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Distribution, morphology and habitats of saline wetlands: a case study from Monegros, Spain

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ABSTRACT

Wetlands in semiarid regions have received less attention than wetlands in humid-temperate areas, and the limited amount of information has resulted in little regulatory recognition. A comprehensive map of the saline wetlands that occur in karstic depressions in the semiarid region of Monegros, NE Spain, was developed from historical data, topography, and surveys of vascular flora. Playa-lakes and other saline depressions are expressions of solution dolines largely founded on groundwater dynamics and favored by the limestone and gypsum-rich substrate. Substrate composition, groundwater dynamics, and the network of infilled valleys are key factors in the distribution of the wetlands. In spite of the anthropogenic imprint, wetlands morphometrics are the expression of geological processes. Significant correlations were found between basin area and depth, and between elongation and substrate composition. The predominantly subelongated shape of the Monegros saline wetlands reflects their origin and a geometry strongly influenced by fractures. Grouping these saline wetlands based on geological and vegetation features, provide a predictable relationship of surficial processes with the occurrence of otherwise complex and undetectable hydrological connectivity. Our ten geology-based Groups showed a high intra-group variation in depth, elongation, and vegetation cover. The eight vegetation-based categories mirror the gradation in flooding frequency and the soil salinity of the Monegros saline wetlands. The significant contrasts existing in-between the groups of wetlands and the disclosure of their causal factors provides a functional perspective at the landscape scale. This approach will help to monitor the ongoing environmental alterations associated with new on-farm irrigation developments.

KEYWORDS **Desert. Endorheic. Halophytes. Karstic. Playa-lake.**

INTRODUCTION

Wetlands are striking features of the landscape when they occur in deserts or other drylands where water deficit strongly constrains life. Worldwide, most saline wetlands occur in arid countries and host animals, plants, and microorganisms adapted to extreme conditions such as hypersalinity, high solar radiation, temperature extremes, and irregular, alternating periods of drought and flooding. Saline lakes from drylands account for a similar proportion of world water (about 0.008%) than freshwater lakes (0.009%) from humid areas (Ramsar Convention Secretariat, 2010). Some of the best-known inland saline wetlands include those of Australia (Bowler, 1986; Duguid *et al.,* 2005; McEwan *et al.,* 2006; Tweed *et al.,* 2011) and those in the southwestern parts of the United States (Lines, 1979; Senger *et al.,* 1987; Stafford *et al.,* 2008). Unlike most of the wetlands in temperate-humid regions, the ecosystems of saline wetlands in arid environments rely on intermittent flooding with saline water. Then, the anthropogenic inputs of freshwater to those wetlands pose one of the various threats to salt lakes, as reviewed by Williams (2002). Traditionally, saline wetlands have been scorned for being unproductive and often ignored in inventories of wetlands (Hollis, 1990). In the last century, saline wetlands have become an environmental concern; usually, only because they provide habitats for wintering and breeding birds. The dearth of saline inventories of wetlands, and maps of soil and vegetation, has prevented the understanding of saline wetlands evolution.

In western Europe, only Spain has natural inland saline wetlands in arid and semi-arid environments (Williams, 1996, 2002). About 10% of Spanish Ramsar sites are inland saline wetlands. The uniqueness of the saline wetlands scattered throughout Monegros, NE Spain, has been recognized for some time (Dantín, 1929, 1942) and they provide habitat for rare and threatened plants, animals, and microbes according to the review of Pedrocchi (1998) and the inventory of habitats of Conesa *et al.* (2011). Several of the geologic, hydrologic, and edaphic characteristics of those wetlands have been addressed during the last decades (*e.g.* Pueyo, 1978/79; Samper-Calvete and García-Vera, 1998; Sánchez *et al.,* 1998; Schütt, 1998; Valero-Garcés *et al.,* 2001; Gutiérrez-Elorza *et al.,* 2002; Castañeda and Herrero, 2005; Herrero, 2008; Mees *et al.,* 2011; Domínguez *et al.,* 2013a). Meanwhile, many of the Monegros saline wetlands have been degraded. Centuries-old agriculture and new on-farm irrigation developments (Castañeda and Herrero, 2008; Domínguez *et al.,* 2013b) have led to geomorphic and hydrologic changes that have blurred many features of the landscape.

The present study undertakes a comprehensive approach to the Monegros saline wetlands distribution pattern, aimed at understanding their natural functioning as a system before modification by irrigation. For this purpose we follow two main steps: i) to recognize and delimit Monegros saline wetlands as functional saline depressions based upon topography and vegetation, and ii) to characterize the distribution of wetlands using geological and physiographic criteria, and analyzing their morphometrics. The results of this study indicate the extent to which a multidisciplinary approach applied in similar environments is significant to understand the functions of wetlands and their response to changes in land use.

STUDY AREA

The Monegros saline wetlands (41º 25.5'N, 0° 9.9'W) are ~70km southeast of the city of Zaragoza, within the semiarid Central Ebro Basin, NE Spain. Mean temperature is 14.9ºC. Low rainfall (mean= 334mm yr^{-1}) and high evaporation (mean reference evapotranspiration ET_0= 1311mm yr^{-1}) produce one of the highest mean annual water deficits in Europe (Herrero and Snyder, 1997). The highly erodible soils of the area are exposed to frequent winter NW winds blowing at >10m s^{-1} (all data from "Valfarta" meteorological station, for the period 2004 to 2012).

More than a hundred saline wetlands (Castañeda *et al.,* 2005) are scattered across a Miocene structural platform (~400m a.s.l.) that lies 200m above the Ebro River. This platform grades slightly (1º-2º) to the North and is sharply delineated by escarpments on the south side. The platform exhibits a high density (absolute maximum of 8.36km km^{-2}) of lineaments, most of them corresponding to normal faults, with a dominant NW-SE orientation (Quirantes, 1965; Arlegui and Soriano, 1998). A secondary set of NE-SW lineaments (less than 5%) developed in the western sector of the platform. The Zaragoza Gypsum Formation constitutes the near-horizontal strata of the platform (Quirantes, 1978); gypsum and limestones are predominant in the area and are interbedded with lutites and marls (Fig. 1). The vertical and lateral alternance of these lithologies contributes to the hydrogeological complexity of the area. Typic Haplogypsids, Typic Haplocalcids, and Gypsic Aquisalids (Soil Survey Staff, 2010) are the most common soils of the depressions, whereas Typic Calcigypsids are found on slopes and plains.

The karstification of the bedrock has formed depressions and solution dolines, some of them dated from ~24000 years BP (González-Sampériz *et al.,* 2008). The excavation of these closed basins by karstification and deflation (Sánchez *et al.,* 1998) has been counteracted by infilling with the materials transported by the sporadic [<10% of the rainfall (Samper-Calvete and García-Vera, 1998)] but erosive surface runoff. Saline wetlands occur

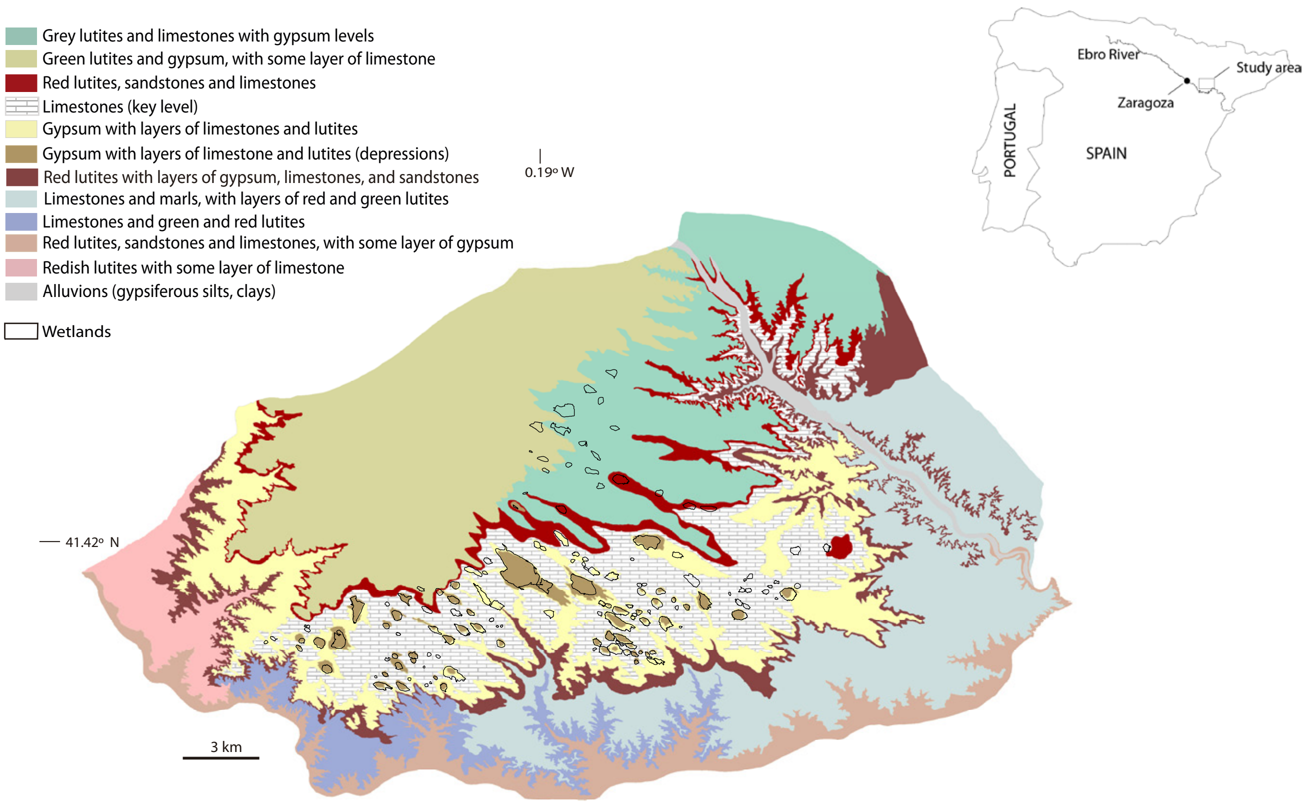

FIGURE 1 | Location of the Monegros saline wetlands and lithological map of the study area, partially modified from Salvany *et al.* (1996).

at the bottom of the depressions. They show a variety of habitats, from playa-lakes to small saline basins, and can be identified by means of different vegetation, soil, and hydrology indicators (Brostoff *et al.,* 2001). They host ephemeral brines and waterlogged to moist soils, even in periods of hydric deficit, due to the proximity of a permanent shallow water table. The drivers of the high salinity of the groundwater (>100g L^{-1}) are: i) dissolution of soluble salts occurring in the geologic materials (especially in lutites), ii) high evapotranspiration (3.44mm/day, Castañeda and GarcíaVera, 2008), and iii) long residence time, between 10 and 100 years (García-Vera, 1996; Samper and García-Vera, 1998). Half of the water input into the wetlands comes from rains, a 40% from groundwater, and a 10% from surface runoff (Castañeda and García-Vera, 2008).

Vegetation around the typically bare floors of the playa-lakes consists on a complex fringe of perennial and annual halophytes whose distribution depends on soil moisture and salinity. Xerohalophilous scrubs (*Arthrocnemum macrostachyum, Suaeda vera* subesp. *braun-blanquetii, Limonium latebracteatum*) and grasses, particularly *Lygeum spartum*, predominate in saline soils, together with ephemeral plants *(Frankenia pulverulenta, Sphenopus divaricatus, Halopeplis amplexicaulis, Salicornia patula, Microcnemum coralloides)*. Other than the playas, the floors of the wetlands in depressions have xerohalophilous and halonitrophilous scrubs and grasses, interspersed with meadows of halophilous therophytes or tamarisk communities (*Tamarix canariensis*).

MATERIALS AND METHODS

Figure 2 gives an overview of the methodology followed in this study. The first step was to produce an updated georeferenced inventory of the Monegros saline wetlands. Their delineation in the field was based upon surveys of vascular flora conducted between 2004 and 2009 (Conesa *et al.,* 2011). The cartography of vegetation was carried out in the field using a GPS and mapping in the field on 1:6,000 scale color orthophotographs. Map legend was based on the hierarchical classification of European habitats developed by the CORINE Biotopes Manual (Commission of the European Communities, 1991). The distribution of halophilous and halo-nitrophilous communities were used as evidence for soil salinity related to saline groundwater discharge. The Monegros saline wetlands maps of the habitats recorded in the field were treated using ArcGis®.

Apart from the very limited sight due to the flatness of the landscape, the main difficulty encountered in the recognition of some depressions in the field was the

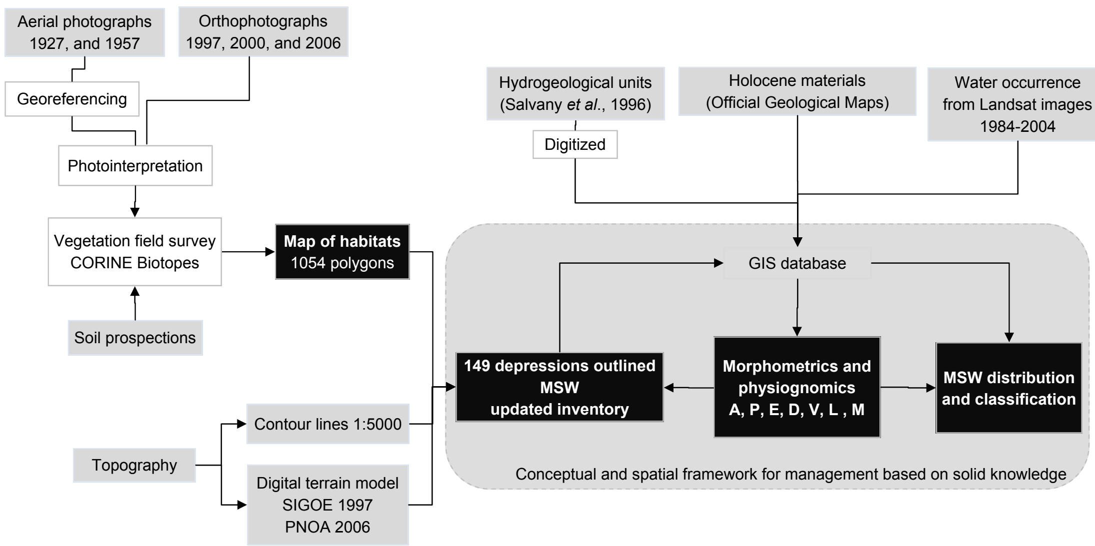

FIGURE 2 | Scheme of the methodology showing the main input data (in grey), processes (in white) and results (in black).

destruction of their vegetation and the blurring of their geomorphic expression by centuries of agricultural use and the recent generalized earth movements with heavy machinery. To overcome this difficulty we used photointerpretation and topography. Photointerpretation was based on two sets of historical aerial photographs taken in 1927 (1:10,000 scale) and 1957 (1:33,000 scale), which were previously georeferenced, and three sets of orthophotographs (0.5 to 1m per pixel) taken in 1997, 2000, and 2006. Historical and current photographs were analyzed in a geographical information system. Soils prospection helped to identify saline depression with plowed floors, by determinations of the electrical conductivity in soil extracts (Serrate, 2009; Castañeda *et al.,* 2010).

The outlines of the Monegros saline wetlands were refined using a 1:5,000-scale topographic map with a 5m-contour interval, and two complementing digital terrain models, SIGOE (SIG Oleícola Español) from a 1997 flight, which has a 20-m pixel size and an absolute vertical error <5m, and PNOA (National Aerial Orthophotography Plan) from a 2006 flight, which has a 5m pixel size and an absolute vertical accuracy of 1-2m in terms of root mean square error at 68% confidence level.

Subsequently, we established sectors in the platform based on hydrogeological and geological maps. The hydrogeological units were extracted from the 1:50,000 scale printed lithological map (Salvany *et al.,* 1996) digitized for this purpose (Figs. 1; 2). The Holocene materials infilling the depressions and flat-bottom valleys, as extracted from the 1:50,000 scale official geological maps (Ramírez, 1997; Solà and Costa, 1997). Additionally, we used the available records of water occurrence in the saline depressions (Herrero and Castañeda, 2009).

The Monegros saline wetlands physiognomics and morphometrics were derived using common operations of ArcGis® and TAS software (Lindsay, 2005). They were the following: area (A), perimeter (P), elevation (a.s.l.) of the centroid (E), depth (D) derived from topographic data and calculated as the difference between the lowest and the highest points within each wetlands, and proportion (%) of the saline wetlands covered by vegetation (V). The morphology of the wetlands was characterized by the elongation (L) and the margin irregularity (M), which are non-dimensional indexes. L was the ratio between the maximum length and maximum width, drawn orthogonally, which yields a value of 1 when the basin is perfectly round. The margin irregularity index or development of shoreline measured the sinuosity of the perimeter of the basin (Hutchinson, 1957) and was calculated as $M = P/2\sqrt{\pi A}$, (with 1, the minimum value, for a circle).

We classified the Monegros saline wetlands in terms of: i) wetlands type, ii) geologic features, and iii) water occurrence and vegetation. Descriptive statistics and Principal Component Analysis (PCA) analysis were calculated using Minitab® and SSPS®.

RESULTS

Extent and physiognomy of saline wetlands

The 149 saline wetlands that we delineated in the field covered 19.16km^2, a 9% of the area of the platform (~220km^2). Thus, the density was 0.7 wetlands km^{-2} and the pitting index (the reciprocal of wetlands area / total area; Day, 1983) was 11.1. The average size of the wetlands was 0.13km^2 (range= 0.6 10^{-2} km^2 to 2.40km^2) and 95% were

<0.40km^2. A distribution pattern of the wetlands regarding their size was not observed. The largest depressions were located in the center of the platform (Fig. 1), aligned with well-developed flat-bottom valleys. Size was significantly ($p<0.001$) negatively correlated with elevation ($r= -0.35$).

The elevation (E) of the Monegros saline wetlands ranged from 315m to 367m a.s.l. but most (78%) of the wetlands floors were within a 30m range in elevation (between 330m and 360m a.s.l.); about 8% of the wetlands were above 360m and on the southern platform; and 14% were below 330m, which were in the northern and central platform. Only three of the wetlands were below 320m. The elevation and elongation of the wetlands were not significantly correlated. Most of the elongated (L> 2.5) Monegros saline wetlands occurred at intermediate elevations (330 - 350m) and, on average, the wetlands above 350m were more circular (median L= 1.5).

The depth (D) of the Monegros saline wetlands ranged from 0.3m to 25.8m and 78% of the wetlands were <5m deep (Fig. 3). Only three of the largest wetlands (La Playa, Pito, and Larga) were deeper than 20m, although their morphometrics differed. The depth of the saline wetlands was significantly ($p<0.001$) correlated with the area ($r= 0.59$) and the best fitting ($R^2= 0.62$) was attained by a potential curve ($y= 1.06\ x^{1.33}$) (Fig. 3). Some wetlands, such as Benamud and Agustín, which are in valley bottoms, differed by their high size to depth ratio. The smallest depressions (A<4ha) were shallow (mean D<2m).

The elongation index (L) allowed grouping the Monegros saline wetlands in four types, from circular to elongated (Table 1). The average L was 1.8 (range= 1.0 - 4.4), and a high proportion (39%) of the wetlands had an elongated or subelongated shape. About 40% of the wetlands had a circular shape; however, because the maximum width (*i.e.* the maximum distance between margins measured relative to the maximum length) used to calculate L usually is shorter than the mean width (size to maximum length ratio, Hutchinson, 1957), L tends to underestimate, slightly, the degree of elongation. L was not significantly correlated with the size or the elevation of the wetlands.

The average margin irregularity index (M) of the

TABLE 1 | The proportion (%) of the saline wetlands in Monegros, Spain, that were assigned to one of four shape classes based on elongation index (L) values

Shape class	L	%
Circular	< 1.50	40
Subcircular	1.50 to 1.75	21
Subelongated	1.76 to 2.00	16
Elongated	> 2.00	23

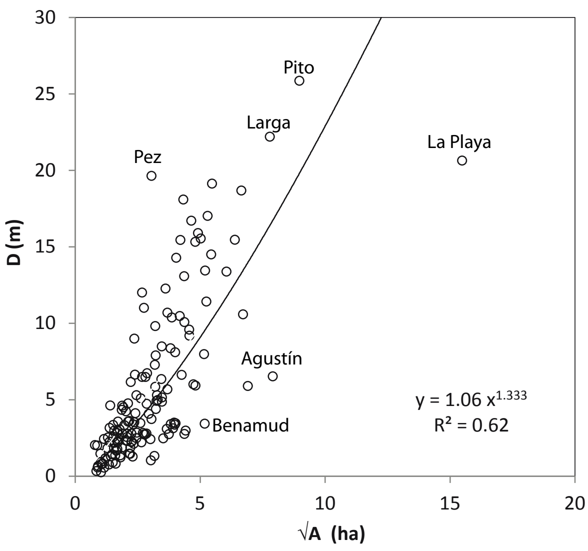

FIGURE 3 | Scatterplot of wetlands depth (D) and area (√A). The area is plotted by its square root.

Monegros saline wetlands was 1.27 + 0.2 SD (range= 1.02 - 1.83), and M was significantly ($p<0.001$) correlated with the elongation index ($r= 0.55$) and depth ($r= 0.45$). Using the criteria of Hutchinson (1957) and Timms (1992), about 11% of the wetlands had a perfect doline geometry (1.00<M<1.25), and 29% had 1.25<M<1.50, which indicated dolines modified by deflation. The shapes of the remaining (60%) wetlands were very close to subcircular.

The Principal component anaysis for the seven physiognomic descriptors analyzed (A, E, L, D, M, P, and V) produced clear results (Table 2). The varimax Principal component anaysis revealed that the three first components, with eigenvalues ≥1, accounted for 77% of the total variability of wetlands physiognomy. The variability explained by each descriptor with these three factors was high for all the descriptors except for elongation (Table 2), ranging from 64% for depth up to 96% for elevation. Factor 1 was size, with the maximum contributions of perimeter and area, and showing their predictable positive intercorrelation. High values of the first principal component are related to large wetlands. Elevations showed a negative contribution, in agreement with the statistically significant negative correlation between area and elevation mentioned above. Elongation totally loaded on factor 2, showing an inevitable intercorrelation with margin irregularity index. Vegetation was the only variable supporting factor 3. This analysis identified the main physiognomic descriptors (A, E and V) and corroborated their direct correlations.

Playa-lakes and other wet saline basins

Table 3 summarizes the main attributes of playa-lakes and the other wet saline basins. Almost 9% of the Monegros

TABLE 2 | Varimax-rotated factor matrix for the morphometric attributes of saline wetlands in Monegros, Spain

Attribute	PC1	PC2	PC3	Communalities
Area, A	0.908	0.058	0.092	0.836
Elevation, E	-0.594	-0.073	0.230	0.955
Elongation, L	0.033	0.935	-0.046	0.410
Depth, D	0.721	0.211	0.270	0.637
Margin irregularity index, M	0.413	0.755	0.191	0.877
Perimeter, P	0.929	0.262	0.155	0.777
Vegetation (%), V	0.075	0.055	0.942	0.896
Eigenvalues	3.28	1.13	0.97	
% of variance	39.1	22.4	15.5	
Accumulative %	39.1	61.5	77.0	

saline wetlands were playa-lakes (*sensu* Brière, 2000), which represented the most developed morphological expression of the geological processes. Their mean and median surfaces were 0.47km^2 and 0.27km^2, respectively, and they were the most obvious depressions. A barren floor is their distinctive facies (Castañeda *et al.,* 2005), which was 30% - 84% of the total area of each playa. Playa-lakes were the product of an advanced stage of bedrock karstification and deflation. They were discharge playas (*sensu* Yechieli and Wood, 2002), although it is possible that brine percolated into the groundwater system (Samper-Calvete and García-Vera, 1998). The size of the playas and their drainage basins were not significantly correlated (Castañeda and Herrero, 2005).

From 1987 to 1990, the flooding frequencies of all the playas ranged from 40% to 82%, based on field monthly monitoring (Berga, 1993), and from 1993 to 1997, the flooding frequencies ranged from 48% to 78%, based on field weekly monitoring (Castañeda, 2002; Castañeda *et al.,* 2005). From 1984 to 2004, the water occurrence of playas based on remote sensing ranged from 40% to 100% (Herrero and Castañeda, 2009). No relationship was found between the flooding frequencies of wetlands and their area and elevation. For the three periods surveyed using different temporal scales, Salineta and La Playa wetlands, with a similar low elevation (325.1m), had the highest flooding frequencies, 100% and 85%, respectively.

The brines reach concentrations >400g L^{-1}. Those harsh conditions prevent perennial halophytes from becoming established; however, where the flooding frequency is less, the floor is colonized by *Arthrocnemum macrostachyum*, which is the most salt tolerant perennial halophyte in Monegros (Herrero, 2008; Conesa *et al.,* 2011; Domínguez *et al.,* 2013a). Depending on the amount of precipitation, several wet-dry cycles per year are common in playa-lakes. Because of the unpredictable and rapidly changing moisture levels on the floors of the playa-lakes, they are most commonly colonized by hypersaline microbial mats and annual succulent halophytes (*Halopeplis amplexicaulis*) that can respond to changes in moisture by rapidly germinating, maturing, and setting seed. Perennial prairies are restricted to the margins of the playas where they extend into the lakes from a few to hundreds of meters. Nevertheless, the barren bottom of the playas can be covered by perennial halophytes after several successive dry years, as was the case of Agustín.

In the Monegros saline wetlands, the playa-lakes were subcircular, and the mean elongation index (1.7) was

TABLE 3 | The wetlands groups established on the North (NES) and South (SES) endorheic systems on the MSW platform in Monegros, Spain, their primary attributes, and the number of wetlands

Average	Playa-lakes	Other wet saline basins
Area (km^2), A	0.47	9.3 10^{-2}
Elevation (m a.s.l.), E	329.58	345.15
Depth (m), D	12.0	5.8
Elongation, L	1.7	1.8
Margin irregularity index, M	1.4	1.3
Flooding frequency*	40%-100%	< 5%
Main distinctive facies**	Barren floor, intermittent flooding	Halophytes

*From 1984 to 2004, based on remote sensing data
**Following facies definition from Castañeda *et al.* (2005)

slightly lower than the overall mean of the wetlands. On average, the playa-lakes were 12m deep, and the deepest (~25m) was Pito, which is in the center of the platform. Many of the playas preserved a cusp-shaped morphology (Fig. 4A) with the cusp pointing upwind indicating unidirectional winds (Goudie and Wells, 1995). As noted

FIGURE 4 | Some appearances of saline wetlands in Monegros. A) Aerial view of Guallar playa-lake in June 2010 illustrating the cusp-shaped morphology flanked by the straight lee side of aeolian sediments; B) Salt crust developed in Salineta playa-lake floor, in June 2010; C) Perennial halophytes pioneering the limestone strata at the base of the northern escarpment of Muerte playa-lake, in August 2008; D) Halophytes highlighting the bottom of Larga, wet saline basin rarely flooded which formed at a flat bottom valley, partially plowed in June 2009; E) Aerial view of Farnaca, wet saline basin showing the distribution of different plant communities in June 2010; F) A distinct soil color highlighting the bottom of Escobedo wetland, plowed in June 2010.

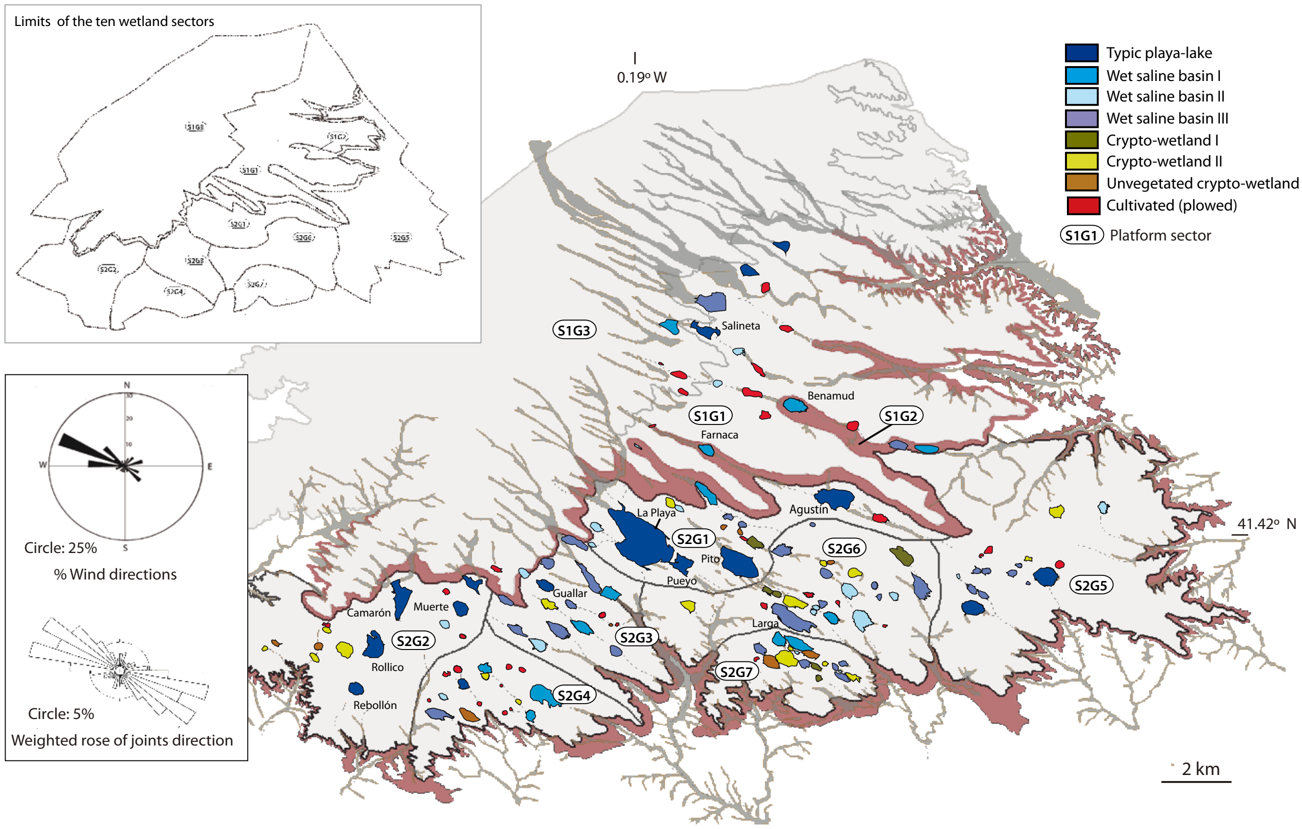

FIGURE 5 | Distribution of the vegetation-based wetlands categories within the platform in Monegros. In the map are drawn: i) the two red lutite layers from the lithological map of Salvany *et al.* (1996), ii) the flat-bottom valleys network from the geological maps (references in the text), and iii) the ghost drainage patterns (dashed lines). The left-upper box shows the limits between the ten wetlands sectors and the left-down box shows the wind rose (Gutiérrez *et al.*, 2002) and lineaments direction (Arlegui and Soriano, 1998) in the area.

by Pueyo (1978/79), the playas were usually flanked by a straight lee side transverse to wind formed by dunes (Fig. 4A). The flat playa floors may expose the bedrock in places at the base of the escarpment (Fig. 4C). The playa floor may be gradually deepened by end-currents erosion towards the leeside (Goudie and Wells, 1995). Under the high flooding frequency regime of the Salineta wetland, this deepening reaches a bathymetry of ~90cm.

In 89% of the Monegros saline wetlands, the expression of the hydrologic and geomorphic processes is not as advanced as in the playa-lakes. Those wetlands are less frequently flooded, similar to the crypto-wetlands found in coastal environments (Carreño *et al.,* 2008). Groundwater is responsible for their permanently wet soils and the occurrence of halophytes. The surveys of vascular flora were instrumental for identifying many of these wetlands. The mean M index (1.3) was within the range of dolines modified by deflation (Hutchinson, 1957; Timms, 1992). The wet saline basins had a mean depth markedly lower than that of playas, 5.8m. Several Monegros saline wetlands occupied dolines forming a widened portion of flat-bottom valleys.

Distribution of the Monegros saline wetlands

The Monegros saline wetlands are located in two hydrogeological systems (Salvany *et al.,* 1996), *i.e.* the upper and lower aquifer (Samper-Calvete and García-Vera, 1998). The North Endorheic System in the northern section of the platform contains 23 wetlands, which are mainly fed by the upper water-table aquifer. Most of those wetlands are in basins that have been excavated in green lutites and are concentrated along the lithological contact between the western gypsum-rich lutites and the eastern carbonate-rich lutites. A few of the North Endorheic System wetlands occur along the rather continuous thin key layer of red lutites (Fig. 5), which hinders leakage between the upper and lower aquifers (García-Vera, 1996). The South endorheic system contains 126 wetlands, which are fed by the lower aquifer and are on a predominantly gypsum and limestone substrate.

At the scale of the geological map and the resolution of the elevation model, ten sectors were identified in these hydrogeological systems. The ten resulting Monegros saline wetlands groups are characterized by the predominant bedrock composition combined with the mean

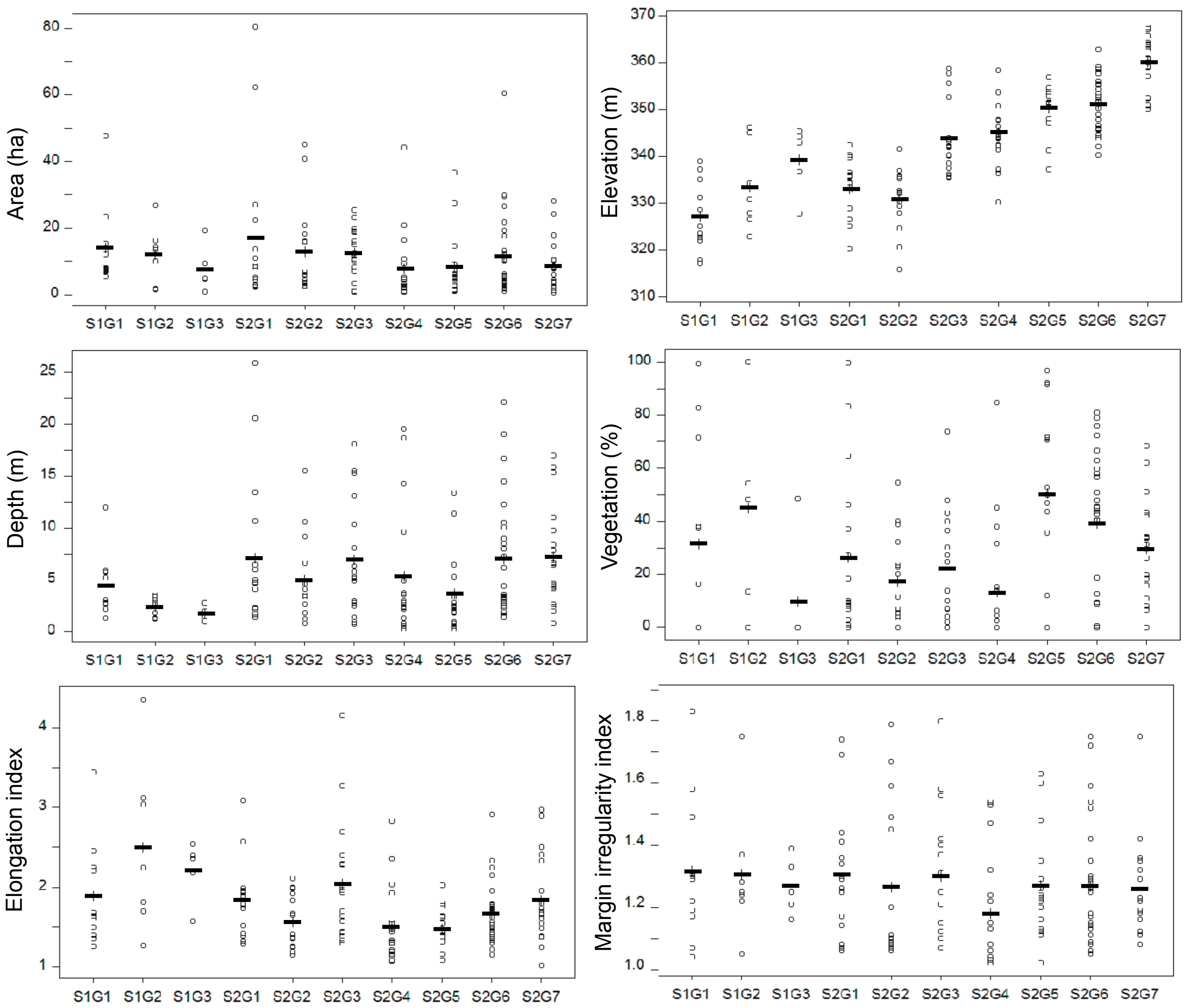

FIGURE 6 | Distribution and mean value (horizontal bar) of the morphometric features of each group of wetlands in Monegros, Spain. La Playa was not included in the first graph (Area) because it was exceptionally large.

elevation (Table 4; Fig. 5). In Figure 6 the morphometrics and physiognomics of each group are presented for visual comparison using graphical methods (Chambers *et al.*, 1983) for exploratory data analysis (Tukey, 1977).

The North endorheic system contained three groups (S1G1, S1G2, and S1G3), which include the most elongated (mean elongation index (E)= 2.2) and the shallowest (mean depth (D)= 2.9m) wetlands. The S1G1 group was within the carbonate-rich lutites of the eastern North endorheic system and they had the largest mean area (~14ha) of the North endorheic system wetlands and the lowest mean elevation (327m a.s.l.) of all ten groups (Fig. 7). The S1G3 group was in the gypsum-rich lutites in the western section of the North endorheic system. At the base of the upper aquifer, the S1G2 group extended along the key layer of red lutites (Fig. 5) and had the lowest mean area (7.7ha) and the highest mean elongation (Elongation index =2.5).

About 86% (1641ha) of the total area of the Monegros saline wetlands was within the South endorheic system, which contained seven groups (S2G1 to S2G7) whose proportion of limestone bedrock and the mean elevation increased towards the East. S2G1 and S2G2 had predominantly gypsum substrates and low mean elevations (333m and 331m a.s.l., respectively), whereas a limestone substrate and an intermediate-high mean elevation (350m a.s.l.) characterized the S2G5 group. The other four groups (S2G3, S2G4, S2G6, and S2G7) were on mixed substrates of gypsum and limestone. The wetlands that had the lowest

TABLE 4 | The wetlands groups established on the North (NES) and South (SES) endorheic systems on the MSW platform in Monegros, Spain, their primary attributes, and the number of wetlands

System	Group	Platform Sector[1]	Platform composition[2]	Elevation		Nº of wetlands	
				Mean m a.s.l.	Category	Total	Vegetated[3]
NES	S1G1	East	Lu-L	327.0	Very low	11	6
	S1G2	South	Lu	333.4	Low	7	5
	S1G3	West	Lu-G	339.4	Low – intermediate	5	1
SES	S2G1	Central	G	333.1	Low	16	14
	S2G2	West	G	330.9	Low	15	12
	S2G3	West central	G-(L)	343.9	Intermediate	17	15
	S2G4	Southwest	G-(L)	345.3	Intermediate	18	9
	S2G5	East	L	350.4	Intermediate – high	16	13
	S2G6	East central	L-(G)	351.3	Intermediate – high	26	22
	S2G7	Southeast	L-(G)	360.2	High	18	17

[1] Sectors established in the platform
[2] Predominant composition of each platform sector based on the lithological map (Salvany *et al.*, 1996): Lu: Lutite; L: Limestone; G: gypsum
[3] Crops excluded

elevations (Rebollón, Rollico, and Pito) were on gypsum-dominated substrates. All of the South endorheic system groups, except the gypsum reach S2G1 and S2G2 groups, were at higher elevations (mean= 350m) than the North Endorhreic System groups (mean= 333m a.s.l.).

The mean depth of the South endorheic system wetlands (6.2m) was almost twice the mean depth of the North Endorhreic System wetlands (3.3m). On average, the South endorheic system wetlands were subcircular (mean elongation index= 1.7) and the North Endorhreic System were elongated (mean elongation index= 2.2). The mean elongation index of the groups ranged from 1.5 to 1.8, and was highest in the S2G3 group. This group was in the west-central section, conspicuously aligned within NW-SE flat bottom valleys.

Excluding the La Playa wetlands (239ha), which was an order of magnitude larger than the other Monegros saline wetlands, the mean size of the South endorheic system groups ranged from 7.9 to 31.1ha. The different median size of the North Endorhreic System (6.9ha) and South endorheic system wetlands (9.2ha) showed the dissimilarity of distributions and size heterogeneity of the two systems.

Classification of the Monegros saline wetlands based on vegetation

One hundred and fourteen (77%) of the wetlands had natural vegetation on their floors and/or on their slopes. The mean proportion of each wetlands covered by vegetation was 38%, and ranged from 22% to 63% for the groups of wetlands (Fig. 6). The proportion of the wetlands covered by vegetation was not correlated with the size or the elevation of the Monegros saline wetlands. The wetlands <0.20km^2 had the lowest proportions of ground covered by vegetation because their small size makes them easier to plow. In 2011, about 35% of the Monegros saline wetlands were plowed and, 42% of those, had more than half of their area plowed.

Halophytes, both perennials and annuals, were present in 91 (61%) of the Monegros saline wetlands. The halophytes are often associated with halonitrophilous plants. The presence/absence of specific vegetation communities allowed clustering

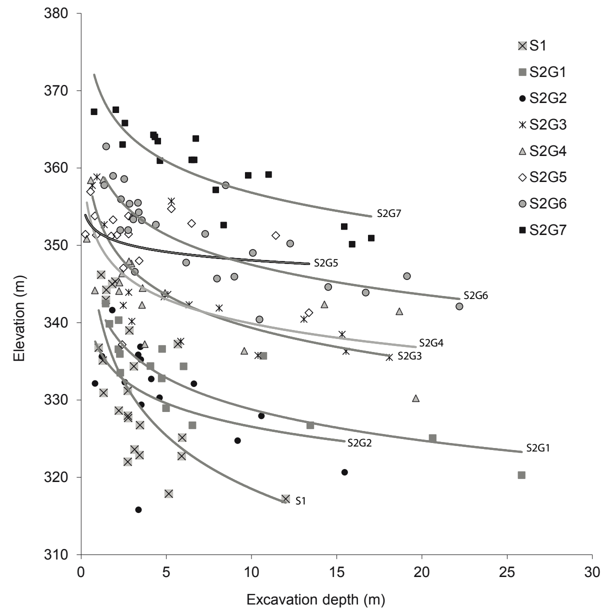

FIGURE 7 | Scatterplot of the MSW elevation and the depth and the curves fitted for each group of wetlands in Monegros, Spain. North Endorhreic System groups are fitted to a single curve.

TABLE 5 | Wetlands categories with their main vegetation communities and the CORINE habitats code locally adapted (Benito, 2011), and main soil features of the eight MSW categories

Category	Vegetation (CORINE habitat code)	Flooding[1] %[2]	Soil features[1] EC[3]	Number of Wetlands
Typic playa-lake	Annual glasswort (*Salicornia* spp., *Microcnemum coralloides*), seablite (*Suaeda maritima*), and other therophyte succulent plants. Formations pioneering periodically inundated muds of inland salt-basins (15.11).	Annual 66%	Persistent soil saturated or close to saturation even in summer, salt crusts, and algal mats. Highly saline soils EC 16.7 dS m^{-1}	16
Wet saline basin I	Tall rush saltmarshes dominated by *Juncus maritimus* and / or *J. acutus* (15.51) and Iberian salt meadows (*Puccinellion fasciculatae*) with *Puccinellia* spp. and *Aeluropus litoralis* (15.54)	Variable, not annual 18%	Long periods of persistent soil moisture and summer drought. Highly saline soils. EC 8.9 dS m^{-1}	13
Wet saline basin II	Perennial vegetation of continental saline muds mainly composed of scrub, essentially with a Mediterranean-Atlantic distribution (*Limonium* spp. and *Suaeda* communities) and belonging to the *Sarcocornetea fruticosi* class (15.6)	Temporal and rare 8%	Seasonal periods of persistent soil moisture and summer drought. Highly saline soils. EC 5.6 dS m^{-1}	19
Wet saline basin III	Perennial vegetation of continental saline muds mainly composed of scrub, essentially with a Mediterranean-Atlantic distribution (*Suaeda* and *Atriplex* communities) and belonging to the *Sarcocornetea fruticosi* class (15.6) and halo-nitrophilous scrubs belonging to the *Pegano-Salsoletea* class, typical of dry soils under arid climates (15.72).	Rare 4%	Short periods of soil moisture and summer drought. Dark compact saline soils nitrified by shepherding	33
Crypto-wetland I	Halo-nitrophilous scrubs belonging to the *Pegano-Salsoletea* class, typical of dry soils under arid climates (15.72) and Mediterranean halo-nitrophilous pioneer communities (*Frankenion pulverulentae*): formations of halo-nitrophilous annuals (*Frankenia pulverulenta*, *Spergularia diandra*, *Hordeum marinum*, *Sphenopus divaricatus*) (15.12)	Non	Dark compact saline soils nitrified by shepherding	6
Crypto-wetland II	Halo-nitrophilous scrubs belonging to the *Pegano-Salsoletea* class, typical of dry soils under arid climates (15.72)	Non	Dark saline soils nitrified by shepherding. Intermittently and /or partially plowed	18
Unvegetated crypto-wetland	Dwarf scrub mostly on calcareous and eroded marly soils (32.42) and occupying gypsum-rich soils, usually very open (15.9), and grasses and annuals of the *Thero-Brachypodietea* (34.5)	Non	Dark saline soils nitrified by shepherding. Plowed / cultivated	9
Cultivated	Absent	Non	Cultivate soils, much darker than the surroundings	35

1: As indicated by vegetation
2: Percent data from total observations, from available remote sensing records
3: EC: electrical conductivity of the 1:5 soil:water extract, averaged in a 0 to 100 cm depth

the Monegros saline wetlands into eight categories (Fig. 5) of decreasing flooding frequency/soil moisture, and soil salinity (Table 5). The available soil data shown in Table 5 corroborate this gradation. Category 1 encloses the typic playa-lakes, *i.e.* wetlands characterized by the occurrence of the most tolerant plants to both soil salinity and flooding. Most playa-lakes concentrate in the sectors of the platform having low mean elevation (S1G1, S2G1, and S2G2) (Fig. 5). The distribution of the wetlands other than category 1 does not reveal any association with the geologic sectors. The relative amount of wetlands of category 8 in S1G2 is due to antropogenic factors, *i.e.* the on-going transformation of this area into irrigation.

The saline wetlands belonging to the categories 2 through 4 (Table 5) were characterized by the occurrence of perennial halophytes which are less tolerant to flooding. The soil moisture at the bottom of these wetlands is ensured by the proximity of the groundwater, frequently <1m. Non flooded wetlands were classified as crypto-wetlands ss. Crypto-wetlands types I and II (categories 5 and 6) correspond to the presence and absence of pioneering annual halophytes, respectively. The less conspicuous saline wetlands have subtle margins difficult to delineate in the field. They are the most heavily degraded wetlands by human activities, particularly those that have been partially (category 7) or totally plowed (category 8).

From category 1 to category 8, the mean elevation increased whereas the percentage of vegetation, depth, area, and margin irregularity decreased. The vegetation communities of the first four categories were diagnostic of saline wetlands. Overall, the soil salinity of wetlands floors was beyond the tolerance of any common cultivated plant.

Key geological features for the distribution of wetlands: confining lutites and valleys network

The wetlands and flat-bottom valleys are prominent morphodynamic elements of the platform landscape. Typically, the wetlands formed strings, juxtaposed, and coalesced to form uvalas, and a few remained isolated. Wetlands were aligned with valleys or were at their bottoms, which reflect the strong influence of main joint-set orientation, NW-SE, in the Miocene bedrock (Arlegui and Soriano, 1998) which affects: i) the distribution of depressions and valleys, and ii) the orientation of the maximum length of the wetlands. The influence of the secondary joint-set orientation, NE-SW

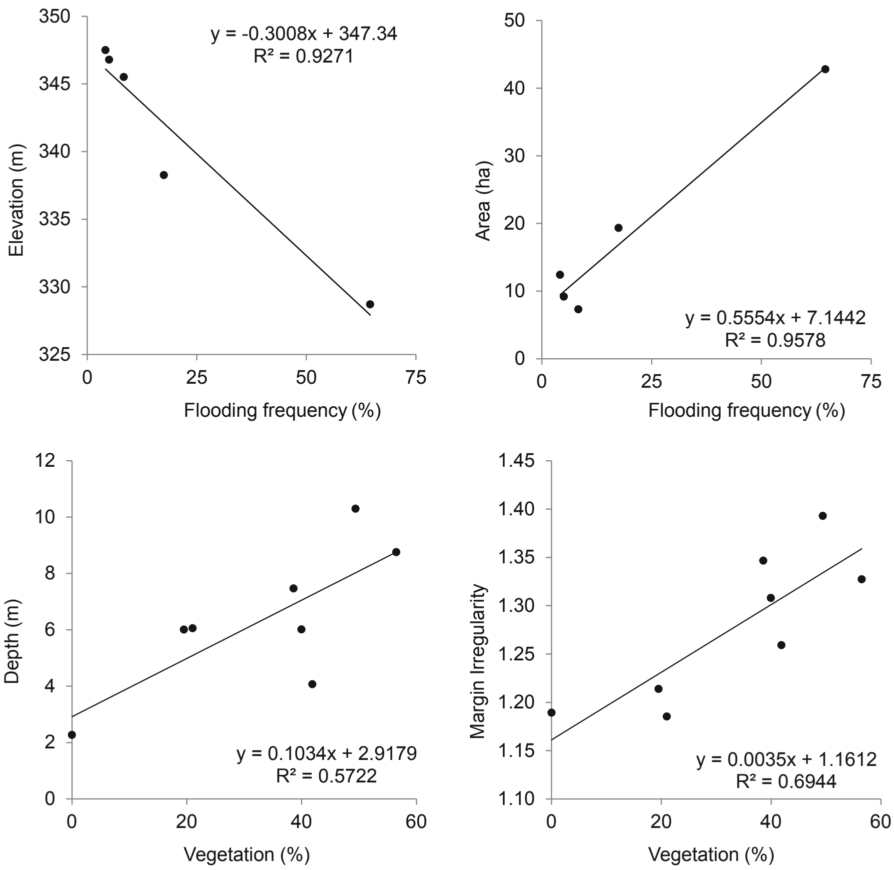

FIGURE 8 | Relationships between mean morphometrics of the vegetation-based groups of wetlands in Monegros

(Arlegui and Soriano, 2003) on the development and the morphology of the wetlands is especially evidenced in the southwestern sector of the platform by the playa-lakes which developed their maximum length in the NE-SW orientation (*e.g*. Camarón and Rollico), and by the NE-SW alignment of wetlands within each group (Fig 5).

The predominant NW-SE orientation of the valleys and wetlands coincides with the NW-SE direction of the prevailing winds and the contour of the water table modeled by Samper and García-Vera (1998). The common lateral changes of the lithological facies (Quirantes, 1978) suggest the influence of lithological contacts on the distribution of the wetlands. This is evidenced by the presence of the NES wetlands spread along the contact line between the two lutitic facies.

Some of the straight infilled valleys that cross the North Endorhreic System system have a rather continuous and parallel or subparallel drainage pattern typical of materials that have low permeability and vegetation-free terrain. Most of those valleys flow into closed depressions at the South endorheic system. This ending of valleys at swallow holes is a frequent geomorphological feature of gypsum karst areas (Sauro, 1996; Ford and Williams, 2007). Moreover, a ghost drainage pattern (Fig. 5), apparent in many aligned wetlands, was inferred from digital terrain models. The largest NW-SE flat bottom valleys extend >10km toward the border of the platform and are noticeable in the field. A few of the valleys are oriented along the NE-SW secondary trend of regional joints. The largest dolines (La Playa, Pueyo, and Pito) were at the confluence of the two join sets, in the central platform. They were at a low elevation sector (320m) and were the deepest wetlands (>25m).

The floors of 13 of the South endorheic system wetlands were underlain by the impermeable red lutitic key layer (Solà and Costa, 1997). Most of those "red-lutites" wetlands were subelongated (mean E= 1.8), of variable size and depth, and had high elevations because of the slight (1º-2º) northward tilting of the platform.

DISCUSSION

Updated inventory and delineation of the Monegros saline wetlands

The integration of historical and current data from various sources yielded a map that identified 149 saline wetlands in Monegros that, collectively, were highly consistent with the 130 dolines and the valleys infilled with Holocene materials drawn in the geological maps of Ramírez (1997) and Solà and Costa (1997), and completed the early sketch of Balsa *et al.* (1991) containing 99 wetlands non georeferenced. The morphology of the basins exhibited several degrees of excavation which ranged from small hollows and smooth depressions to distinct sinkholes that were >20m deep. The topographic data derived from the digital elevation models provided subtle topographic details that were not discernible in the field. Aerial photography is a valuable resource for identifying the potential locations for wetlands based on soil surface colors and textural differences in the images, most of them undetectable by eye in the field.

The elevation range where most wetlands concentrated (~30m) nearly coincided with the thickness of the gypsum-rich unit (40m, Salvany *et al.,* 1996) bounded by the two red lutite layers (Figs. 1; 5), and with the elevation range where the saturated levels concentrated (Berga, 1993). The flooding frequency of wetlands (with highest values in Salineta and La Playa), as extracted form field surveys and remote sensing, was consistent with the discharge areas identified using hydrogeological modeling (García-Vera, 1996; Samper-Calvete and García-Vera, 1998). The lack of relationship between the flooding frequencies of wetlands and their size and elevation suggested that flooding frequency can be related with their location along preferential groundwater flows.

Hydrology, soils, and vegetation are the factors that permit the delineation of wetlands, even in arid environments (Brostoff *et al.,* 2001); however, centuries of agriculture, land consolidation in the 1980s, and the development of new irrigation systems make it difficult to delineate wetlands in Spain. Saline wetlands are recognized easily on soil maps because of their distinctive soils, which differ considerably from the soilscapes of plains and slopes (Castañeda *et al.,* 2010; Moret-Fernández *et al.,* 2013). In the absence of soil maps, the presence and nature of the vegetation aids the identification and delineation of wetlands. A persistent, shallow, fluctuating saline water table at the bottoms of the Monegros saline wetlands, even when surface water is not present, maintains the high soil salinity, which varies spatially as reflected by the distribution of plant communities. The halophilous vegetation was a diagnostic criterion for many wetlands identification. The surveys of vascular flora were essential in substantiating previous inventories and the information in historical aerial photography, and for delineating the wetlands and identifying crypto-wetlands that had degraded morphologies. Probably, the inventoried wetlands surface is a minimum estimate if it is assumed that the visible wetlands margins have shrunk because the vegetation has been removed. In those areas, soil salinity transects and electromagnetic induction surveys (Serrate, 2009) can overcome the problems of ambiguous indicators of wetlands function.

The proportion of the platform covered by wetlands in Monegros was similar to the proportion of alluvial sinkholes found in an area where the Zaragoza Gypsum Formation is covered by Quaternary alluvium, in a stretch of the Ebro River Valley 70km upstream (Galve *et al.,* 2009). In that area, the hydrological setting differs from the Monegros saline wetlands, particularly because of the influence of centuries-old practice of surface irrigation using unlined ditches. On the platform of the Monegros saline wetlands, a significant, continuous water input into the evaporitic bedrock was absent until 2011, although new irrigation systems are going to operate in half of the platform. Thus, an increase in bedrock dissolution might occur in response to irrigation, especially because of: i) the exposed, densely fractured bedrock, ii) the shallow calcareous and gypseous soils, and iii) an increase in the water dissolution potential caused by the mixing of fresh irrigation water (<0.1dS m^{-1}) and the existing hypersaline groundwater (>100dS m^{-1}).

The mean size of the Monegros saline wetlands (13ha) was greater than the average size of the playas in the High Plains of United States (7.6ha) (Smith, 2003), though wetlands density was similar in these two arid sites (0.7 and 0.4 playas/km^2 for Monegros saline wetlands and the High Plains, respectively). In contrast, the Monegros saline wetlands density was much lower than the densities reported by Gracia-Prieto (1991) (6.5-35dolines/km^2) in Spanish karstic doline fields on limestone. The relatively high proportion (9%) and mean size (13ha) of wetlands in Monegros compared to limestone karstic doline fields (Gracia-Prieto, 1991) is a result of intense karstification over a moderately small area (~220km^2), probably, enhanced by the solubility of gypsum in the Monegros area, which can be favored by the occurrence of lithogenetic fissures (Klimchouk and Andrejchuk, 1996).

The predominantly subelongated shape of the Monegros saline wetlands reflects their karstic and aeolian origin and a geometry strongly influenced by fractures, which is unlike the High Plain playas roundness caused by surface runoff (Sabin and Hollyday, 1995). A relationship between the area of the wetlands and the lithology did not exist because of the presence of interbedded facies (*i.e.* gypsum, limestone and clay) with frequent lateral and vertical shifts throughout the platform (Quirantes, 1978). Large depressions were common in platform sectors where gyprock was predominant, and the two wetlands groups (S2G5 and S2G7) that had the smallest average sizes formed in platform sectors where limestone predominated (Figs. 1; 5).

The excavating of the basins is expected to be limited once impermeable layers are reached. It was the case of the 14 Monegros saline wetlands with floors that reached the impermeable red lutitic layer that underlies the South endorheic system. However, those “red-lutites wetlands” did not share common hydrological features since they included playa-lakes and wet depressions; moreover their size indicates that the karstification process was not limited by the lutitic bedrock, as those wetlands were twice as deep as and larger (most >20ha) than the average Monegros saline wetlands.

Wetlands relationships and causal factors

The principal component analysis pointed out the correlations between the individual variables and suggests that a higher number of variables will probably give enhanced weighted factors and decrease the redundancy on basins geometry (Table 2). Intra-group variation in depth, elongation, and vegetation cover (Fig. 6) explains the lack of significant differences in the geometric attributes of the basins. Significant differences in morphometrics only occurred between sectors that had very dissimilar values. Unlike the elevations of the Monegros saline wetlands, which are stable, the physiographic features were altered by anthropogenic factors (Castañeda and Herrero, 2008). Many differences between sectors are related with elevation (Fig. 6). Based on Tukey’s Test at $p<0.005$, elevation differed significantly between the wetlands which were on limestone rich sectors (S2G3 through S2G7 groups), and those which were on a gypsum rich substrate in S2 (S2G1 and S2G2) and most S1 wetlands. The S2G7 group, which had the highest mean elevation, differed significantly from the other groups.

In Monegros, the origin and development of the basins in a mixed carbonate and gypsum karst is strongly influenced by the excavation of the bedrock. Overall, the depth and elevation of the wetlands were not correlated; however, when analyzed within sectors (with S1 groups pooled), each fit a power function of the form $y= a\ x^b$, with x: excavation depth, y: elevation, and b: ranging from -0.005 to -0.031. Power functions have been widely used in landform studies to correlate variables (Denizman and Randazzo, 2000). In Figure 7, the curvatures were similar among all of the groups except S1 and S2G5. The pronounced curvature of the S1 system indicates the strong effect of elevation on depth, and the flat curve of the S2G5 group indicates the weak relationship between those parameters. The lutite-rich substrate and the elongated shape (L= 2.1) of the wetlands in the S1 groups contrasted with the predominant limestone substrate and pronounced circularity (L= 1.47) of S2G5 wetlands, probably, because of differences in the mechanisms of excavation. The S2G5 wetlands developed by limestone dissolution with negligible deflation and runoff, while the lutitic substrate of the S1 wetlands is prone to deflation, and runoff can be more intense because they are at relatively low elevations.

In addition, the wetlands groups differed in how well they fit their curves. The limestone-rich groups S2G6 and S2G7 ($R^2= 0.73$) and the gypsum-rich group S2G1 ($R^2= 0.64$) exhibited the best fit. All the other groups had $R^2<0.50$. The similar behaviors suggested by the strong fit of some of the groups might be due to their relatively homogeneous substrates. The dissimilarity between the S1 and the S2 groups is consistent with the grouping in two different hydrological systems and with the presence of the impermeable key layer of red lutites between the North Endorhreic System and South endorheic system wetlands (Fig. 5).

The power function family observed in our study was consistent with the hypothesis of Sánchez *et al.* (1998) which posited that depressions enlarge with age and maturity, and involve dissolution of the bedrock and subsidence. In addition, that hypothesis applies to basin size, which increased with depth (Fig. 3). Most of the deep playa-lakes were at low elevations; however, shallow basins were not restricted to the highest elevations. The trend showed by the power function occurred only within groups (Fig. 7) emphasizing the heterogeneity of the platform, demonstrated by hydrogeologists (García-Vera, 1996).

In contrast with the intra-group variation of the ten geologic groups of Monegros saline wetlands (Fig. 6; Table 2), the eight vegetation-based groups of Monegros saline wetlands (Fig. 5; Table 4) were significantly different in vegetation percentage ($p<0.01$), flooding frequency ($p<0.001$), and depth ($p<0.05$), denoting intra-group homogeneity. These differences are related with the dissimilarity between the pattern of the geologic groups, determined by long-lasting geomorphic processes, and that of the vegetation-based groups which is based on a much faster process related with the establishment of the plant communities. In the same way, the correlations between the mean morphometrics of the vegetation-based groups of Monegros saline wetlands were more evident. The flooding frequencies of the Monegros saline wetlands groups showed a significant ($p<0.001$) negative correlation with their elevations ($r= -0.879$), and a significant ($p<0.001$) correlation ($r= 0.939$) with their sizes (Fig. 8), indicating that wetlands maturity and functioning were better expressed on the largest dolines and at lowest elevations.

The percentages of vegetation were significantly correlated with depth ($r= 0.757$, $p<0.05$), and with perimeter ($r= 0.718$, $p<0.05$) and margin irregularity ($r= 0.839$, $p<0.01$). These relationships (Fig. 8) indicate that the conservation of the vegetation is controlled by the deepness and the irregularity of the dolines shape, in consistence with the fact that the destruction of the vegetation has been more intense in shallow dolines, especially if they were small.

Distribution patterns of the Monegros saline wetlands and implications

The flat-bottom infilled valleys, most of which did not have a creek, were difficult to identify *in situ* because of the relatively smooth topography and the agricultural imprint. The continuous detailed topography provided by digital elevation models along with aerial photographs are advantageous in identifying the network of valleys, the association valleys-dolines, and the chains of dolines in the nearly horizontal platform landscape. Wetlands associated with valleys result from the "drying up" of pre-existing valleys (Sauro, 1996; Ford and Williams, 2007). Similar associations of dolines-valleys occur elsewhere in the Ebro Basin, when a very low structurally-controlled topographic gradient occurs. In Monegros, the valleys did not appear active because downstream run-off was scarce and the infilling has been dated to the Late Pleistocene-Holocene in nearby areas (Sancho *et al.,* 2011). The capturing of the surface drainage network by small dolines has been evidenced in other areas by the alignment of dolines and sinkholes as the only evidence of the original fluvial drainage (Calaforra and Pulido-Bosch, 2003). However, no overall patterns could be determined in other gypsum karst areas as in Southern Spain (Calaforra and Pulido-Bosch, 1999) where a chaotic structure prevails without alignment of the principal axes of the dolines.

In applying the classical endorheic model to the platform in Monegros, most of the previous authors assumed that the Monegros saline wetlands were isolated basins because of the absence of surface hydrological connections. Nevertheless, the analysis of the Monegros saline wetlands patterns reveals a defined infrastructure based on the dry valleys network, indicating that a subsurface connection exists between depressions and dry valleys, as suggested by: i) the alignments of the basins following joints in continuity and combined with infilled valleys, ii) the large size of the recharge area of some of the Monegros saline wetlands (Agustín, 5km long, García-Vera, 1996), and iii) the mineralogical (Mees *et al.,* 2011, 2012) and hydrological similarities (Castañeda and Herrero, 2005) between neighboring wetlands. Previous hydrogeological studies (Berga, 1993; Álvarez, 1996; Samper-Calvete and García-Vera, 1998) demonstrated preferential flows through subsurface layers.

CONCLUSION

Our wetlands classification based upon abiotic (geology) and biotic (habitats) features was an approximation to the delineation of land units. The present study has provided saline wetlands grouping for functionality, thus, simplifying the platform system and reducing the apparent complexity of habitats capable of rapid change over time and space. The morphometric analyses of the basins indicated the platform is very complex because of the intricate geomorphic structure of the wetlands basins together with the network of infilled valleys. The spatial connection patterns between the Monegros saline wetlands and the valleys network provide preferential ways for water flows. Our grouping of Monegros saline wetlands in different sectors related to geological and vegetation features provide a predictable relationship of surficial processes with otherwise complex and undetectable hydrological connectivity. A better understanding of the Monegros saline wetlands distribution patterns can support the design and management of irrigation schemes. Heavy ecological effects of water application can be foreseen even in the areas excluded of irrigation, due to the internal connection between wetlands.

A hypothesis for the entire platform should include the current distribution of wetlands in Monegros and a model based on karstic erosion that preferentially removes gypsum and develops wetlands and valleys. This approach would help to explain and to predict the hydrological dynamics.

Our approach can be implemented in other regions around the world for integrating the geological and ecological factors driving the evolution of wetlands. Sound generalizations about the wetlands in Monegros and their distribution will allow the development of management guidelines and will be helpful for the soil surveys needed to reconcile the protection of wetlands with the new on-farm irrigation developments.

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