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Soil variability in La Violada Irrigation District (Spain): I Delineating soil units for irrigation

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ABSTRACT

The knowledge of the soil variability is essential for its hydrologic characterization, for irrigation management and planning and especially for water movement modeling. Nevertheless, the scarcity of soil information in Spain precludes its use in irrigation management and, particularly, in the on-going irrigation modernization process. The Violada Irrigation District (VID) comprises 5234 ha and is located in a semi-arid gypsum-rich region in northeast Spain. VID has been under flood irrigation since the mid-20th Century and has been modernized recently to sprinkler irrigation. Since the early 1980s water balances in VID have been based on average soil properties and bulk irrigation data. The current irrigation system provides detailed irrigation data at plot level, thus allowing for performing distributed balances (in hydrologic homogenous zones) that require detailed or semi-detailed soil information in the form of a soil map. The objective of this two-part study is to define homogeneous zones in relation to hydrological properties relevant for irrigation management, first defining the soil variability within the VID and then analyzing the soils hydrologic and salinity features (in a companion paper). The specific objectives of this paper were (i) to draw the VID semi-detailed soil map; (ii) to explain the variability of soil properties; and (iii) to map the main soil characteristics related to irrigation management. Thirty four soil pits, located on all the different geomorphological areas, were opened and described. Samples were taken from all the horizons and analyzed for chemical and physical properties. The limits of soil units were drawn with the aid of 32 additional auger holes, the data from 72 pits opened during the irrigation transformation works, and all the previous soil information available. Finally the soils were classified down to family level. The main soil formation processes in VID were carbonation and gypsification. Thirteen soil units were defined, included in five soil subgroups and six particle size families. “Fine” particle sizes were dominant along the gypsum-rich valley bottoms. Coarser textures were found on the heights and showed higher $CaCO_3$ equivalent content and no presence of gypsum accumulations. A priori, the main limitation for irrigation in the valley soils was the limited drainage (due to fine textures and reduced slope) while in the highland soils it might be constrained by their low retention capacity. The high gypsum and carbonate content of the VID soils may prevent the development of infiltration problems. The soil properties map in this work will be the basis for a companion paper delineating the hydrologic properties of the soils, the basis for improved soil water balances.

1. Introduction

The distribution of soils in the landscape and the variability in soil properties may be explained as the result, among other factors, of the parent materials, climate and land uses (Jenny, 1941); and according to Diek et al. (2014) “The knowledge of the distribution of soils is essential for an understanding of the natural environment”. The hydrologic characteristics and agroecological capabilities in a specific region are affected by these soil properties (Lee and Yang, 2010). Determining the field distribution of soil properties is thus essential for planning new irrigation schemes (usually involving relatively high investments), defining modernization plans for old schemes (FAO, 1979; Maletic

Abbreviations: ANOVA, Analysis of the Variance; AWUA, Almudévar Water User Association; CCE, Calcium Carbonate Equivalent Content; EC_e, Electrical Conductivity of the saturated paste extract; ET, Evapotranspiration; FC, Field Capacity; GC, Gypsum Content; LSD, Least Significant Difference; OM, Organic Matter; SAR, Sodium Adsorption Ratio; VID, Violada Irrigation District; WP, Wilting Point; WUA, Water User Association

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and Hutchings, 1967), or applying soil water models on irrigated areas.

The soils of semi-arid climates (where irrigation is more widespread) are usually high in gypsum and calcium carbonate, originating from the parent materials or as accumulations in the lower layers. Smith et al. (1986) pointed to the importance of gypsum content in irrigated areas. Although gypsic soils cover a small portion of World's agricultural lands (Casby-Horton et al., 2015), it is foreseeable that the gypsum irrigated land will increase due to the continuing pressure on soil and water resources in arid lands (Alexandratos and Bruinsma, 2012), calling for a better understanding of soils with high gypsum levels under irrigation.

In Spain, Poch et al. (1998) and Moret-Fernández and Herrero (2015) found that gypsum-rich soils under irrigation tend to have lower water and nutrient retention capacity. Nevertheless, the study and classification of gypsum-rich soils has lagged somewhat behind, and the descriptive terminology used before the Eleventh Edition of Keys to Soil Taxonomy (Soil Survey Staff, 2010) had been inadequate for gypsum-rich soils (Casby-Horton et al., 2015). This edition and next (Soil Survey Staff, 2014) introduced taxonomic changes and revised the gypsic horizons nomenclature.

Soil maps synthesize the physical and chemical soil properties by the delimitation of homogenous units properly defined and described. Maps of soil variability distribution should be used in soil management (Fernández-Getino and Duarte, 2015; Iñigo et al., 2012) and should grant full access to information for non-specialists in soil science. Therefore, soil maps are essential tools for running irrigation management models (for improving water use efficiency or helping in the design of modernization plans). Furthermore, the hydrologic characterization of soils is essential for the correct evaluation of irrigation return flows and pollutant loads to water bodies (Dechmi et al., 2013); for understanding the evolution of soil salinity or sodicity (Herrero et al., 2011; Herrero and Pérez-Coveta, 2005; Nogués et al., 2006) and the changes in irrigation water consumption (Barros et al., 2011a; Jiménez-Aguirre et al., 2014a; Nogués and Herrero, 2003); or for establishing the interest or necessity of irrigation modernization for each soil unit included in an irrigation district (Herrero et al., 2007).

Spain has 3.5 Mha of irrigated lands (13% of total agricultural land). The government has designed two National Irrigation Modernization Plans (MARM, 2002, 2006) with the alleged objectives, among others, of saving water and improving water quality. Nowadays, the on-going modernization process of 1.1 Mha is getting ready for evaluation. But, despite the evident utility of soil maps in the evaluation and planning of irrigation practices and irrigation modernization (and other studies), there is a lack of detailed or semi-detailed soil maps with adequate information in Spain (Nogués et al., 2000; Nogués, 2002).

Pilot areas with plentiful, high quality data (irrigation, soil and management practices) should be used to develop accurate tools (models) for the environmental and resource use efficiency evaluation of these modernization actuations. The Violada Irrigation District (VID; Fig. 1), located in a semi-arid, gypsum-rich region in the Ebro River Basin (northeast Spain) has been recently modernized (2008–09), providing abundant, detailed information on water use in the modernized system. The VID has been subject to more than twenty published studies since the 1980s in regard to crop, fertilizer, irrigation or land management with the drawback that in all of them the water balances and evapotranspiration (ET) calculations (following Feddes and Lenselink, 1994) were based on low detail level soil maps (Torres, 1983) and average soil properties (Playán et al., 2000), enough for the scarce available information about crop surface, and irrigation volumes before modernization.

After the VID modernization, disaggregated information became available (crop distribution, irrigation practices, and fertilization management) to perform distributed soil water balances over the different soil types (homogeneous zones) and actual crops in each plot, thus leading to better estimates of ET. These estimations may improve the studies performed in the VID and would help the decision-making process in irrigation planning or crop management. They could also be used in setting up distributed models of water movement in the unsaturated zone and ground-water in the VID, or other nearby areas, or other semi-arid areas with similar soil characteristics.

In addition, soil water movement models use hydraulic conductivity, infiltration and soil water retention as essential input data in agricultural, hydrological and environmental studies (Minasny and Hartemink, 2011; Nguyen et al., 2015). The inaccurate estimation of these soil hydrologic properties may influence the outputs of the modeling process and hence the quality of the research. Therefore, these hydrologic properties need to be carefully assessed (Botula et al., 2012; Nguyen et al., 2015; Rawls and Brakensiek, 1989; Tombul et al., 2004; Thony et al., 1991; Valdés-Abellán et al., 2015). The distribution of these properties should be obtained from detailed soil information from soil maps.

The present two-part study focused on establishing the soil hydrologic features in the VID (5234 ha) and their variability over the landscape so that they can be used as an aid in irrigation management (under the new irrigation system) and in the application of distributed soil water models (making use of the distributed information on irrigation and fertilizer application available after the modernization). This work is aimed at improving the soil water balances in the VID, allowing for a comparison of district level water balances and water use before and after the modernization.

The objective of the present paper is to characterize the variability within the VID of the soil properties of major interest for irrigation management. The specific objectives are: (i) to draw (as a required preliminary step) the VID soil map down to family level; (ii) to explain the variability of soil properties in relation to forming processes and parent materials (gypsum and calcium carbonate); and (iii) to map the main soil characteristics related with irrigation management. As a result, the VID soil map and relevant thematic maps will be outlined.

The output of this paper will be the basis for a companion paper dealing in depth with the soil hydrologic and salinity features related to the irrigation within the soil units defined in the VID. Additionally, with these results a deeper analysis of salinity and sodicity in the VID will be carried out.

2. Site description

The Violada Irrigation District (VID; 5234 ha) is located in the Ebro River Basin, in northeast Spain, between 41° 59′N and 42° 04′ N and 0° 32′W and 0° 40′ W. The altitude ranges from 345 m above sea level at the gauging station n° 230 (Ebro River Authority) (Fig. 1) to 414 m at some elevations. The study area comprises the lower reaches of La Violada Gully Basin (19,637 ha), upstream of the gauging station. It is contoured by three irrigations canals: Monegros to the northeast, La Violada to the west, and Santa Quiteria to the south. Four gullies originating from the Northern drylands define the basis of the drainage network in VID, joining to the South of the VID to make up La Violada Gully (Fig. 1).

2.1. Climate

The climate is dry, subhumid and mesothermic. The mean annual precipitation was 458 mm for the period 1964–2014, with a clear decreasing trend (19 mm per decade). The precipitation is concentrated in spring and autumn and is lower in summer and winter. The driest year in this period was 1998 with 228 mm and the wettest 1969 with 819 mm. The mean temperature for the period was 13.5 °C with mean monthly maximum temperature of 30.5 °C and mean monthly minimum temperature of 0.7 °C. The hottest month is July (mean temperature of 22.8 °C) and the coldest is January (mean temperature 5.0 °C). The reference evapotranspiration (ET_0; Penman-Monteith) was 1166 mm for the period 1995–2008 (Barros et al., 2011a).

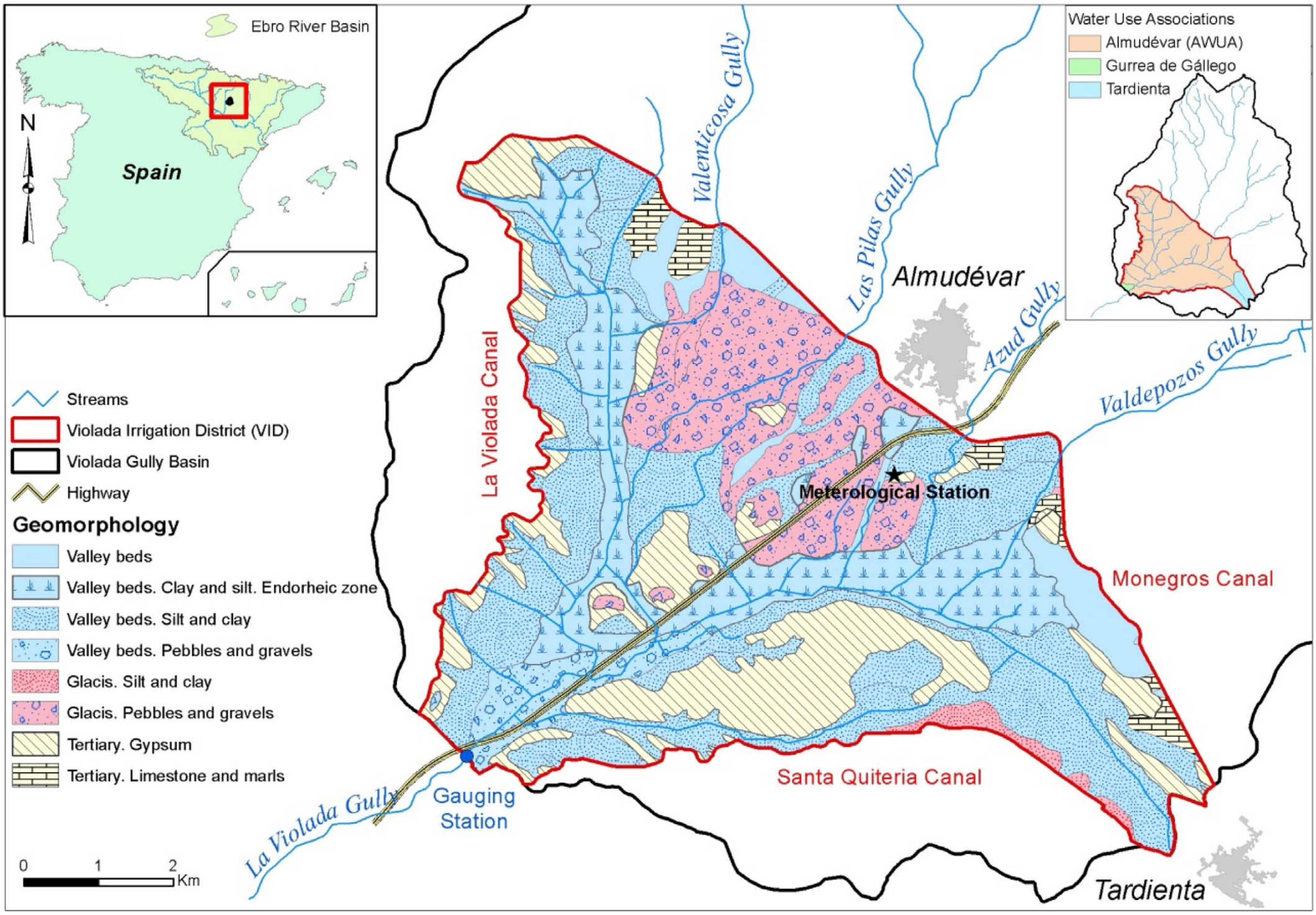

Fig. 1. Location and simplified geomorphological map of the La Violada Irrigation District (VID) (Source: ITGE, 1995a, 1995b) within La Violada Gully Basin. The Water User Associations and the main gullies in VID are drawn in upper-right corner inset.

2.2. Geology and geomorphology

The Ebro River Basin was formed during the Tertiary as eroded materials from the surrounding mountains deposited around and in the interior sea located in what is currently the center of the basin (Pinilla Navarro, 1968; Quirantes, 1978). The evaporation from the sea under very hot conditions led to the precipitation of calcite and gypsum and finally halite to the center of the Basin. The Quaternary relief consists mainly of alluvial deposits formed after the opening of the ancient sea to the Mediterranean.

The Violada Gully Basin is located in the middle reaches of the Ebro River Basin and presents extensive gypsum and carbonate deposits in the higher areas. Upstream of the gauging station, the basin is divided in two parts by the Monegros Canal (Fig. 1). The north-dryland part is dominated by Tertiary calcareous rocks and clay, with fine Quaternary materials at the valley fills (alluvial deposits of sand, clay and silt along the four principal gullies: Azud, Las Pilas, Valdepozos and Valenticosa). The VID is located south of the Monegros Canal, the main materials are Quaternary clays and silts along the valley beds with some Tertiary calcite and gypsum on the heights (ITGE, 1995a,b).

Three geomorphological areas can be defined in VID (Fig. 1): (1) Valley beds associated with the principal creeks that drain to the gauging station and occasionally with wide waterlogged areas due to irrigation (Trébol, 1988); (2) Glacis and alluvial fans west and south of the town of Almudévar, characterized by calcareous gravels with sandy matrix and calcareous cement and gypsum particles; (3) Residual finger-like highlands formed over Tertiary gypsum materials in west VID (along La Violada Canal) and over the southern highlands dominated by massive gypsum sometimes crystallized forming nodules interspersed with sand and gypsiferous silt. Other Tertiary residual areas are conformed by sediments of limestone and marl loam along Monegros Canal and over the little hillocks distributed on a line from north-east to south-west along the highway crossing the district.

2.3. Irrigation system

The VID covers 5234 ha (3985 ha irrigated in 2014), 92% under modernized sprinkler irrigation and 8% under traditional surface irrigation. There are three Water User Associations (WUA) on VID (Fig. 1): the Almudévar Water User Association (AWUA) with practically its entire surface (98%) inside the VID and contributing to 92% of VID's irrigated surface; and Tardienta and Gurrea de Gállego WUA (7% and 1% of VID irrigated area respectively).

Since the Monegros Canal was built in the 1920's (until 2008–2009, when the AWUA was modernized), the three WUA have operated flood irrigation systems. The irrigation establishment brought along deep changes in topography, soil-water relationships, vegetation, and agrarian landscape, as well as new infrastructures (roads, pathways, canals, and ditches) (Torres, 1983). The beginning of irrigation evidenced the difficult drainage conditions of the district (derived from the semi-endorheic conditions of the area) and led to the installation of subsurface drainage systems in the 1940's (De los Rios, 1966) that many farmers have been complementing in their own plots until now.

The AWUA was modernized to pressurized irrigation in 2008–09, leading to a sharp decrease in outflow and to an improvement in agronomic efficiencies and in the quality of the irrigation return flows (Jiménez-Aguirre et al., 2014a, 2014b). Also, the irrigation modernization implied additional changes on topography (terrace removal) and

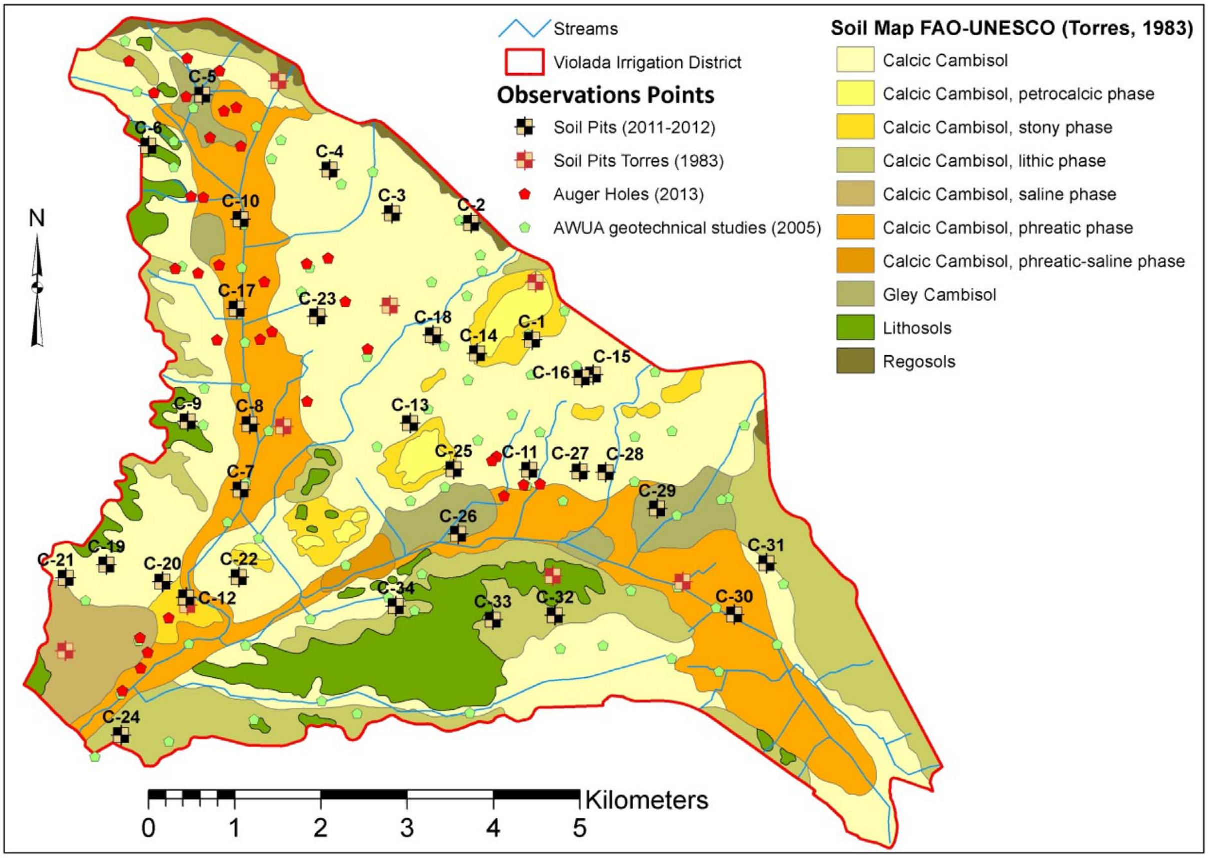

Fig. 2. Distribution of all observations used for the soil map in the Violada Irrigation District: 34 Soil pits done in 2011–12, 32 auger holes (2012 – 13), 10 previous soil pits (Torres, 1983), and 79 observations from two AWUA geotechnical studies (TerraControl, 2005a, 2005b); over the Soil Map of the Violada Irrigation District made by Torres (1983) according to the FAO classification system.

agrarian landscape (land consolidation), and new infrastructures: construction of the new elevated Violada Canal (in 2002), burying of secondary drainage ditches and building of new roads. The other two WUA's maintain their traditional surface irrigation systems.

In the new AWUA irrigation system, water is delivered from five reservoirs to each hydrant and the irrigation in each hydrant is controlled through telecontrol software. This software allows for retrieving actual irrigation information (day, time and volume) applied at hydrant (almost plot) level.

2.4. Previous soil studies in the area

Torres (1983) made a soil map of VID (Fig. 2) system with a low sampling intensity (10 pits for 5234 ha, two of them outside the VID) and supported in low-scale information. Four soil units were defined under the FAO soil classification system in use in the date (FAO-UNESCO, 1974): Lithosols, Regosols, Calcaric Cambisols, (with 6 different phases: Petrocalcic, Stony, Lithic, Saline, Phreatic and Phreatic saline) and Gley Cambisol. With the available information, the soils lie in the same classes under the revisited World Reference Base for Soil Resources (WRB; IUSS Working Group WRB, 2015). Additional soil information for particular plots was collected by Campillo (1987), Esquisábel (1987), and Trébol (1988) for analyzing nutrient and energy fluxes on the main crops.

Slatni (1996), Faci et al. (2000) and Playán et al. (2000) measured the soil water retention properties (FC, and WP) in 92 points [one compound sample (0–1.2 m) per point] scattered throughout the AWUA. The methodology followed did not account for the high gypsum content in VID and may have resulted in overestimation of the water holding capacity of the soils (Artieda et al., 2006; Herrero et al., 2009).

The combination of this information allowed Isidoro (1999) and Isidoro et al. (2004) to define 5 hydrological homogeneous soil classes aggregated by FC, WP and soil depth, to calculate soil water balances from 1995 to 1998. Later, Barros et al. (2011a) checked that the balance results with the five-class disaggregation of the VID were not different from the results using average soil hydrological values for the whole VID, because the water balances were made with the same irrigation practices and crop distribution for the 5 classes except for the lower Available Water Capacity (AWC) class. Barros et al. (2011a) also extended the soil water balances from 1995 to 2008. The results were the basis for the water balance studies in VID (Isidoro, 1999; Isidoro et al., 2004; Barros et al., 2011a, 2011b).

3. Materials and methods

From November 2011 to April 2012, thirty-four georeferenced pits were opened by a backhoe down to 2 m, impenetrable layer, or phreatic level (Fig. 2). The pit locations were chosen by relief stereoscopic photo-interpretation using the element analysis method developed by Buringh (1960) with aerial photographs, scale 1/33000. This analysis was supplemented with the old soil maps information (Torres, 1983) and the geologic and geomorphological maps (ITGE, 1995a, 1995b). The pits were labelled with the letter “C”.

The environmental and physiographic characteristics, location on the local landscape, vegetation, and anthropogenic factors from the 34 pits were described and recorded. The genetic horizons were morphologically defined following the criteria SINEDARES from the manual of Edaphological and Agronomical Information System (CBDSA, 1983) of the Ministry of Agriculture of Spain. One disturbed sample per horizon was taken, identified, photographed, dried at ambient temperature and sieved through 2 mm mesh for laboratory analysis.

Texture was determined on the fine fraction by the pipette method

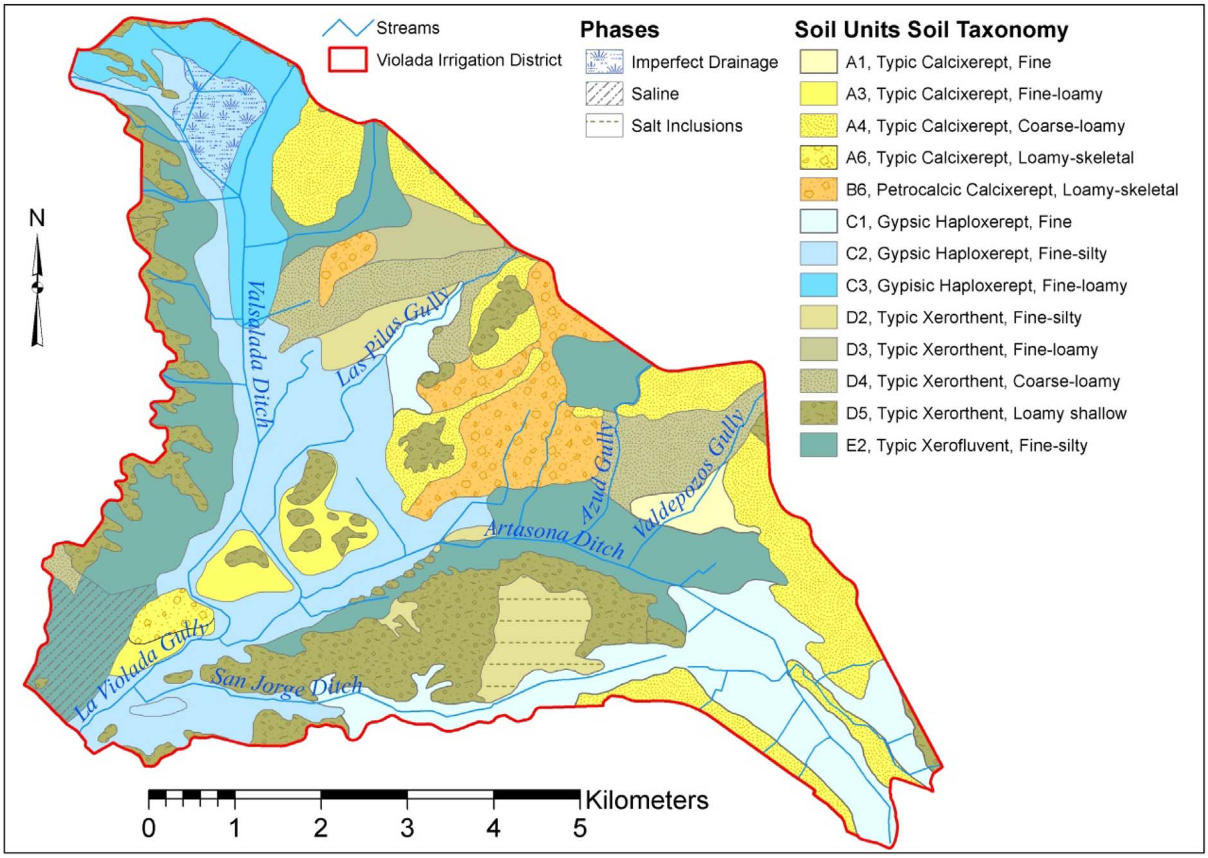

Fig. 3. Soil Map of La Violada Irrigation District (VID), classified down to the family level (Soil Taxonomy; Soil Survey Staff, 2014) and drainage ditches in the irrigated area.

(Soil Survey Staff, 2011) into the clay (particles with diameter < 0.002 mm), silt (between 0.002 and 0.05 mm) and sand (0.05–2 mm) fractions. Calcium carbonate equivalent (CCE) was measured using a Bernard calcimeter. The gypsum content (GC) was determined according to the method proposed by Artieda et al. (2006). Organic matter (OM) was determined by Walkley-Black method. Field capacity (FC) and wilting point (WP) were measured using the Richard membrane (Soil Moisture Santa Bárbara, California) drying the sample at 105 °C (48 h) or 40 °C (5 days) if the sample had gypsum (Artieda et al., 2006; Herrero et al., 2009). The pH was measured in a 1:2.5 soil:water suspension and the soil electrical conductivity in the soil extract 1:5 ($EC_{1:5}$). The electrical conductivity (EC_e) and the concentration of the main ions were measured in the saturated paste extract and the Sodium Absorption Ratio (SAR_e) calculated (USSLS, 1954).

A total of 110 samples were analyzed and 54 non-disturbed samples were taken for measuring the bulk density. These samples were collected in 98 cm^3 cylinders, dried at 105 °C during 48 h (or 40 °C during 5 days if gypsum present) and weighted before and after drying.

The soil profiles were classified according to the *Keys to Soil Taxonomy* (Soil Survey Staff, 2014), down to family level. Due to the original materials in the VID, the main characteristic at subgroup level was the presence of calcium carbonate and gypsum secondary accumulations in deep horizons (Inceptisols order) as well as cementation processes. For the Entisol order the distinctive character was the presence of a fluventic horizon. The subgroups were labelled with capital letters (A to E). The particle-size class at the control section (from the bottom of the A horizon to 100 cm deep) was used to differentiate at the family level. The different Particle Size Families established were identified by numbers (1 to 6): the higher the number, the coarser the particle size. If dissimilar characters, too small to be delineated separately, but useful in irrigation management were found, phases or inclusions were defined following *Soil Survey Manual* (Soil Survey Division Staff, 1993).

The soil unit delimitation was made with the information obtained by relief stereoscopic photo-interpretation of the aerial photographs and used to draw the preliminary boundaries. Thirty-two auger holes (Fig. 2) were opened and georeferenced to help delineate the unit boundaries and to obtain further descriptive information and additional laboratory determinations (FC and WP). All that information, combined with the previous soil map of Torres (1983) and two geotechnical studies (79 observations points) (TerraControl, 2005a, 2005b) made for the AWUA Modernization Project, had been used to refine soil unit boundaries. The results were integrated on a Geographical Information System using the software ArcGIS Desktop 10.3 to delineate the soil map and elaborate thematic maps (calcium carbonate, gypsum and organic matter) for each soil horizon.

The differences in the main parameters (texture, calcium carbonate, gypsum, field capacity, wilting point, organic matter) among the defined groups or at different depths related to the master horizon were tested through an analysis of the variance (ANOVA), with the group or horizon means compared by the Least Significant Difference (LSD) test. Also, a Factor Analysis was performed on the observations of each horizon defined in each pit using as variables the FC and WP; the clay, silt, and sand fractions; and the CCE, GC, and OM. The variables were standardized so that they had the same weight in the factor definition process. The main principal components selected were rotated by the varimax method to achieve mutually independent (orthogonal) factors (Harman, 1967).

4. Results and discussion

The VID soils present little or no edaphic-development (inceptisols or entisols). The main pedogenic process identified were carbonation (and cementation), gypsification and to a lesser extent, gleyfication.

Table 1
Surface area in hectares (and percentage of the VID) of the subgroups (A: Typic Calcixerept, B: Petrocalcic Calcixerept, C: Gypsic Haploxerept, D: Typic Xerorthent and E: Typic Xerofluvent) and particle size families [1: Fine, 2: Fine-silty, 3: Fine-loamy, 4: Coarse-loamy, 5: Loamy (shallow soils) and 6: Loamy-skeletal] defined at the Violada Irrigation District. The dominant units are highlighted.

		Particle size family					
Subgroup		1	2	3	4	5	6
A	859 (16)	56 (1)		127 (2)	638 (12)		38 (1)
B	308 (6)						308 (6)
C	1794 (34)	586 (11)	946 (18)	263 (5)			
D	1317 (25)		196 (4)	67 (1)	339 (6)	714 (14)	
E	955 (18)		955 (18)				
Total	5234	642 (12)	2097 (40)	457 (9)	977 (19)	698 (13)	346 (7)

Table 2
Descriptions of the subgroups described in the VID.

			Typic/petrocalcic Calcixerept (A/B)	Gypsic haploxerept (C)	Typic xerorthent (D)	Typic xerofluvent (E)
Location			Glacis Alluvial fans Hillocks	Valley bottoms	Highlands Hillocks	Valley bottoms Colluvial slopes
Particle size family			Fine Fine-loamy Coarse-loamy Loamy skeletal	Fine Fine-silty Fine-loamy	Fine-silty Fine-loamy Coarse-loamy Loamy Shallow	Fine-silty
Drainage			Good exc. fine class	Good with exceptions	Good or moderate	Moderate
Horizon sequence			A-Bk(m)-(C)	A-Bw-C	A-Bw/By-C	A-Bw-C/Cy
Soil depth			> 1.00 m exc. skeletal soils (0.70 m)	> 1.20 m	> 1.00 m exc. D5 (0.50 m)	> 1.50–2.00 m
Horizon lower limit range		A	0.30–0.50 m	0.15–0.55 m	0.15–0.50 m	0.35–0.45 m
		B	0.70–1.65 m	0.65–1.70 m	0.25–1.10 m	0.90–2.00 m
		C	1.35–1.50 m	> 1.70 m	1.00–1.50 m	> 1.40 m
$CaCO_3$ equivalent			Very high	High	High	High
$CaCO_3$ accumulations			Nodules Pseudomicelya Pendants	–	–	–
Gypsum content			Low	High	Medium-high	Low
Gypsum accumulations			Deep nodules	Vermiform	Superficial or deep vermiform	Very deep nodules and vermiform
Dissimilar characters (pit soil)				Low drainage (C-5)	Salt inclusions (C-32) Saline phase[a]	Buried soils (C-19)
Horizon saturated soil paste extract	EC_e	A	1.90 dS/m	2.27 dS/m	4.38 dS/m	1.70 dS/m
		B	2.31 dS/m	2.58 dS/m	4.87 dS/m	2.33 dS/m
		C	3.03 dS/m	2.82 dS/m	2.77 dS/m	3.58 dS/m
	SAR_e	A	1.02 $(mmol_c/l)^{1/2}$	0.60 $(mmol_c/l)^{1/2}$	2.76 $(mmol_c/l)^{1/2}$	0.63 $(mmol_c/l)^{1/2}$
		B	1.65 $(mmol_c/l)^{1/2}$	0.65 $(mmol_c/l)^{1/2}$	4.63 $(mmol_c/l)^{1/2}$	0.81 $(mmol_c/l)^{1/2}$
		C	1.59 $(mmol_c/l)^{1/2}$	0.49 $(mmol_c/l)^{1/2}$	–	1.10 $(mmol_c/l)^{1/2}$

[a] In Torres (1983)

Carbonation was evident by CCE over 40% in whole VID and by the presence of secondary $CaCO_3$ accumulations (nodules, pseudomycelia and pendant were found). The high levels of GC over 60% in some horizons and the presence of gypsum secondary accumulations pointed to gypsification processes. The texture of the soils in VID was generally fine and high in silt, particularly in the deeper horizons (horizon B had around 60% of silt on 77% of the VID surface).

The soils in VID were classified into five subgroups according to the Soil Taxonomy classification (Soil Survey Staff, 2014): Typic Calcixerept (A), Petrocalcic Calcixerept (B), Gypsic Haploxerept (C), Typic Xerorthent (D), and Typic Xerofluvent (E) (Fig. 3; Table 1). The most prevalent subgroup was the Gypsic Haploxerept followed by Typic Xerorthent.

In the same way, six particle size families were defined: Fine (1), Fine-silty (2), Fine-loamy (3), Coarse-loamy (4), Loamy (shallow soils) (5) and Loamy-skeletal (6). The prevalent family was Fine-silty, followed by the Coarse-loamy. Some soils at the gypsiferous heights were shallow due to the absence of a B horizon and the slight depth to the C horizon, but within the Loamy family. The coarser particle size family found was Loamy-skeletal southwest of the town of Almudévar.

The combination of soil classification subgroups and families outlined the soil map of VID with 13 soil taxonomic units (Fig. 3; Table 1).

The more extended, representative soil units in VID were Typic Xerofluvent Fine-silty (E2; 955 ha, 18% of the total area) and Gypsic Haploxerept Fine-silty (C2; 946 ha, 18%), and were very similar in their profile description and properties. C2 and E2 together covered 1901 ha (36% of VID area) at the valley bottoms and represented the main share of the irrigated area. The difference between these two units was the absence of a gypsic horizon in the unit E2.

4.1. Description of the subgroups

Table 2 summarizes the description of the soil subgroups in the VID. The Calcixerept subgroups (A and B) were found on the glacis and alluvial fans in the northeast of VID along the Monegros Canal, and on the hillocks along the north side of the highway. Gypsic Haploxerept (C) is the greatest soil subgroup in surface area together with the Typic Xerorthent (D). C was found at the valley bottoms all along the Valsalada Ditch and the lower reaches of Las Pilas Gully and Artasona and San Jorge ditches (Fig. 3). The D subgroup was located in two

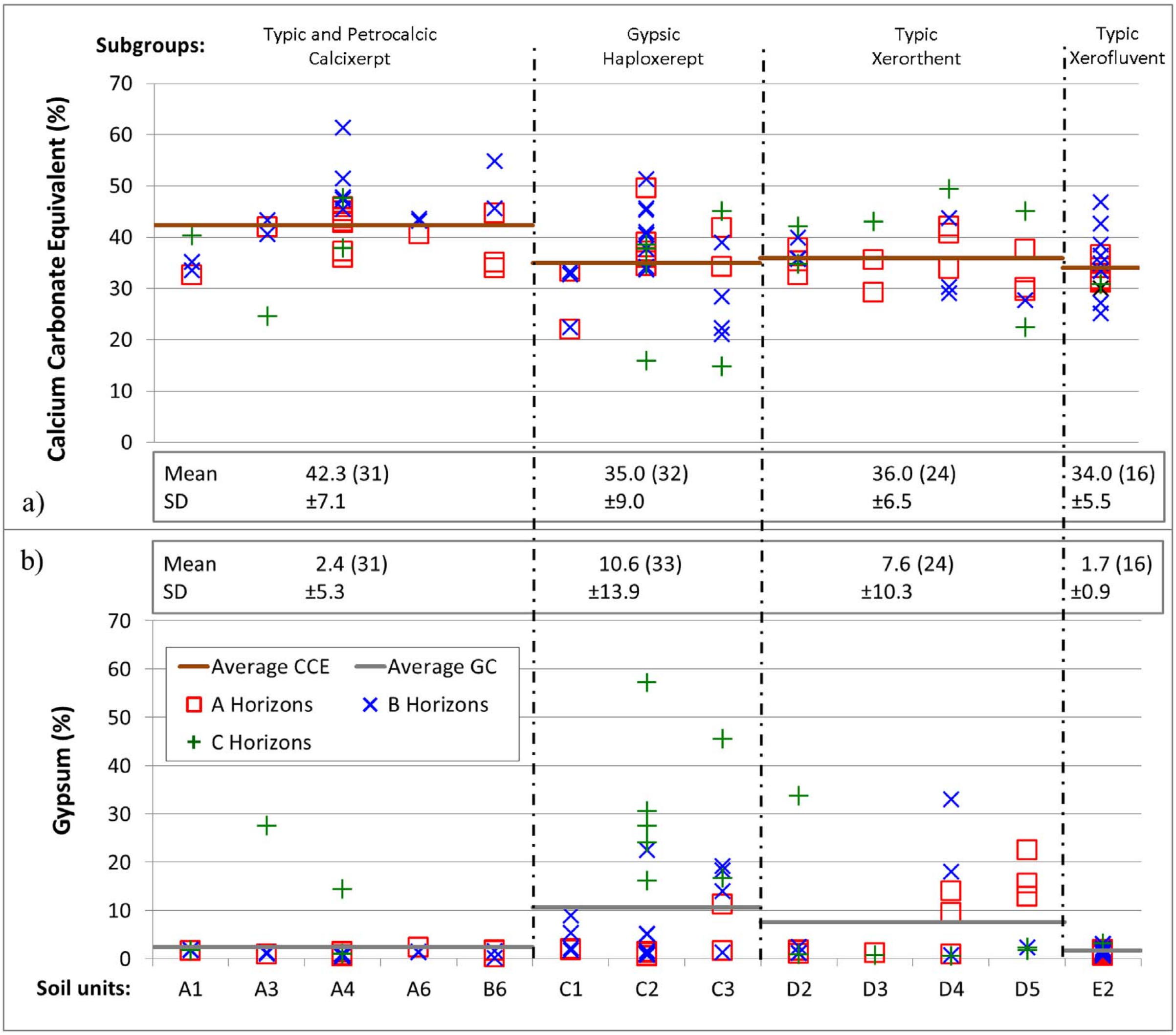

Fig. 4. Calcium carbonate equivalent (a) and Gypsum content (b) distribution for all the samples at family level. Table inset: mean, standard deviation (SD) and number of samples (in brackets) in each subgroup.

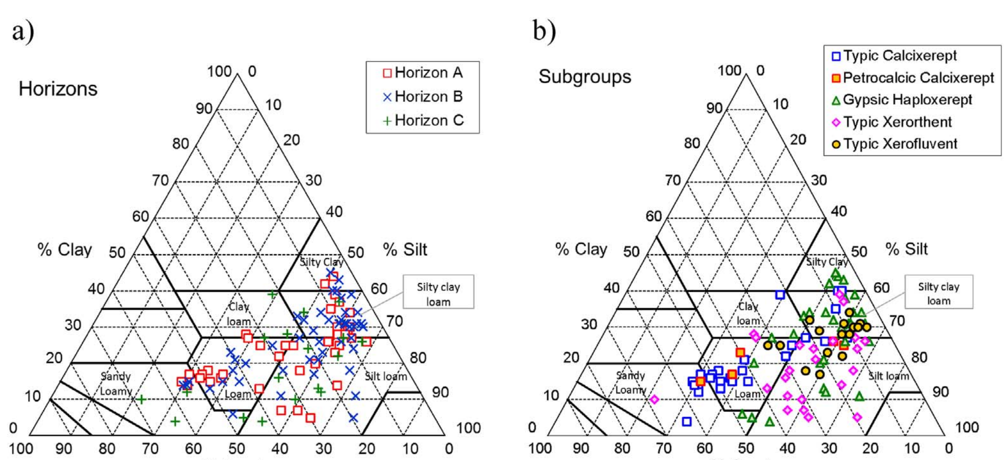

Fig. 5. Texture triangles by horizons (a) and by subgroups (b) of all samples.

different areas: (i) Tertiary residual soils: the finger-like highlands along the Violada Canal, the southern highlands of VID, and the linear calcareous hillocks along the highway, and (ii) as elevated areas inside the glacis southwest of Almudévar. The fifth group is the Typic Xerofluvent (E) located at some valley bottoms (next to the Monegros Canal and Artasona ditch) and at La Violada Canal colluvial slopes in the west.

Four dissimilar characters were found (Table 2): (i) imperfect drainage phase (gleying) in the northwest of the VID (C2 unit; soil pit C-5; Fig. 2) was evidenced by redox processes (red and black spots in

Table 3
Average sand, silt and clay fractions and, textural class for the five soil subgroups described in VID. Different letters show significant differences between subgroups by the LSD method test ($P < 0.05$).

Subgroup	Sand	Silt	Clay	Textural class
A: Typic calcixerept	38.7 a	40.8 a	20.5 a	Loam
B: Petrocalcic calcixerept	33.5 ab	45.2 a	21.3 ab	Loam
C: Gypsic haploxerept	16.1 c	56.4 b	27.5 b	Silty-clay-loam
D: Typic xerorthent	24.1 bd	56.2 b	19.7 b	Silty-loam
E: Typic xerofluvent	15.2 cd	57.8 b	27.0 b	Silty-clay-loam

the soil matrix); (ii) salt inclusions at the gypsum southern highlands (D2 unit; pit soil C-32: EC_e of 23.0 dS/m for the A horizon and 12.9 dS/m for the B horizon, with evidences of salinity on cereal development); (iii) saline phase (E2 unit) at southwest VID [EC_e at the B horizon of 9.9 dS/m (Torres, 1983)]; and (iv) buried soil (E2; pit soil C-19; Fig. 2) due to the recent AWUA modernization works.

4.2. Soil variability within VID

4.2.1. Calcium carbonate equivalent and gypsum content

The analysis of the variance showed no significant differences in CCE ($p > 0.05$) between horizons. Fig. 4a shows the high levels of CCE in all the horizons. The maximum level (61.4%) was found in the unit A4 (B horizon) and the minimum (14.8%) in the C3 unit (C horizon). There were significant differences ($p < 0.001$) in GC between horizons. The GC (Fig. 4b) increased with depth (except in the D subgroup due to the high surface GC in D4 and D5 units), reaching a maximum of 57.2% in the C horizon of a pit in the C2 unit.

4.2.2. Texture and bulk density

The ANOVA (for the individual factors subgroup and horizon and for both factors combined) showed no significant differences in texture ($p > 0.05$) between horizons, which means that there were no changes in the sand, silt and clay content with depth (Fig. 5a); but showed highly significant differences ($p < 0.01$) between the subgroups

Table 4
Correlation coefficients between the soil properties and factors.

Soil property	Texture factor	Carbonates-Gypsum factor	Organic Matter factor
Sand	− 96.5	6.2	− 6.1
Silt	85.9	25.0	− 12.9
Field capacity (FC)	89.3	5.4	30.8
Wilting point (WP)	81.2	− 6.3	43.0
Calcium carbonate equivalent (CCE)	–28.0	− 82.7	− 18.0
Gypsum (GC)	− 16.4	89.0	− 21.7
Organic matter (OM)	12.6	− 2.7	93.4

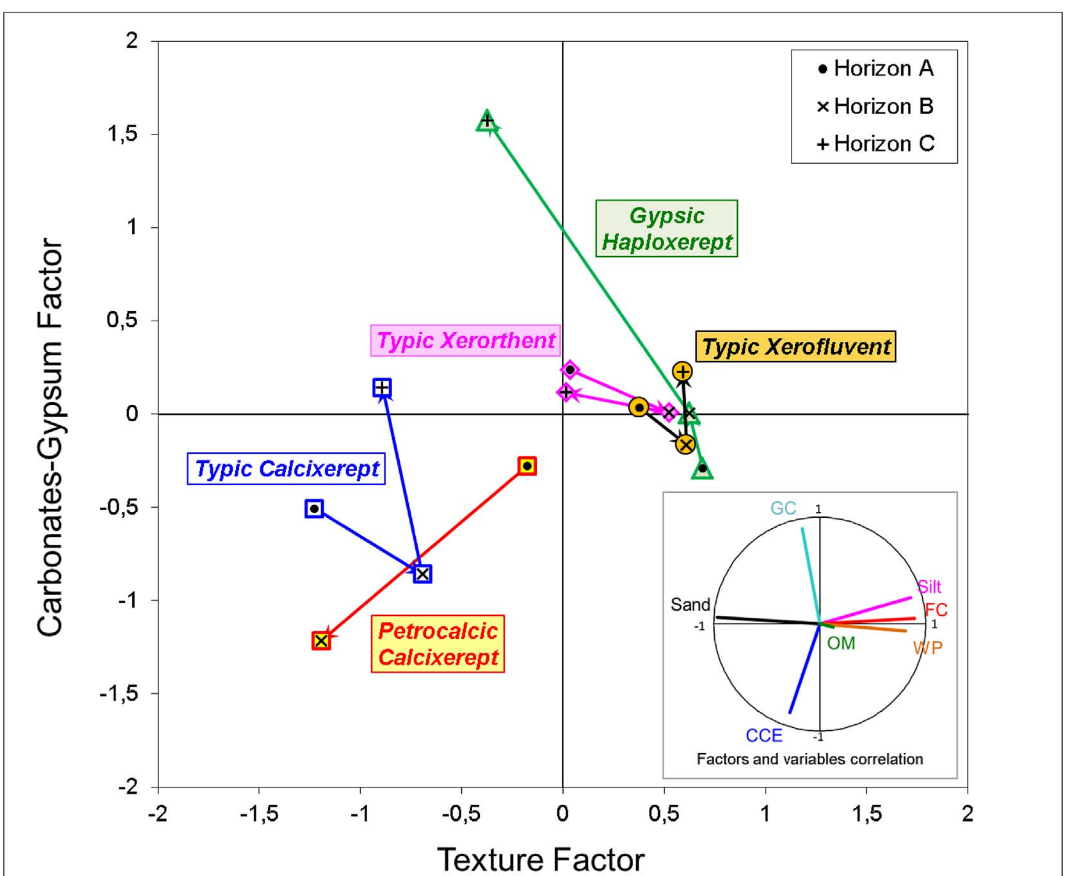

Fig. 6. Average scores of each horizon in the soil subgroups identified in the VID in the two first factors. Arrows show the sequence of horizons in each subgroup. The circle at the bottom-right corner (radius 1) shows the coefficients of correlation of the variables used in the analysis with the two first factors.

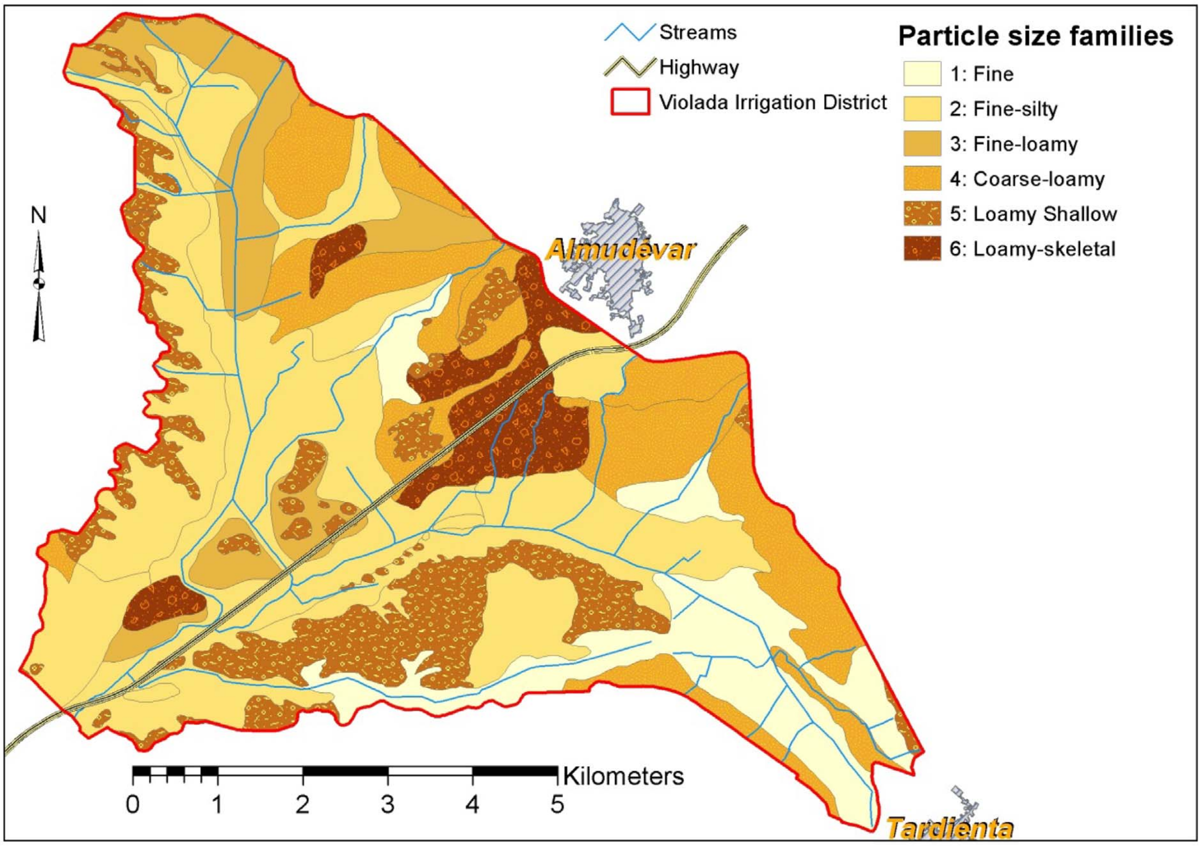

Fig. 7. Map of particle size families in the Violada Irrigation District.

(Fig. 5b; Table 3). Although the silt fraction was the main fraction to all VID soils, Typic Calcixerept (A) and Petrocalcic Calcixerept (B) had sandier texture (over 30% sand fraction and close to the silt percentage) than the other subgroups; whereas the Gypsic Haploxerept (C), Typic Xerorthent (D) and Typic Xerofluvent (E) presented higher values of silt content (over 50%) compared to sand and clay (around 20%; Fig. 5).

The average bulk density was 1.50 g/cm^3 for A horizons (1.39 g/cm^3 for the uppermost A sub-horizon and 1.55 g/cm^3 for the deeper A sub-horizon when differentiated), 1.54 g/cm^3 for B horizons and 1.43 g/cm^3 for the C, without significant differences between the A and B horizons (with enough data for comparison) but with significant differences between B and C horizons (with the few C horizon samples available for comparison). The slight increase in bulk density from A to B and the decrease to C along with the high bulk densities found in the whole profile, point to an initial process of compaction. No significant differences between the subgroups or particle size families were found. The high bulk density for all horizons seems to point to a process of compaction, possibly due to trafficking and mechanization (that may be worsened by the limited drainage of some areas; Porta et al., 1994) or induced by the 60-year long surface irrigation in VID.

4.2.3. Soil properties

The variability of soil properties in VID was explained by the factor analysis performed on field capacity (FC), wilting point (WP), percentage of sand and silt (clay excluded to avoid co-linearity), GC, CCE and OM content. This analysis showed that the 86.4% of the variability was related to three independent factors, linked to (1) texture, (2) chemical properties and (3) organic matter.

The first factor (accounting for 50.4% of the variance) was related positively to FC, WP and silt and negatively to sand (Table 4); therefore it was labelled "Texture Factor", taking high positive values in the finer-textured samples, and being negative in the coarser-textured samples. The second factor (Carbonates-Gypsum Factor; 22.7% of the total variance) was found positively correlated to gypsum, and negatively to calcium carbonate, showing that samples high in gypsum were generally low in calcite and vice versa. Finally, the third factor (OM Factor; 13.3% of the variance) was strongly correlated only to OM, showing that the OM content was independent of the textural or chemical properties of the samples.

The average values of the first two factors for the horizons of each soil subgroup are presented in Fig. 6. Deep horizons had higher gypsum content (except for the Typic Xerorthent subgroup with very similar contents in all horizons). This relationship was especially evident for the Gypsum Haploxerept subgroup and to a lesser extent Typic Calcixerept subgroup (where gypsum was minimum for the B horizons, increasing again in the Cs). On the other hand, Calcixerept subgroups (Typic and Petrocalcic) have shown coarser textures (lower water retention capability) and low gypsum content. The low variability between the horizons in the Typic Xerofluvent subgroup was also evident, with texture, GC and CCE constant down the profile.

4.3. Thematic maps

4.3.1. Particle size families map

The map of the particle size families at VID is showed in Fig. 7. The "fine" classes (Fine, Fine-silty and Fine-loamy) were dominant and spread mainly along the valley bottoms: Fine-silty was the major particle size class, covering 40% of the VID surface (Table 1), along Valsalada and Artasona ditches; the Fine class represented the 12% of the area, (on the headwaters of the Artasona Ditch and along San Jorge Ditch); and the Fine-loamy class was defined on 9% of the area (upper reaches of Valsalada Ditch and other lowlands in the north of VID). Together, the fine classes spread over almost two thirds (61%) of the VID.

The second class in importance (19%) was the Coarse-loamy. It was associated to the Calcixerepts and Xerorthents located at the glacis and

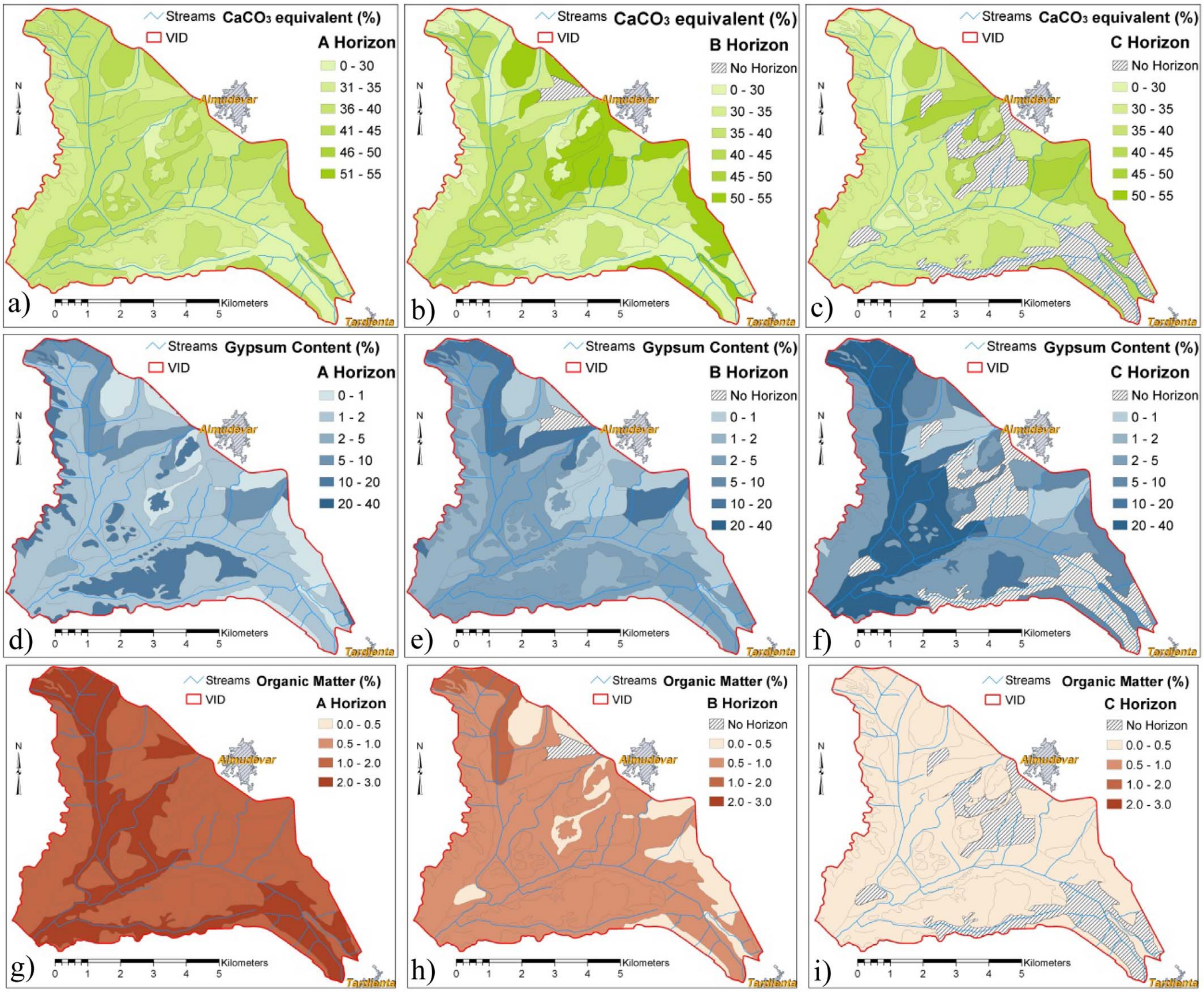

Fig. 8. Maps of calcium carbonate equivalent (CCE), gypsum content (GC) and organic matter (OM) for each soil horizon over the Violada Irrigation District.

at the slopes of the Tertiary residual hillocks along the highway.

The higher zones presented the coarser classes: Loamy (shallow soils) (13%; on top of the Tertiary residual hillocks) and Loamy-skeletal, the coarsest class, located on the glacis SE of Almudévar (7%). These areas were evidenced in the field by more coarse elements and crushed stones.

Due to the prevalence of the fine classes, the tillage at VID is not difficult except on the coarser classes. Coarser soils were often dedicated to fruit trees and non-irrigated crops (Torres, 1983), or even used as quarries (Loamy-skeletal zone). On the other hand, these fine classes can also produce some tillage problems after heavy rains, as was observed during the field works, and often have difficult drainage in the lower lying areas, requiring an artificial drainage network (Isidoro, 1999; Torres, 1983).

4.3.2. Calcium carbonate equivalent and gypsum content maps

The CCE, GC and OM over the VID and their evolution with depth (A, B and C horizons) are showed in Fig. 8 and 9. The whole VID had high levels of CCE over 27.7% (Fig. 8a,b,c). The distribution of the surface CCE (A horizon; Fig. 8a) was very homogenous, likely due to the $CaCO_3$ mobilization to lower layers (Fig. 9a). On the other hand, big differences in CCE appeared at the B horizons (Fig. 8b) as $CaCO_3$ precipitated and accumulated at different rates in different soil units. The highest CCE's (50.7 and 50.3%) were found on the glacis close to Monegros Canal (Calcixerepts: soil units A4 and A6, respectively) they also correspond with the coarsest particle size families. High carbonate levels in the B horizon (41.1%) were also found along the Valsalada Valley, on the Gypsic Haploxerept Fine-silty unit (C2). The C horizons (Fig. 8c) presented lower CCE except for the Xerorthent units (D2; D3 and D4) likewise located at the glacis and along the Monegros Canal.

The distribution of GC was in opposition to CCE (Fig. 9b), as indicated by the factor analysis too. Surface gypsum presented big differences (Fig. 8d), from 17.0% to 0.8%. About 74% of the VID surface was low or medium-low (< 2%). High values of gypsum appeared on shallow soils (D5) with coarser particle size classes (not skeletal) at the heights (along Violada Canal, and on the Tertiary hillocks along the highway and in south VID) usually as gypsum stones or outcrops. The highest value in an A horizon, found in the Typic Xerorthent Loamy (shallow) soil unit (D5), corresponded with one of lowest CCE (Fig. 9a and b). The GC increased in the B horizon (13.2% in C3 and 17.3% in D4) (Fig. 8e) except in the Calcixerept units, where GC remained similar to the A horizon or decreased slightly. The GC increased clearly in the C horizons (Fig. 8f), (average 31.1% in C2 and C3) reaching maximum levels of 57.2% at one C2 pit (Fig. 4), while the CCE decreased to around 30% in the same units, the lowest in VID.

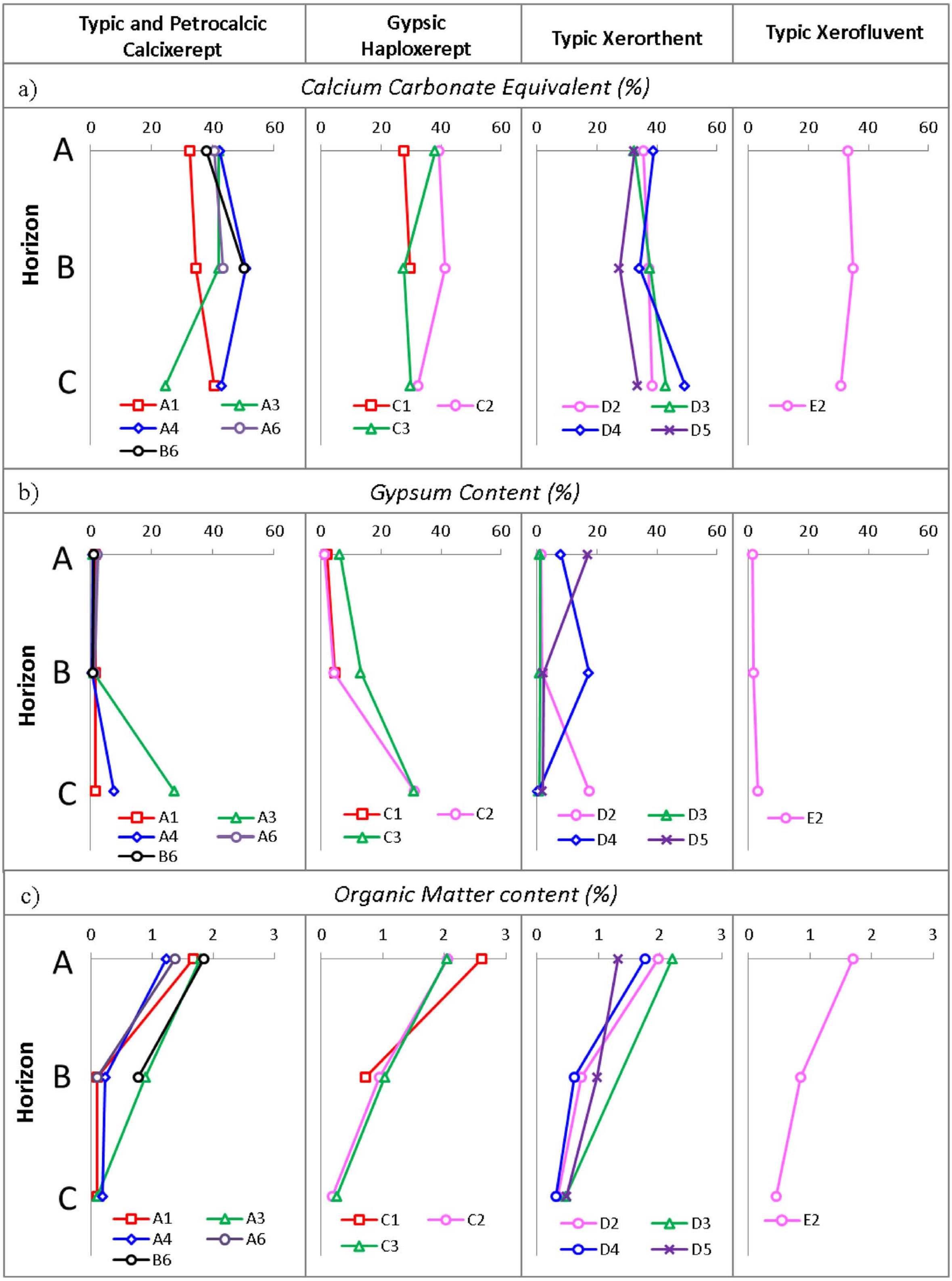

Fig. 9. Average calcium carbonate equivalent (CCE), gypsum content (GC) and organic matter (OM) for the horizons in each soil subgroup defined in the VID.

4.3.3. Organic matter content map

The OM was low (2–3%) on surface horizons (Fig. 8g) and lower, even negligible, for B and C horizons (Fig. 8h and i). In the surface horizons, the Gypsic Haploxerept Fine unit (C1) presented the highest OM (2.6%), the rest of Gypsic Haploxerept units (C2 and C3) and Typic Xerorthent Fine-silty and Fine-loamy (D2 and D3) also had values over 2% (Fig. 9c). These units (that corresponded to the valley bottoms) presented hydromorphic evidences (bad drainage, redox spots and grey soil color) and these conditions may have inhibited the organic matter mineralization and caused higher OM contents.

The subsurface horizons presented lower OM, especially in some Typic Calcixerepts units (A1, A4 and A6). Fig. 9c shows the abrupt OM decline from these units as compared to others. The units D2 and D4, showed the same change in OM. All of them had high CCE which favored OM mineralization, although the factor analysis has shown the independence between the OM factor and the Carbonates-Gypsum factor (Fig. 6).

4.4. Linking soil properties to irrigation management

The classification down to family level allows for a preliminary assessment of the spatial distribution of soil hydraulic and salinity properties in the VID that may call for specific irrigation practices. These properties are developed further in a companion paper.

The “fine” textured soils, located at the valley floors (especially C subgroup), may cause tillage difficulties when humid and call for the implementation of a drainage network (already present in many areas) to avoid waterlogging problems. In many lowlands, drainage is being implemented onsite by farmers (personal communications) after the construction of the new irrigation system collapsed many old tile drains. This drainage has proven necessary even though sprinkler irrigation has greatly reduced the drainage volume compared to the previous surface irrigation system (Jiménez-Aguirre et al., 2014a, 2014b). On the other hand, the finer soils (C, D and E) have higher water holding capacity (Aznar et al., 2013), making them more adequate for low frequency irrigation, while high frequency irrigations (drip or sprinkler) might be better for the coarser A-B soils with limited water holding capacity. Playán et al. (2000) already proposed a modernization of VID based on the surface irrigation of the higher water holding capacity soils (lowlands) and sprinkler irrigation in the rest (highlands). A deeper study of the water retention properties (FC and WP) and conductivity in the soils of VID is dealt with in a companion paper, along with their implications for management.

Salinization and sodicity call for attention in semiarid irrigated areas. The EC_e and $EC_{1:5}$ found in VID were similar to nearby areas (Artieda, 1996; Herrero, 1991; Nogués, 2002). The values of EC_e generally found (around 2 dS/m) may result from the dissolution of gypsum (Table 2) and (except for one location, C-32) there was no evidence of salinity in VID. In the same way and with the same exception, no sodicity evidence was found (average $SAR_e < 2$ $(mmol_c/l)^{1/2}$ for all horizons; Table 2), although soil crusting issues have been known to be a problem in the past.

The presence of gypsum all over VID, especially in the surface horizons, may help to prevent soil crusting and avoid losing soil structure due to the low salinity irrigation water from the Monegros Canal (Porta et al., 1994). However, soil crusting was a threat to corn emergence in the 1990's (Isidoro, 1999) under surface irrigation, that demanded supplemental irrigation in early crop stages (Isidoro et al., 2004). Soil crusting may be enhanced by the new sprinkler irrigation system, more prone to soil surface crusting (Al-Qinna and Abu-Awwad, 1998) and thus deserves subsequent consideration.

5. Conclusions

The soil variability in an irrigated, semi-arid, gypsum rich zone as the VID was explained by three factors: Texture Factor (linked to field capacity, wilting point, sand, clay and silt), Carbonates-Gypsum Factor (gypsum and calcium carbonate equivalent content) and Organic Matter Factor. The main soil formation processes in VID were carbonation and gypsification, linked to the Carbonates-Gypsum factor. The prevalence of one process entailed a lesser presence of the other (as confirmed by factor analysis).

Soil textural differences delineate broadly two areas in VID with apparently different implications for irrigation management: The finer textures are located on the colluvial gypsiferous slopes (Typic Xerofluvents, E), on top of the residual gypsiferous heights (Typic Xerorthents, D), and along the valley bottoms (Gypsic Haploxerepts, C); while the coarser textured soils (Typic Calcixerept, A, and Petrocalcic Calcixerept, B) occupy the glacis and residual hills. The former frequently present drainage limitations (by their texture, and their physiographic position in the case of C) and have higher water retention capacity. At first sight, the main limitation for irrigation in these finer-textured soils is the removal of excess water applied (drainage). On the other hand, in the calcixerepts the practice of irrigation is constrained mainly (a priori) by the limited water holding capacity, not by drainage limitations. The prevalence of gypsum or lime in both groups is another difference with possible implications on irrigation management.

A more thorough analysis of the salinity of the saturation extract and other factors may help identifying areas with limited drainage or primary salinity, also with potential implications on irrigation management. All these issues are analyzed in a companion paper.

This work makes up a start-point for mapping the soil hydrologic features of VID related to irrigation, which are the basis for the application of hydrologic models and for further works on soil water balances located in semi-arid irrigated gypsum-rich areas with scarce soil information.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.geoderma.2017.04.025. This data includes the Google map of the most important areas described in this article.

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