (Amezketta, 2007; Corwin, 2008;

60 Herrero et al., 2011; Swanhart et al., 2014; Aldabaa et al., 2015;). Studies addressing the temporal variation in the ionic composition of soil solutions are much less abundant. Most of these studies are based either on laboratory analyses of soil samples taken at different times (Pisinaras et al., 2010; Corwin, 2012; Ammari et al., 2013) or on chronosequences of soil use (Barbiéro et al., 2004; Dou et al., 2011).

65 Monitoring soil salinity is difficult due to its spatial and temporal variability and is complicated by management practices, such as irrigation, drainage, and plowing; by weather, and by the salinity and depth of water tables (Herrero and Snyder, 1997; Rhoades et al., 1997; Akramkhanov et al., 2011). The multivariate nature of ionic composition makes monitoring more difficult, often resulting in different variation
70 patterns for each particular ion or ionic ratio. In this regard, multivariate analysis (MVA) can be very useful because this technique can simplify multivariate datasets (e.g., ionic composition) without a substantial loss of information. It also allows for handling of complex and often highly collinear matrices of data, as is often the case in soil studies, and accounting for the effects of environmental and management variables
75 (Johansson and Stenberg, 2000; Young and Hammer, 2000). There are three main classes of MVA which are used in environmental analyses: (i) cluster analysis, in which the observations are assigned into groups (clusters) on the basis of their similarity; (ii) indirect gradient analysis, such as principal components analysis (PCA), which ranks observations along variation axes that represent gradients derived from intrinsic and/or
80 environmental factors; and (iii) direct gradient analysis, such as the redundancy analysis (RDA) in which a second set of explanatory variables is incorporated to ordination, and the effects of this set on the original variables are evaluated by regression techniques (Legendre and Legendre, 2012). Cluster and indirect gradient analysis are commonly used when studying the ionic composition of soil solutions (e.g., Mora et al., 2005; Aguilera et al., 2011), while direct gradient analysis has been used to study the effects
85 of the ionic composition of soil solutions on vegetation (Álvarez Rogel et al., 2001; Rodríguez et al., 2005; Tug et al., 2012). However, direct gradient analysis has not been used frequently to study the environmental or management factors responsible for the spatial variability in the ionic composition of soil solutions. To our knowledge, no
90 works are available that use all of these tools to examine the temporal variation in soil salinity.

In the present article, MVA (i.e., PCA, RDA, and cluster analysis) was used to analyze salinity (i.e., ECe) and sodicity/alkalinity (SAR, pH) indices as well as the salt composition (e.g., Na^+ , $\text{Ca}^{2+} + \text{Mg}^{2+}$) of soil solutions, in a semi-arid irrigation district using data collected at three time steps (i.e., 1975, 1985/1986, and 1999). Our aim was to determine the usefulness of MVA to discern the temporal impact of environmental (e.g., landscape position) and management (e.g., land use) factors on the soil salt composition over this period.

2. Methods

2.1. Study area

The study was conducted in the irrigated district of Flumen, located in the Ebro basin of north-east Spain, between $41^\circ 40'$ and $42^\circ 5'$ N, and $0^\circ 0.5'$ and $0^\circ 35'$ W. The Flumen district is representative of the changes produced by irrigation in the semiarid middle Ebro Basin. In this area, salinity mostly stems from the weathering of the saliferous Miocene strata, which were often brought to the surface by the movement of soil needed to establish new irrigation districts in the middle 20th century. Currently, a significant amount of irrigated lands in the Ebro Basin are salt-affected, despite that, in the last decades, drip and sprinkler irrigation using water of low ionic content has driven the abatement of water tables and the desalination of many soils. The abatement of the salt-affection of soils in Flumen between 1975 and 1999, with a more pronounced trend in more saline soils, was reported by Herrero and Pérez-Coveta (2005); however, examining the changes in the ionic composition remained outside the scope of that study.

The studied area is bound by the rivers Flumen and Alcanadre and by the Flumen Canal (Figure 1). The area is 263 km² (including non-agricultural lands). The elevation ranges from 260 m to 400 m above sea level with an overall decrease from N to S. The climate is Mediterranean semiarid; the mean-annual precipitation is 423 mm and the mean-annual temperature is 14.5 °C (Herrero and Pérez-Coveta, 2005). The potential evapotranspiration (ET_0) has an annual value of approximately 1150 mm according to the FAO Blaney-Criddle method, with the ET_0 exceeding precipitation from February to October (Marínez-Cob et al., 1998). In these conditions, irrigation practices began at least 600 years ago at the riverbanks and were extended to include most of the land in the 1950's. The main crops are alfalfa (*Medicago sativa* L.), barley (*Hordeum vulgare*

L.), forage (*Lolium multiflorum* Lam.), corn (*Zea mays* L.), rice (*Oryza sativa* L.),
125 sunflower (*Helianthus annuus* L.), and wheat (*Triticum aestivum* L.). The traditional
controlled flood basin and border irrigation is gradually being changed to sprinkling,
except the rice paddies, which are inundated from May to September. Most water comes
from reservoirs in the Pyrenees, and its ionic contents are low with an electrical
conductivity $< 0.4 \text{ dS m}^{-1}$ and an SAR $< 1 \text{ (mmol L}^{-1}\text{)}^{-0.5}$ (Nogués et al., 2000; Herrero
130 and Pérez-Coveta, 2005). Following the FAO guidelines (Ayers and Westcot, 1994),
such low electrical conductivity poses no salinity hazard but may cause slight to
moderate infiltration problems, even though the SAR is low.

The geological materials are subhorizontal Miocene strata of alternating sandstone
and lutite, the latter being often saliferous. The main landforms are platforms (A),
135 slopes (B), terraces (C), and valley bottoms (D) (Table 1), and the characteristics of the
soils on the different landforms are very different. The calcium carbonate content of the
soils is always $> 25\%$. Saline soils are common in several landform units (B1, B2, C2,
C3, C4, and D), but saline-sodic soils occur only in spots at C3, C4, and D (Nogués et
al., 2000; Nogués and Herrero, 2003).

140 2.2. Sampling design and field work

The soil samples in this study were taken from soils cultivated under irrigation in
three sampling campaigns. The first campaign was between June 26 and August 20,
1975; the second was from July 19, 1985 to June 16, 1986; and the third was between
145 April 19 and May 15, 1999. The soil sampling campaign in 1975 was designed by
INYPSA (Informes y Proyectos, S.A., Madrid, Spain), a consulting company contracted
by the Spanish Government. The aim of the 1975 campaign was to serve as the base of
a soil map intended for the development of the irrigated district, and the results were
recorded and discussed in an unpublished report. The second and third campaigns were
150 designed and performed by one of the authors (J.H.) to appraise the evolution of salt-
affected soils. For this purpose, the strategy was to relocate and resample the sites that
were sampled in 1975, using the 1975 campaign as a baseline set of data. The sites were
re-sampled using an auger. Several of the sites from 1975 were excluded in the
successive samplings because the documentation from 1975 made the sites difficult to

locate or because the results of the analyses were illegible due to the degradation of the 1975 report.

More details about the study sites selection and field work can be found in Herrero and Pérez-Coveta (2005). In the present study, we considered only those sites where the sampling depth was considered sufficient in the three campaigns, which made 42 sites (of the 66 sites studied by Herrero and Pérez-Coveta (2005)).

2.3. Laboratory data

All soil analyses were performed on the fine earth fraction obtained after air-drying the samples and passing them through a 2 mm sieve. The soil analyses performed for the three sampling campaigns were pH in water and potassium chloride (KCl), electrical conductivity of the saturated soil paste extract (ECe), and determining the ion concentrations of Cl^- , Na^+ , and $(\text{Ca}^{2+} + \text{Mg}^{2+})$ in each extract. In the second and third sampling campaigns, sulfate (SO_4^{2-}), bicarbonate (HCO_3^-), Ca^{2+} , and Mg^{2+} were also titrated. Chemical determinations were performed per the official methods of the Spanish Ministry of Agriculture (MAPA, 1974, 1994), with some adaptations (Table 2) related to advances in laboratory equipment. As discussed in the paper by Herrero and Pérez-Coveta (2005), the high quality and coherence of the analytical results from the three sampling campaigns allowed for comparisons between these results, with some indicated exceptions.

2.4. Data processing

At many sites, the sampling depth or the depth intervals were not consistent between the three sampling campaigns, thus making a direct comparison between sampling dates unsound. To overcome this, a comparable soil depth was selected for each soil to compare the data obtained at different campaigns. For all sites where a 1 m depth was attained, we used this depth as the comparable depth. According to Herrero (1987), the average salt content of the upper meter of the soil is almost constant during a single year; moreover, this soil layer contains the roots of most cultivated plants and is thus related to the effects of salinity on crops. At the sites where the sampling depth was

between 0.8 m and 1.0 m, we used the minimum attained depth as the comparable depth. For soils with similar shallow sampling depths in the three campaigns, we also used the minimum depth as comparable depths.

After determining the comparable depth for each sampling site, we calculated a comparable value for E_{Ce}, pH, and ionic contents in the saturation extract, i.e., an averaged value for the soil between the surface and the comparable depth. The comparable values were calculated for each site and sampling date per Eq. 1:

$$X_{comp} = D^{-1} * \left[\sum X_i * d_i - X_n * \left(\sum d_i - D \right) \right] \quad [\text{Eq. 1}]$$

where X_{comp} is the comparable value of the studied property, D is the comparable depth, X_i is the value of this property in the i -th sample from the surface, d_i is the thickness of the i -th sample, and n is the first of the successive samples whose lower limit is $\leq$ the comparable depth. The comparable values were calculated using the software Slices version 1 (<http://hdl.handle.net/10261/60892>). To avoid averaging the pH measures (which is senseless from an arithmetic point of view), we transformed pH into the concentration of hydrogen ions $[H^+]$ expressed as mol L⁻¹ and then calculated the comparable $[H^+]_{comp}$. For ease of interpretation, the $[H^+]_{comp}$ was back transformed to a logarithmic scale, obtaining the pH_{comp}.

The sodicity was evaluated by calculating the SAR for each analyzed horizon per Eq. 2:

$$SAR = \frac{Na^+}{\sqrt{\frac{1}{2} * (Ca^{2+} + Mg^{2+})}} \quad [\text{Eq. 2}]$$

We considered that the undesirable effects of SAR were best represented by the maximum SAR recorded in the profile than by an averaged SAR. Thus, for each soil and sampling date, we compared the maximum SAR value of the horizons within the comparable depth (SAR_{comp}).

Changes in the investigated soil properties were measured per the relative variation of the comparable values per Eq. 3:

$$\Delta X_{t1-t2} = \frac{X_{comp}(t1) - X_{comp}(t2)}{X_{comp}(t1)} \quad [\text{Eq. 3}]$$

where $X_{comp}(t1)$ and $X_{comp}(t2)$ are the comparable values of the studied property at the beginning ($t1$) and end ($t2$) of the considered period. In this way, we calculated the relative variations in the comparable values of ECe, SAR, Cl^- , Na^+ , and $Ca^{2+} + Mg^{2+}$ that occurred between the three campaigns. We also calculated the variations for Ca^{2+} , Mg^{2+} , SO_4^{2-} , HCO_3^- , $[H^+]$ -water, and $[H^+]$ -KCl from the second to the third campaign. The pH values from the first campaign were disregarded for these calculations due to uncertainty in the soil dilutions used in the laboratory (Table 2).

2.5. Statistical analysis

Several environmental and management factors were examined in relation to their influence on soil ionic composition. Thus, we considered the elevation (meters above sea level), the location of the soils in the landscape units, rice cropping in 1990 and 2000 and the productive intensity according to the Cadaster Service of Spain. The landscape units, described in Table 1, included the following: structural platforms (A1-A2), slopes (B1-B2), terraces (C1-C4), and bottoms (D). The rice paddies were separated from the other irrigated crops using the System of Territorial Information of Aragon (<http://sitar.aragon.es/>; accessed May 2016) that was based on the CORINE Landcover maps at level 3 from 1990 and 2000, which were considered approximate proxies for rice cropping in 1986 and 1999, respectively. The productive intensity was based upon the land capacity for crop production, which is attributed to each site by the Cadaster Service of Spain (<https://www1.sedecatastro.gob.es/>; accessed May 2016) and based on actual crop use. Landscape units and rice cropping were coded as dummy variables (1 = yes, 0 = no) for their use in PCAs and RDAs.

We used a PCA of the laboratory data of the three sampling campaigns to investigate the relationships between the soil ionic components and their consistency over time. Prior to analysis, the data were centered and standardized by standard deviation. Environmental (elevation, landscape unit) and management (rice cropping, productive intensity) factors were entered into the PCA as supplementary variables (not affecting the ordination but allowing an appraisal of their relationship with the soil solution composition).

A similar centered and standardized PCA was performed on the relative variations of the ionic contents of the soils to study the patterns of temporal variation between the first and second campaigns and between the second and third campaigns. The scores of

the three first principal components were used as the base of a cluster analysis, which
was based on the K-means method and squared Euclidean distance and intended to
construct groups of soils showing coincident temporal variation. Previously, we used
Ward's hierarchical technique to provide the K-means algorithm with the optimum
number of clusters, following Hair et al. (2010).

The RDA can be used as a regression technique for multivariate data (Legendre
and Legendre, 1998). We used RDAs to determine how much of the variance in (a) the
soil solution composition and (b) the variations that occurred in the two periods (first to
second and second to third campaigns), can be explained by a set of explanatory
variables, including environmental and management factors. In each case, from the full
set of explanatory variables, i.e., elevation, landscape unit (A1, A2, B1, B2, C1, C2, C3,
C4, and D) and landscape unit type (platforms, slopes, terraces, and bottoms,
respectively, A, B, C, and D), rice cropping in 1990 and 2000, and productive intensity,
the best minimum set of explanatory variables was selected by a forward stepwise
procedure, using Monte Carlo tests with 1,000 permutations. This procedure enabled us
to include only those factors with a significant ($P < 0.10$) contribution to variance and
discard the remaining factors with less explanatory power or with redundancy. The
statistical significance of the first axes and all canonical axes obtained were also
determined by Monte Carlo tests (1,000 permutations).

The PCAs and RDAs were conducted with Canoco for Windows version 4.5
(Microcomputer Power, Ithaca, NY). Cluster analyses were performed with SPSS
Statistics version 19 (SPSS Inc., Chicago, IL).

3. Results

3.1. General features of the soil solution composition

3.1.1 Salinity and sodicity/alkalinity status

Figure 2 shows the frequency distributions of EC_{comp} , $pH_{-water_{comp}}$, $pH_{-KCl_{comp}}$, Cl_{comp}^- , Na_{comp}^+ , $(Ca^{2+}+Mg^{2+})_{comp}$, and SAR_{comp} in the three soil sampling campaigns, and those of $SO_4^{2-}_{comp}$ and $HCO_3^{-}_{comp}$ in the second and third campaigns. Comparing the comparable values of EC_e , SAR and pH with the threshold values set by

the United States Salinity Laboratory Staff (1954), the soils can be described as mostly
275 non- or very slightly saline ($\text{ECe} < 4 \text{ dS m}^{-1}$), not or very slightly sodic ($\text{SAR} < 13$
($\text{mmol L}^{-1})^{-0.5}$), and moderately or strongly alkaline ($7.9 < \text{pH} < 9.0$) for the three
campaigns.

3.1.2 Main gradients in the soil solution composition

Figure 3 shows the results of the PCA carried out on the soil solution data of the
280 three sampling campaigns. The factor loadings of the soil solution components and of
the explanatory (environmental and management) factors and the scores of the
individual soils on the four first axes are displayed. Based on these results, the
following can be seen:

- Axis I had large positive loadings (Figure 3a, right half) for ECe , Cl^- , SO_4^{2-} , and
285 Na^+ and represents the major gradient of salinity. The distribution of the soils
along this axis was conspicuously related to their landscape position. Thus, most
soils of the terraces (units C1-C4) had large positive scores (Figure 3a, on the
right) corresponding to high salinity levels, while the soils from the platforms
(units A1 and A2) had the lowest scores (Figure 3a, left) and salinity. The soils
290 from the slopes and bottoms (units B1, B2, and D) showed intermediate scores
(Figure 3a, center) and salinity levels.
- Axis II had positive loadings (Figure 3a, top) for pH-water, pH-KCl, HCO_3^- , and
SAR and was therefore considered a representation of sodicity-alkalinity. Rice
cropping in 1990 and 2000 showed large loadings on axis II, and a position in
295 the diagram close to those of SAR and pH. This finding mirrors the location of
rice crops on sodic/alkaline soils.
- Remarkably, the loadings on axes I and II for the same soil properties measured
in the different sampling campaigns (1975, 1985/86, and 1999) appeared
generally plotted close to each other. This result mirrors both a general
300 agreement in the salinity distribution patterns across different dates and a high
temporal consistency of the analytical methods.
- In contrast, axes III and IV (Figure 3b) accounted for variation in the soil
solution composition that was specific to each the sampling dates. Thus, axis III
had large negative loadings (Figure 3b. left) for the ECe , Cl^- , HCO_3^- , Na^+ , Ca^{2+} ,
305 Mg^{2+} , SAR, and pH-KCl measurements from the second sampling campaign.

Conversely, axis IV had notable positive loadings (Figure 3b, top) for ECe, Cl^- , SO_4^{2-} , HCO_3^- , Na^+ , Ca^{2+} , and SAR from the third campaign, and corresponding negative loadings (Figure 3b, bottom) for the measurements for ECe, Cl^- , Na^+ , $\text{Ca}^{2+} + \text{Mg}^{2+}$, and SAR from the first campaign.

3.1.3 Main factors affecting the soil ionic composition

According to the RDA, the soil solution composition was mainly determined by the location at the valley bottoms (units C1-C4) ($P < 0.01$) and the rice cropping in 1999 ($P < 0.10$). The other environmental and management factors were less relevant or redundant ($P > 0.10$). An ordination model based on these two factors was statistically significant ($P < 0.05$ for the first canonical axis as well as for the first two axes), despite having a low explanatory power for the soil solution composition (10.1% of the variance explained).

3.2. Temporal variations of the soil solution composition

3.2.1 Overall temporal trends in salinity and sodicity

A general trend towards lower ECe_{comp} with time was apparent (Figure 2a) that was consistent with that observed by Herrero and Pérez-Coveta (2005). Accordingly, there were increases over time in the number of soils with lower ($< 8 \text{ mEq L}^{-1}$) values of $\text{Cl}^-_{\text{comp}}$ (Figure 2d), $\text{SO}_4^{2-}_{\text{comp}}$ (Figure 2e), $\text{Na}^+_{\text{comp}}$ (Figure 2g), and $(\text{Ca}^{2+} + \text{Mg}^{2+})_{\text{comp}}$ (Figure 2h). Furthermore, Figures 2b and 2c show a gradual shift in $\text{pH-water}_{\text{comp}}$ and $\text{pH-KCl}_{\text{comp}}$ from a preponderance of soils in the lower pH ranges in the first campaign to a greater number of soils in the higher pH ranges in the third campaign. A marked increase was also observed in the number of soils with extreme values of SAR_{comp} (< 5 and $> 45 \text{ (mmol L}^{-1}\text{)}^{-0.5}$) from the first to the second campaigns (Figure 2i), which was a consequence of a larger increase in $\text{Na}^+_{\text{comp}}$ compared to $(\text{Ca}^{2+} + \text{Mg}^{2+})_{\text{comp}}$ in these ranges.

3.2.2 Multivariate patterns of the temporal changes

Figure 4 displays the results of the PCA of the relative variations of the soil solution components from the first to the second campaigns and from the second to the third campaigns. The loadings of these variations and the scores of the studied soils are plotted for the first three PCA axes. The loadings of the variations from the first to the

third campaigns and of the environmental and management factors are also represented as supplementary variables. A legend is provided to show the membership of the soils in the clusters obtained from the first three PCA axes. Since these axes represent the major gradients of variation within the temporal variation data, clustering was considered to help distinguish groups of soils with coinciding temporal trends. From these results, the following was observed:

- Axis I had positive loadings (Figure 4a, right) for the variations from the first to the second sampling campaigns, and negative loadings (Figure 4b, left) for most of the variations from the second to the third campaign. As seen from these opposite trends, those soils showing positive scores on axis I tended to increase their salinity levels from the first to the second campaigns and decrease their salinity from the second to the third campaigns, and the reverse was the case for the soils with negative scores on this axis. The largest positive scores on axis I were for a group of soils (cluster II) that are plotted close to productive intensity and location in slopes (Figure 4a, right) and opposite to elevation (Figure 4a, left). Therefore, soils in cluster II are largely considered highly productive and are located on slopes of low elevation, which are mainly in the southern half of the study area (Figure 1). Conversely, the lowest scores on this axis (Figure 4a, left) were for a group (cluster IV) of soils from low topographic locations (bottoms and certain slopes), mainly in the northern section of the studied area (Figure 1).
- Axis II had positive loadings (Figure 4a, top) for the variations in pH, Ca, and Mg from the second to the third campaign. Rice cropping in 1990 and 2000 showed the largest loadings on axis II, which indicates that rice cropping was related to these variations. A sample (no. 7) located at the northernmost side of the study area and under rice in 1990 and 2000 had a notable score in this axis (Figure 4a, top), and formed a cluster of its own (cluster I).
- Axis III had positive loadings (Figure 4b, upper half) for all of the variations analyzed. A large group of soils (cluster III) was positioned at the negative part of this axis. This indicates that the soils in this cluster underwent no or only slight changes in salinity or alkalinity during the study periods.

Figure 5 presents the mean values of the soil solution composition for the clusters and shows the following different trends over the study period: (i) cluster I underwent a

decrease in pH and an increase in Ca^{2+} and Mg^{2+} from the second to the third sampling;
370 (ii) the ionic concentration increased in the soils of cluster II from the first to the second
campaign, but decreased in the third campaign back to levels similar or slightly higher
than those at the beginning of the study, with an increase in pH-water; (iii) cluster III
underwent a progressive decrease in salinity throughout the entire studied period and an
increase in sodicity from the second to the third sampling campaign; and (iv) soil
375 salinity decreased in cluster IV from the first to the second campaign and later increased
from the second to the third campaign, often reaching values that were higher than those
at the beginning of the first campaign.

3.2.3 Main factors affecting the temporal changes

The RDA of the temporal variations produced a statistically significant ($P < 0.01$)
380 ordination model that included elevation ($P < 0.01$), rice cropping in 1990 ($P < 0.05$),
and the location on slopes (landform unit type B) ($P < 0.10$) as explanatory variables. In
spite of the low explained variance (16.9%), this model was highly significant ($P <$
0.001 for the first axis and for all the canonical axes).

4. Discussion

4.1. Spatial variation of soil salinity

Our results concerning the factors controlling the ionic composition of Flumen
soils agree with previous studies of salinity in the central Ebro Valley (Badía et al.,
2011; Herrero et al., 2011). These studies showed that, in most cases, the distribution of
390 salinity under natural conditions is related to the location of the soil in the landscape,
ranging from the platforms without salt-affected soils to the moderately to strongly
saline soils in the bottoms.

Additionally, rice cropping showed a significant relationship with the ionic
composition of the soil, which was linked to high sodicity (HCO_3^- , pH, SAR). Rice is
395 not salt-tolerant, but tilling and cropping paddies saturated with continuous flood
irrigation water of very low salinity (Playán et al., 2008; Herrero and Hudnall, 2014)
allows acceptable yields. Generally, rice cropping in Flumen is an indicator of salinity
or salinity-sodicity because rice is the only profitable crop in these soils (Nogués et al.,

2000). However, rice planting expands to soils with higher percolation rates when
400 prices increase (Herrero and Snyder, 1997).

4.2. Temporal variation of salinity

During the study period, the ionic composition of the analyzed soils changed over
time, mainly due to increases and decreases in Na^+ and Cl^- contents. Landscape units
405 governed these variations, and our results highlight the salinity variations on the slopes.
The construction of irrigated districts in the 1950s brought saliferous parent materials to
the surface, making the slopes prone to salination (Herrero and Snyder, 1997). In the
1990s, the generalized use of sprinkling and other irrigation technologies stopped land
leveling and replaced the traditional basin and border flood irrigation. This change in
410 soil management is consistent with our results for the soils found on the slopes and the
slope foothills of the southern area of the study. These soils, grouped in cluster II,
underwent pronounced salination from the first to second campaigns and were related to
land leveling. Between the second and third campaigns, these soils were desalinated
with a slight sodication, which was attributed to the leaching of salts when using water
415 of very low ionic content.

The soils of cluster IV, predominantly located in bottoms in the northern study
area, followed the opposite trend. The salinity of these slightly or moderately saline
soils decreased from the first to the second sampling campaign, but salinity rebounded
from the second to the third campaign. This evolution can be attributed to a two-step
420 process: first, irrigation with water of very low ionic content promoted the leaching of
salts, and second, the water table rose as a result of overabundant irrigation, leading to a
rebound in salinity. This explanation agrees with the magnitude of the irrigation return
flows in this district and its impact on the volume and quality of the surficial waters
(Isidoro and Aragüés, 2007; Martín-Queller et al., 2010). Under similar conditions,
425 Badía et al. (2011) recommended irrigating the soils of platforms and slopes with small
water volumes at frequent intervals to decrease the hazard of water table rise and
salination in the soils of the bottoms. However, the rise of water tables is not only
dependent on the amount of water used for irrigation but also especially dependent on
the irrigation system. For most crops in the area (excluding rice), the amount of water
430 used for flood and sprinkler irrigation is quite similar ($3,500\text{--}10,000 \text{ m}^3 \text{ ha}^{-1}$ vs. $3,000\text{--}$

8,000 m³ ha⁻¹, respectively) but results in different contributions to the water table, since 37-41% of the water used for flood irrigation percolates into the ground compared to 0-26% under sprinkler irrigation (Martínez et al., 2002). Herrero et al. (2003) reported that shallow water tables (< 1.5 m depth) occur in the study area under flood irrigation, and
435 rise to a 0.6-0.8 m depth during the irrigation season, leading to root zone salination of the affected soils.

The explanation is also compatible with desalination that occurred in the soils of cluster III from the first to the second campaign and from the second to the third campaign. This cluster is mainly populated by soils of the terraces, most of the soils
440 from platforms, and the soils of many slopes from the northern area of the study. One interpretation is that these units were not affected by a rise in the water table, thus allowing a continuous leaching of salt to occur throughout the studied period of 1975 to 1999. Cluster III also included some paddies where salinity decreased as a result of the high doses of irrigation water, ~15,000 m³ ha⁻¹ per year, producing significant
445 desalination. A correlative increase of soil sodicity might occur, but the associated descent of soil permeability would not affect rice production in these inundated fields. Cluster III is the largest of the defined clusters, and its desalination trend agrees with the general trend reported by Herrero and Pérez-Coveta (2005) for the same period in the Flumen district.

We found the rice crop to be associated with a variation gradient that distinguished the soil at site no. 7, due to its atypical evolution from the second to the third sampling campaign with a decrease in pH, an increase in Ca²⁺, and a decrease in SAR. This evolution can be explained in puddled soils by the decomposition of straw, which releases CO₂ and Ca²⁺ and decreased sodicity and pH (Bai et al., 2013).
455 Irrespective of the mechanism of this atypical evolution in the study area, this result stresses the power of the MVA technique for detecting singular behaviors of small groups of observations or single cases.

From the environmental and management factors considered, elevation was found to have the highest explanatory power regarding the temporal variation in soil solution
460 composition. Our results, specifically the spatial distribution of the clusters that mirror the temporal changes in salinity, suggest that, in this case, elevation is an indirect measure of a North-South spatial pattern. The southern district, which is located at a

lower elevation, hosts more intense salination processes, while in the northern district these processes are milder. The most striking example of this difference is the severe salination of the soils on the slopes of the southern sector from the first to the second sampling campaign compared with the gentle and sustained desalination of the soils on the slopes in the northern area. Martín-Queller et al. (2010) and Jiménez et al. (2015) reached similar results when they studied the surface waters of the Flumen district, finding higher values for electrical conductivity, Na^+ , Cl^- , SO_4^{2-} , and NO_3^- in the southern area than in the northern area, which they mainly attributed to intense agricultural use in the southern part of the study area. Thus, our results add to other studies in elucidating the influence of agricultural management on temporal variations of salinity through the soil profile.

5. Conclusions

While the work by Herrero and Pérez-Coveta (2005) in the Flumen irrigation district reported on soil desalination from 1975 to 1999, the present article reveals the complexity of the changes in the salinity-sodicity of the soils. These changes differ and diverge depending on the considered sub-period, the location of the soil on the landscape, and the characteristics of the crops. The MVA of the ionic composition of the Flumen soils from 1975 to 1999 has identified several of these divergent processes. In general, temporal variations were related to irrigation, with incidences depending on the location in the district. Many soils on the slopes and foothills became salinated during the initial years due to land leveling, but salination eventually tapered off after sprinkler utilization. At high and middle elevations, most soils were slightly saline in the first campaign but underwent desalination during the study period. At lower elevations, an initial desalination was followed by a pronounced salination and was attributed to water table rise with generalized irrigation in the basin.

Sustainable agriculture in irrigated districts requires information about the salinity-sodicity of the soils and their trends, incorporating the many factors discussed above to reach sound interpretations. In this way, MVA, specifically direct gradient analyses, has performed well and has enormous potential coupled with a GIS treatment for analyzing soil salinity data. The use of MVA techniques in the present study elucidated the role of the studied explanatory factors in the spatial and temporal

variation in soil salinity. However, the modest percent of the variances that were explained suggests that other non-considered environmental and management factors should be incorporated in future research studies. Multivariate analyses can improve our understanding of linkages between topographic controls and management practices on soil salinity to help inform future land management decisions.

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Figure 1. Sampling sites location, landform units, and clustering based on temporal variations of salinity. Black arrows show the flow direction of rivers and channels.

635

Figure 2. Frequency distributions of the comparable values of ECe, (a), SAR (b), and pH (c), in the three soil campaigns.

Figure 3. Biplot diagram of the first and second (a), and of the third and fourth (b) axes obtained from the principal components analysis (PCA) of the soil solution data.

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The cross-marks represent the soil ionic components during the first, second, and third sampling campaigns, and the individual soils are represented with symbols depending on the landform unit type. Other environmental and management factors are displayed as arrows.

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Figure 4. Biplot diagram of the first and second (a), and of the first and third (b) axes obtained from the principal components analysis (PCA) of the temporal variations of the soil solution data during the study period.

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The cross-marks represent the variations in the soil ionic components from the first to the second sampling campaigns, and from the second to the third sampling campaigns. The variations occurred from the first to the third campaign are indicated with x-marks. The individual soils are represented with symbols depending on their membership to clusters with differing temporal variations during the study period. Supplementary (environmental and management) variables are displayed as arrows. A = Platforms; B = Slopes, C = Terraces, and D = Bottoms.

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Figure 5. Mean values ($\pm$ SEM) of the soil solution data in clusters of points with differing temporal variations during the study period.

660 **Table 1.** Main landform units and WRB soil types in the study area (adapted from Nogués and Herrero, 2003)

Units	Landform units	Main soil types (IUSS Working Group WRB, 2014)
A.1	Structural platforms of sandstone and lutite	Eutric Regosols with inclusions of Eutric Leptosols
A.2	Residual platforms with coarse detrital sediments	Haplic Calcisols with inclusions of Petric Calcisols
B.1	Glacis slopes on fine detrital sediments	Association of Eutric Fluvisols and Eutric Regosols, with inclusions of Haplic Solonetz and Fluvic Cambisols
B.2	Other slopes on fine detrital sediments	Association of Eutric Fluvisols and Eutric Regosols, with inclusions of Haplic Solonetz and Haplic Calcisols
C.1	Flumen and Alcanadre rivers terraces on fine detrital sediments	Association of Eutric Fluvisols and Eutric Regosols
C.2	Flumen terrace on fine detrital sediments	Association of Eutric Fluvisols and Eutric Regosols
C.3	Flumen terrace on fine detrital sediments	Haplic Solonchaks
C.4.	Flumen terrace	Eutric Fluvisols
D	Bottoms on fine detrital sediments	Association of Gleyic and Gleyic-Fluvic Solonchaks; with inclusions of Salic Solonetz, Eutric Regosols and Gleyic Cambisols

Table 2. Analytical methods used in 1975, 1985/1986, and 1999

	1975	1985/86	1999
pH-water, pH-KCl	Unknown soil:water ratio	1:2.5 soil:water ratio	1:2.5 soil:water ratio
ECe	Saturated paste	Saturated paste	Saturated paste
Cl ⁻ *	Unknown	Potentiometric titration	Ionic cromatography with a Dionex 2000i/SP (Dionex, Sunnyvale, CA, USA)
SO ₄ ²⁻ *	Not analyzed	Turbidometry with a Beckman 24 spectrophotometer (Beckman Coulter, Fullerton, CA, USA)	
HCO ₃ ⁻ *	Not analyzed	Potentiometric titration	Potentiometric titration
Na ⁺ *	Unknown	Flame photometry	Atomic absortion spectrometry with a Perkin-Elmer 30303 (Perkin-Elmer, Wellesley, MA, USA)
Ca ²⁺ , Mg ²⁺ *	Unknown (jointly)	EDTA titration	

665 *The ionic contents were determined in saturated paste extracts