

## Salinity Tolerance of the Hygrophilous Plant Species in the Wetlands of the South of the Iberian Peninsula

Francisco GÓMEZ MERCADO<sup>1\*</sup>, Fernando DEL MORAL TORRES<sup>2</sup>  
 Esther GIMÉNEZ LUQUE<sup>1</sup>, Sergio DE HARO LOZANO<sup>2</sup>

<sup>1</sup> *Universidad de Almería. Campus de Excelencia Internacional Agroalimentario, CEIA3, Dpto. de Biología Vegetal y Ecología, Ctra. Sacramento s/n, E-04120 Almería, Spain; [fgomez@ual.es](mailto:fgomez@ual.es) (\*corresponding author)*

<sup>2</sup> *Universidad de Almería. Campus de Excelencia Internacional Agroalimentario, CEIA3, Dpto. de Edafología y Química Agrícola, Ctra. Sacramento s/n, E-04120 Almería, Spain*

### Abstract

The aim of this work is to evaluate with the salinity tolerance of the hygrophilous plant species recorded along the River Guadiamar (SW of the Iberian Peninsula) and in four sublittoral wetlands of the bay of Almería (SE of the Iberian Peninsula). The first of these wetlands is an Atlantic-type open wetland. The other four wetlands in Almería are closed lagoon-like wetlands. The data of each species are given and grouped in categories defined by tolerance range. The results obtained for the species found in the two sites are then compared. The salinity conditions of the soils of these two types of wetlands are also compared to discover any possible cause for differentiation. Finally, the different units of measurement of salinity available and some conversion models for them will be discussed. As a result of the present data and analysis, the study proposes a model to estimate total dissolved salts from electrical conductivity.

**Keywords:** halophytes, marshlands, saline soils, salinity, salt marshes, salt tolerance.

### Introduction

Under natural conditions of growth and development, plants are inevitably exposed to different types of stresses, such as drought, salinity, low and high temperatures, flooding and high radiation (Hessini *et al.*, 2009). Salt stress inhibits plant growth by disrupting ion and water homeostasis as well as causing oxidative stress (Cant *et al.*, 2007). The extent of growth and yield reduction due to salt stress depends on the species, duration and severity of the salt stress.

Saline conditions reduce the ability of plants to absorb water, causing rapid reductions in growth rate, and induce many metabolic changes similar to those caused by water stress (Epstein 1980). Halophytes are plants able to complete their life cycle in a substrate rich in NaCl (Schimper, 1891). One of the most important properties of halophytes is their salinity tolerance (Lieth, 1999). For obligate halophytes this substrate offers advantages for competition with salt sensitive plants (glycophytes). There is a wide range of tolerance among the 2600 known halophytes (Amzallag, 1994; Lieth and Menzel, 1999; Pasternak, 1990). However, information about these halophytes needs careful partial checking (Koyro *et al.*, 2009).

A precondition for sustainable utilization of suitable halophytes is precise knowledge about their salinity tolerance and the various mechanisms enabling a plant to grow

in (their natural) saline habitats (Ashraf, 1994; Greenway and Munns, 1980; Koyro *et al.*, 1997; Marcum, 1999; Warne *et al.*, 1999; Weber and D'Antonio, 1999; Winter *et al.*, 1999).

The impact of salinity on plants has been extensively dealt with in scientific literature, in particular as regards toxicity (Mateos Naranjo *et al.*, 2011; Parida and Das, 2005), adaptations (Koyro *et al.*, 2009; Weber, 2009), nutritional problems (Castagna *et al.*, 2009; Flowers, 2004; Martínez-Ballesta *et al.*, 2004), germination (e.g., Ahmed and Khan, 2010; Guma *et al.*, 2010; Li, 2008; Orlovsky *et al.*, 2011; Redondo Gómez *et al.*, 2011; Vicente *et al.*, 2009), biodiversity (El Shaer, 2009), etc. However, there are not many studies on the salinity tolerance of wild plants. In this sense, it must mention the work of Álvarez Rogel *et al.* (2001, 2006, 2007) Pujol *et al.* (2000) and Redondo Gómez *et al.* (2004, 2007, 2008, 2010).

The aim of this study has been three-fold: firstly, to determine the salinity tolerance ranges for the hygrophilous plants growing in the wetlands of the south of the Iberian Peninsula; secondly, to compare the salinity conditions of an Atlantic wetland (open marshland) and a Mediterranean wetland (closed salt marsh); thirdly, to provide data for the conversion of salinity measurements into weight/volume percentage (% w/v), total dissolved salts (TDS g·L<sup>-1</sup>) and electrical conductivity (EC dS·m<sup>-1</sup>).

## Material and methods

### Study area

In this paper results obtained in the area of the River Guadiamar and four littoral wetlands of the bay of Almería (Fig. 1) located in the south of the Iberian Peninsula in the Mediterranean region are shown.

The Guadiamar River is located in the Corredor Verde del Guadiamar, a narrow strip of land about 100 km long and 7900 ha in area connecting the natural parks of Arcena and Picos de Aroche and the Sierra Norte of Seville with the marshlands of the River Guadalquivir (Doñana National Park) where it flows into the Atlantic Ocean. In its upper reaches the river runs over metamorphic materials belonging biogeographically to the Lusitan-Extremaduran Province (Marianic-Monchiquensean Sector) (Rivas Martínez *et al.*, 1997). In its middle reaches the soils are marly-sandy materials of the Betic Province (Hispalensean Sector) and in the lower reaches the terrain adopts the form of a typically marsh-like, mud-clay plain in the Gaditan-Onubensean-Algarvian Province (Gaditan-Onubensean Sector). The bioclimate (Rivas Martínez and Loidi, 1999) is Mediterranean, pluvisasonal-oceanic with two thermotypes, namely, thermomediterranean and mesomediterranean, and two ombrotypes: dry and subhumid.

The wetlands under study in the bay of Almería (Mediterranean coast) are the following: Charcones de Punta

Entinas (131 ha), Salinas de Cerrillos (480 ha), Salinas del Cabo de Gata (312 ha) and Desembocadura de la Rambla Morales (6 ha). These are more or less closed sublittoral wetlands of brackish, salty water coming from the water table or from the sea. The Salinas de Cabo de Gata are still worked for the production of salt and receive a regular supply of sea water. The Salinas de Cerrillos have not been worked since 1988. In biogeographical terms, these sites are located in the Murcian-Almeriensean Province (Almeriensean Sector) and in bioclimatic terms they have a desert-like oceanic bioclimate with a lower thermomediterranean thermotype and a lower semiarid ombrotype.

### Data collection and plant species

To study the behaviour of the plant species recorded in the River Guadiamar (Tab. 1) it was selected 28 plots located along the course of the river. In each of these plots it has been made a relevé of the species present and took a soil sample to estimate EC and Na<sup>+</sup> content of the saturation extract. In the wetlands of the bay of Almería first has been draw a grid of 63 sampling plots in the form of 4x4 m squares (16 m<sup>2</sup>) arranged as transects perpendicular to the banks of the lagoons. The distance between plots and the number of plots per transect (2 to 4) was determined by the vegetation profile. In order to take into account the seasonal fluctuations of the variables under study (EC, Na<sup>+</sup> and TDS), each of the plots was sampled every three

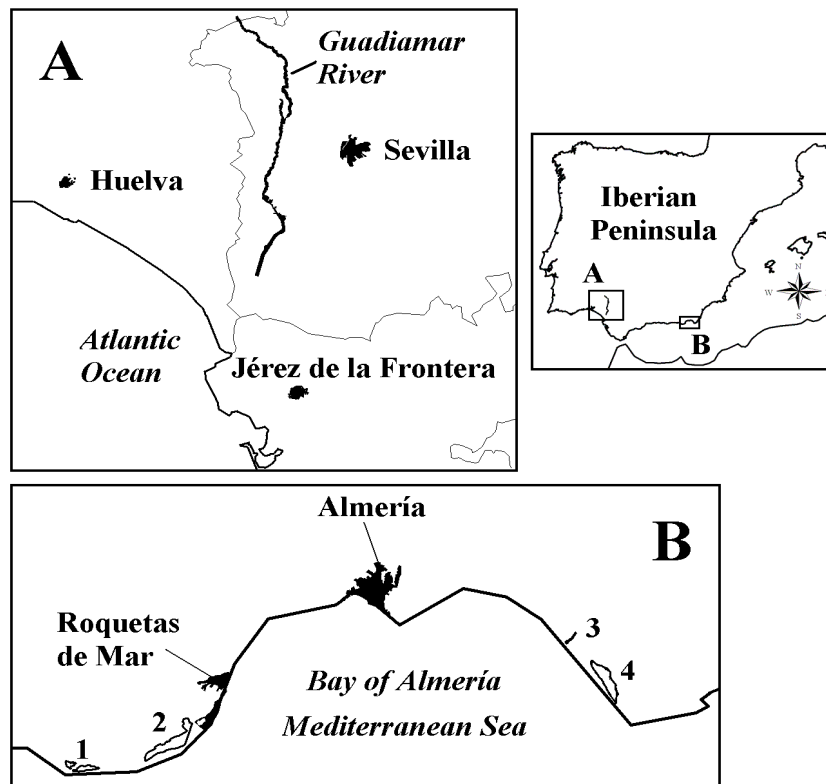


Fig. 1. Location of the study area. A: River Guadiamar. B: Bay of Almería. 1 Charcones de Punta Entinas. 2 Salinas de Cerrillos. 3 Desembocadura de la Rambla Morales. 4 Salinas de Cabo de Gata

months for two years (8 replications). It has been also estimated the vegetation cover rate and the species present (Tab. 1).

The soil sample was made up of five subsamples uniformly distributed in the area under study and reached a final volume equivalent to 3 dm<sup>3</sup>. Soil samples were taken at a depth of 30 cm, whatever the existing horizon sequence (Díaz-Maroto and Vila-Lameiro, 2008; Hagen-Thorn *et al.*, 2004). Soil samples were sieved through a 2 mm screen after removing any plant materials and roots. Electrical conductivity in soil saturation extracts (Rhoades, 1996) was measured by means of a Crison conductimeter 522. Ca<sup>++</sup> and Mg<sup>++</sup> were determined by absorption spectrophotometry (Perkin Elmer AA400), Na<sup>+</sup> and K<sup>+</sup> by flame photometry (Jenway PFP7). Cl<sup>-</sup>, NO<sub>3</sub><sup>-</sup> and SO<sub>4</sub><sup>=</sup> by ionic chromatography (Dionex ICS1000) using a HCO<sub>3</sub>/CO<sub>3</sub> buffer as the mobile phase. HCO<sub>3</sub><sup>-</sup> was measured by titration. The data obtained in this manner was used as a base to estimate total dissolved salts and, except for the Na<sup>+</sup> content, are not shown in this paper.

#### Data analysis methods

The minimum, average and maximum values for each of the variables concerned were estimated using the ana-

lytical results obtained from the samples taken in the plots where each of the plant species under study was recorded. Of the 504 EC-TDS data obtained, as experimental results, from the samples taken in the wetlands of the bay of Almería, 402 (80%) were used to adjust the regression models and 102 (20%) to validate these models. A linear regression model, without including the constant, for all the data and the partial models for the different conductivity ranges were proposed. In this last case, the same proportion of data for the calculation of the models as for their validation was maintained.

#### Results and discussion

##### Ranges of salinity tolerance of the hygrophilous species

Salinity refers to the presence in the soil of salts whose solubility is equal to or higher than that of gypsum (2.4 g·L<sup>-1</sup>). The most common salts are: NaCl, MgCl<sub>2</sub>, Na<sub>2</sub>SO<sub>4</sub>, CaSO<sub>4</sub>, MgSO<sub>4</sub>, Ca (HCO<sub>3</sub>)<sub>2</sub> and Mg (HCO<sub>3</sub>)<sub>2</sub>. Na<sub>2</sub>CO<sub>3</sub> and NaHCO<sub>3</sub> are relatively rare but have a great impact on alkalinity. Salts that are not very soluble (CaCO<sub>3</sub>, MgCO<sub>3</sub> and even CaSO<sub>4</sub>) precipitate before reaching harmful levels for plants.

Tab. 1. Species studied along the River Guadiamar and in the bay of Almería with full names and number of samples (N) for each one

River Guadiamar		Bay of Almería	
Species	N	Species	N
<i>Alnus glutinosa</i> (L.) Gaertner	1	<i>Arthrocnemum macrostachyum</i> (Moric.) Moris	240
<i>Arthrocnemum macrostachyum</i> (Moric.) Moris	7	<i>Asparagus horridus</i> L.	8
<i>Flueggea tinctoria</i> (L.) G.L. Webster	4	<i>Asteriscus maritimus</i> (L.) Less.	8
<i>Fraxinus angustifolia</i> Vahl	7	<i>Atriplex halimus</i> L.	16
<i>Juncus acutus</i> L.	3	<i>Cynanchum acutum</i> L.	8
<i>Nerium oleander</i> L.	5	<i>Frankenia corymbosa</i> Desf.	128
<i>Phragmites australis</i> (Cav.) Trin. ex Steud.	5	<i>Halimione portulacoides</i> (L.) Aellen	56
<i>Populus alba</i> L.	4	<i>Inula critmoides</i> L.	112
<i>Salix salviifolia</i> Brot.	1	<i>Juncus acutus</i> L.	64
<i>Sarcocornia fruticosa</i>	8	<i>Juncus maritimus</i> Lam.	88
<i>Scirpus maritimus</i> subsp. <i>compactus</i> Hoffm.	11	<i>Juncus subulatus</i> Forskäl	8
<i>Spartina densiflora</i> Brongn.	5	<i>Limonium cossonianum</i> Kuntze	56
<i>Suaeda vera</i> Forssk. ex J.F. Gmel.	2	<i>Limonium delicatulum</i> (Girard) Kuntze	128
<i>Tamarix africana</i> Poir.	1	<i>Lycium intricatum</i> Boiss.	72
<i>Tamarix mascatensis</i> Bunge	1	<i>Phragmites australis</i> (Cav.) Trin. ex Steud.	104
<i>Ulmus minor</i> Mill.	3	<i>Salicornia ramosissima</i> J. Woods	8
		<i>Salsola vermiculata</i> L.	8
		<i>Sarcocornia fruticosa</i> (L.) A. J. Scott	104
		<i>Sarcocornia perennis</i> subsp. <i>alpini</i> (Lag.) Castrov.	256
		<i>Sporobolus pungens</i> (Schreb.) Kunth	32
		<i>Suaeda vera</i> Forssk. ex J.F. Gmel.	96
		<i>Tamarix boveana</i> Bunge	8
		<i>Tamarix gallica</i> L.	8
		<i>Tamarix canariensis</i> Willd.	88
		<i>Typha domingensis</i> Pers.	8

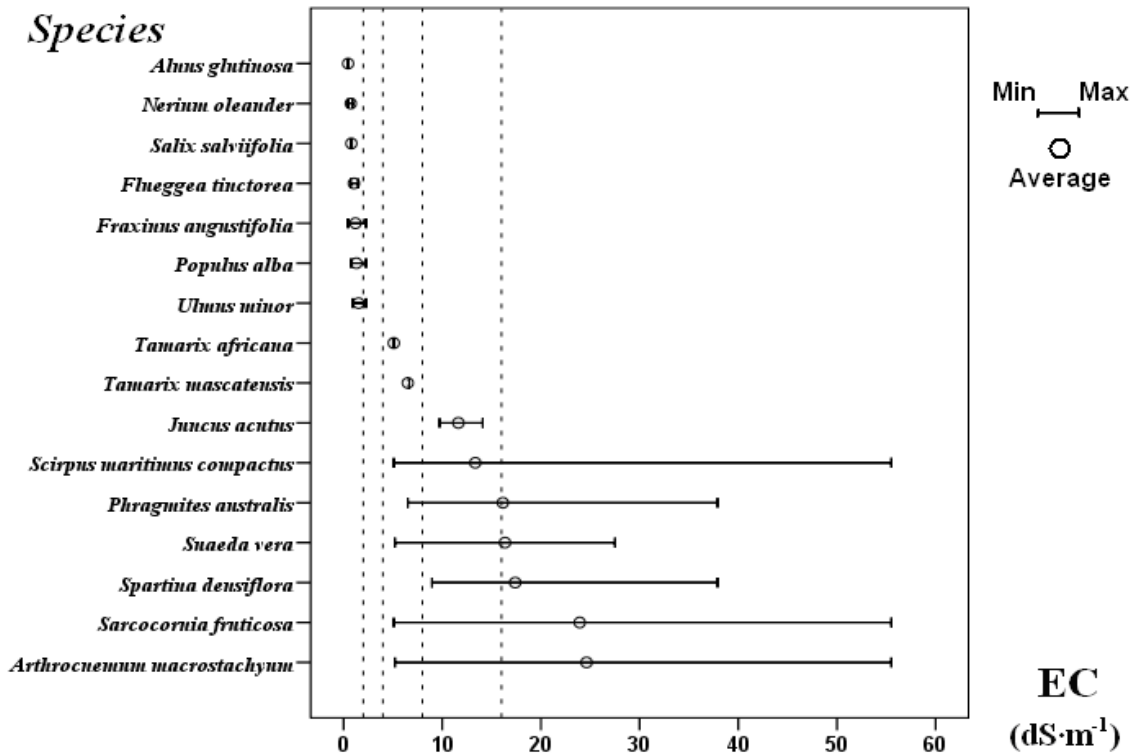


Fig. 2. Ranges of tolerance to electrical conductivity recorded for 16 species along the River Guadamar. Vertical dotted lines show the EC intervals in saturation extracts proposed by Abrol *et al.* (1988) to evaluate saline conditions: 0-2 dS·m<sup>-1</sup> «non saline»; 2-4 dS·m<sup>-1</sup> «slightly saline»; 4-8 dS·m<sup>-1</sup> «moderately saline»; 8-16 dS·m<sup>-1</sup> «strongly saline»; >16 dS·m<sup>-1</sup> «very strongly saline»

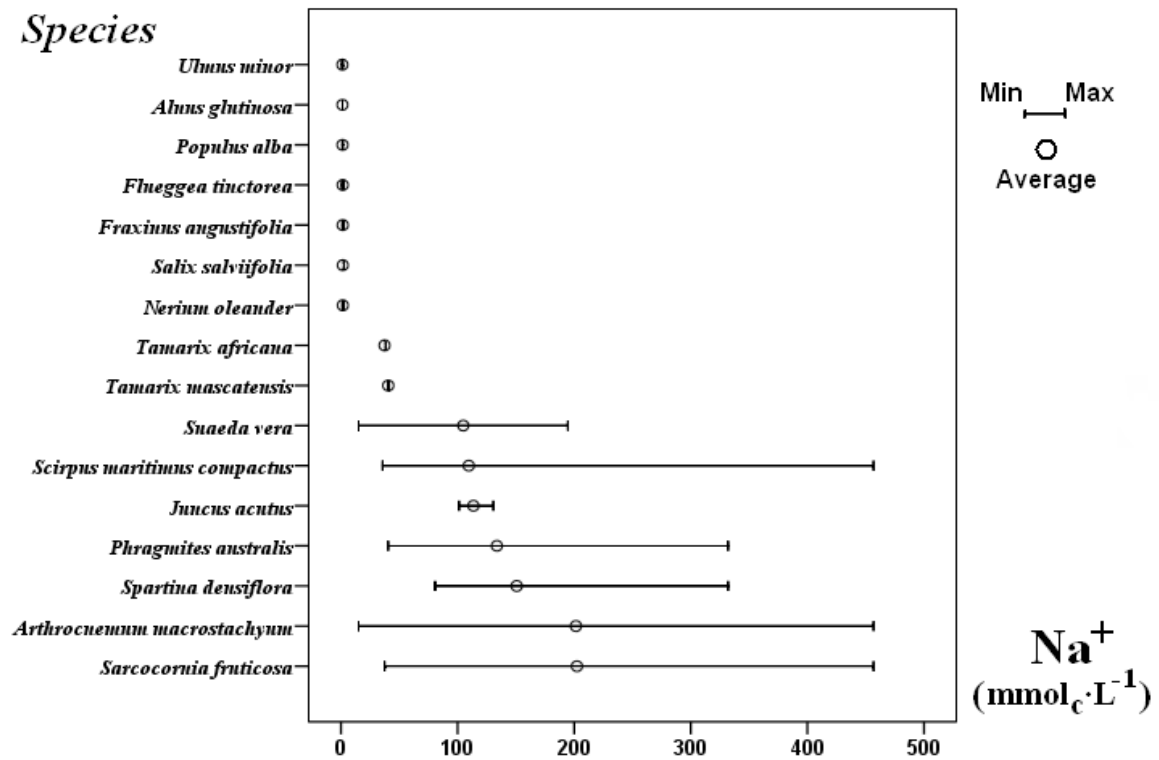


Fig. 3. Ranges of tolerance to Na<sup>+</sup> recorded for 16 species along the River Guadamar

Along the course of the River Guadiamar it was found a succession of hygrophilous species which replace one another, among other reasons, by virtue of their salinity tolerance. At the river headwaters (Lusitan-Extremadurean territory) species such as *Alnus glutinosa*, *Nerium oleander*, *Salix salviifolia* or *Flueggea tinctoria* are found. These species belong to the «non saline» interval (0-2 dS·m<sup>-1</sup>) (Fig. 2), as defined in the arrangement proposed by Abrol *et al.* (1988), which sorts salinity records by the electrical conductivity of the saturation extract. The Na<sup>+</sup> content of the saturation extract of these soils is below 2.3 mmol<sub>c</sub>·L<sup>-1</sup> in all cases (Fig. 3). In both cases the ranges are very narrow. In the middle reaches of the river (Hispalensean territory) these species are replaced by others which, in some cases, co-occurred in the upper reaches of the river. According to the salinity tolerance of these species they can be described as «slightly saline» (2-4 dS·m<sup>-1</sup>), with maximum values just over 2 dS·m<sup>-1</sup>. This is the case of *Fraxinus angustifolia*, *Populus alba* and *Ulmus minor*. Their Na<sup>+</sup> content is extremely low and similar to the previously mentioned species. In the lower reaches of the Hispalensean territory,

where conditions already indicate a transition towards areas influenced only to a small degree by the tidal flow, it was found species such as *Tamarix africana* and *T. mascatensis*, which tolerate «moderately saline» conditions, between 4 and 8 dS·m<sup>-1</sup>. Here the Na<sup>+</sup> content reaches values close to 50 mmol<sub>c</sub>·L<sup>-1</sup>. When the tidal influence is very strong (lower reaches of the river, in the Gaditan-Onubensean territory), species such as *Juncus acutus* and *Scirpus maritimus* subsp. *compactus* appear. The average salinity values of these species fall within the «strongly saline» interval (8-16 dS·m<sup>-1</sup>), although the maximum value of *S. maritimus* subsp. *compactus* is above 55 dS·m<sup>-1</sup>. The average Na<sup>+</sup> content of these species is over 100 mmol<sub>c</sub>·L<sup>-1</sup>, and *S. maritimus* reaches 450 mmol<sub>c</sub>·L<sup>-1</sup>. Consequently, these species can be considered as typically marsh-loving plants. *Phragmites australis*, *Suaeda vera*, *Spartina densiflora*, *Sarcocornia fruticosa* and *Arthrocnemum macrostachyum* exhibit average EC values above 16 dS·m<sup>-1</sup> (i.e., within the «very strongly saline» interval) and wide tolerance ranges. The average Na<sup>+</sup> values are above 130 mmol<sub>c</sub>·L<sup>-1</sup>, with maximum values of 456.73 mmol<sub>c</sub>·L<sup>-1</sup>.

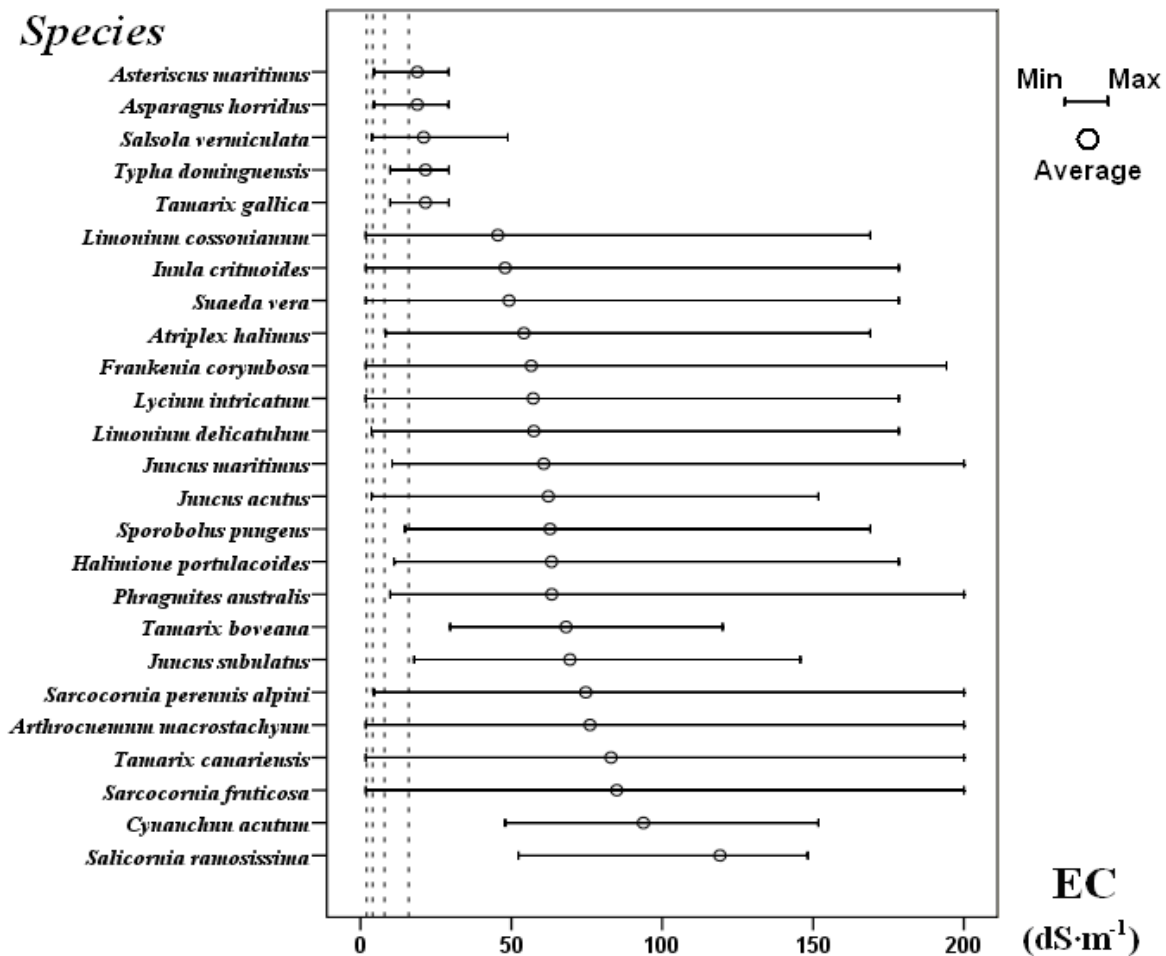


Fig. 4. Ranges of tolerance to EC for 25 species of the wetlands of the bay of Almería. Vertical dotted lines show the EC intervals in saturation extracts proposed by Abrol *et al.* (1988) to evaluate saline conditions: 0-2 dS·m<sup>-1</sup> «non saline»; 2-4 dS·m<sup>-1</sup> «slightly saline»; 4-8 dS·m<sup>-1</sup> «moderately saline»; 8-16 dS·m<sup>-1</sup> «strongly saline»; >16 dS·m<sup>-1</sup> «very strongly saline»

All the species found in the samples taken in the wetlands of the bay of Almería lie within the salinity interval of «very strongly saline», with average EC values over 16 dS·m<sup>-1</sup> (Fig. 4).

*Asteriscus maritimus* (average EC = 18.82 dS·m<sup>-1</sup>), *Asparagus horridus* (average EC = 18.82 dS·m<sup>-1</sup>), *Salsola vermiculata* (average EC = 20.93 dS·m<sup>-1</sup>), *Typha dominguensis* (average EC = 21.55 dS·m<sup>-1</sup>) and *Tamarix gallica* (average EC = 21.55 dS·m<sup>-1</sup>) appear at the lowest end of this interval and exhibit narrow tolerance ranges. Their maximum values are close to 30 dS·m<sup>-1</sup> (48.8 in the case of *Salsola vermiculata*). They tend to grow either in the periphery of the lagoons, where sea water has little or no influence, or in places usually water-logged with less saline groundwater, as in the case of *Typha dominguensis*. Na<sup>+</sup> average contents in the saturation extract are about 150 mmol<sub>c</sub>·L<sup>-1</sup>, with maximum values close to 250 mmol<sub>c</sub>·L<sup>-1</sup>. *Salsola vermiculata* has an average value of 183.62 and a maximum value of 439.18 mmol<sub>c</sub>·L<sup>-1</sup>.

The rest of the species tolerate average EC values above 45 dS·m<sup>-1</sup> with *Salicornia ramosissima* reaching 119.15 dS·m<sup>-1</sup>. Tolerance ranges are extremely wide due to the strong fluctuations induced by the flooding-drying cycle of the lagoons. In most cases, maximum values are close to 200 dS·m<sup>-1</sup>. A similar pattern is found for Na<sup>+</sup> and TDS. Average Na<sup>+</sup> values vary from 500 to 1500 mmol<sub>c</sub>·L<sup>-1</sup> with

maximum values as high as 4868.29 mmol<sub>c</sub>·L<sup>-1</sup> in the case of *Sarcocornia perennis* subsp. *alpini*. Average TDS values range between 45 and 130 g·L<sup>-1</sup> with an absolute maximum value of 368.71 g·L<sup>-1</sup> corresponding again to *S. alpini*.

NaCl, MgCl<sub>2</sub> and MgSO<sub>4</sub> are the predominant salts in sea water and Na<sub>2</sub>SO<sub>4</sub> can occur as a result of the presence of the others. For this reason it is not surprising that they are also the most frequent salts in the soils. Many of the current problems concerning soil salinity derive, more or less directly, from the ancient presence of sea salts.

The first problem brought about by a high concentration of soluble salts is the excessive increase in the osmotic pressure (decrease in the osmotic potential), which prevents unadapted plants from absorbing water adequately.

Another fundamental problem is the result of the presence of alkalinized Na<sup>+</sup> (derived from Na<sub>2</sub>CO<sub>3</sub> and NaHCO<sub>3</sub>) in relatively high concentrations. It is the colloidal dispersion originated by this strong dispersing agent that destroys the soil structure with the ensuing decrease in soil permeability and aeration. This effect induces water-logging, reducing conditions, reduced biological activity, root suffocation, etc. Consequently, it must distinguish between saline soils, which, strictly speaking, always show a high content of soluble salts (of these sodium salts are usually absent) and alkali soils, where, although they are not necessarily high in salt concentration, most salts are

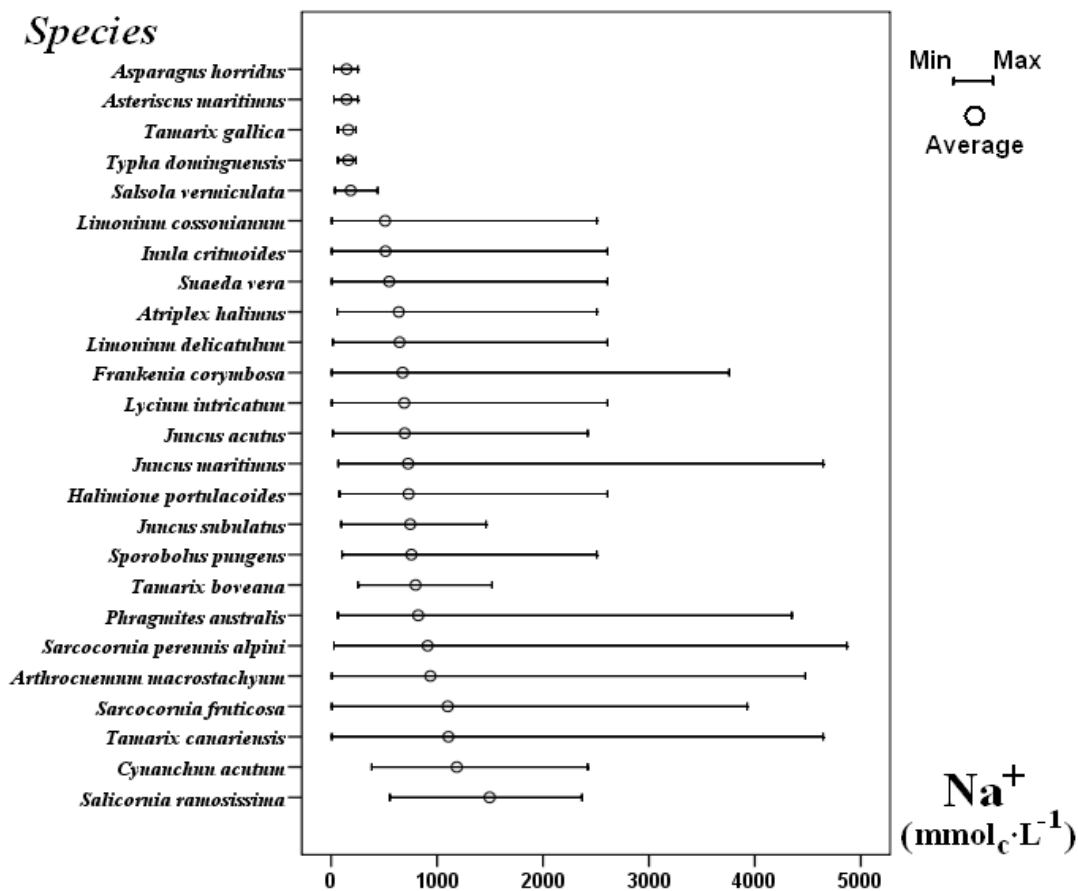


Fig. 5. Ranges of tolerance to Na<sup>+</sup> for 25 species of the wetlands of the bay of Almería

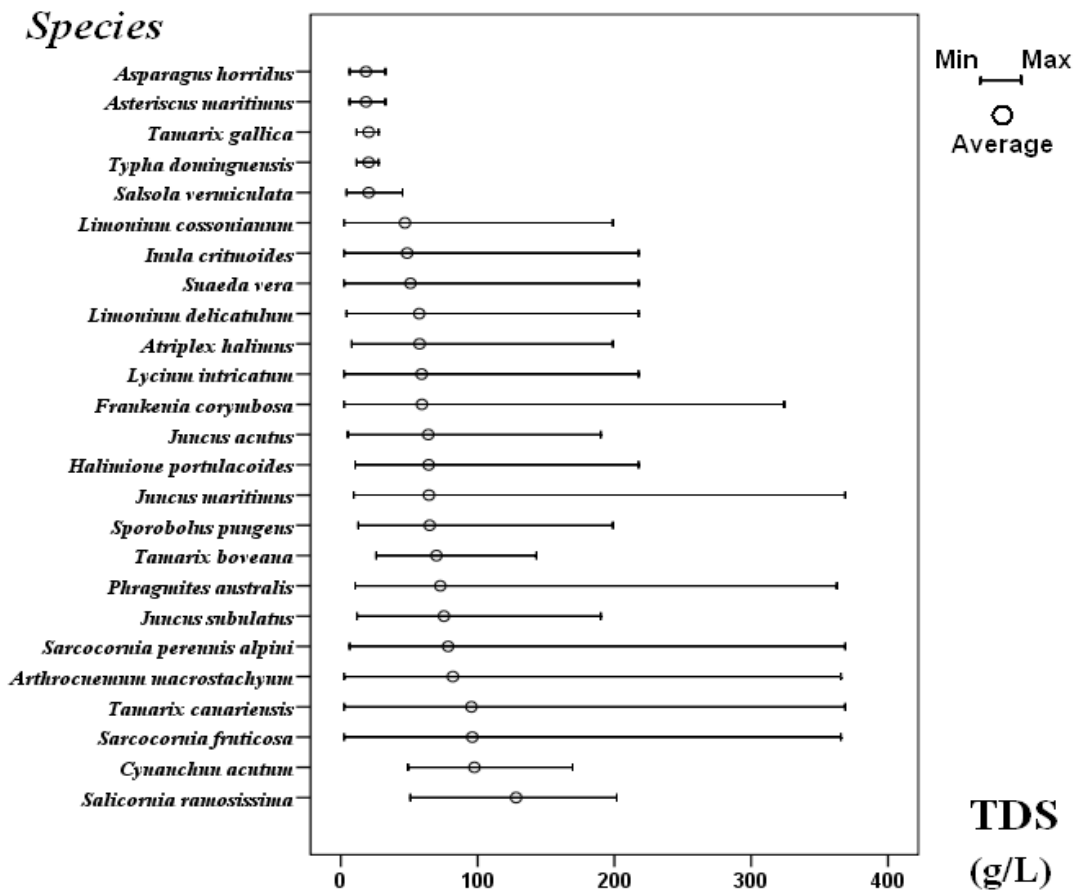


Fig. 6. Ranges of tolerance to TDS for 25 species of the wetlands of the bay of Almería

alkalizing. There are also saline-alkali soils with an in-between soil profile.

Although some authors consider that soil is saline when its total salt content is over 1%, most researchers see the threshold at 1% content (Marañés *et al.*, 1998), which is when many plants begin to be affected. A value of 4 dS·m<sup>-1</sup> for the electrical conductivity (EC) in the water extracted from a saturated paste at 25 °C is usually accepted as the limit for a saline character (Abrol *et al.*, 1988). Likewise, soil is usually regarded as alkaline (sodium soils) when the exchangeable sodium percentage (ESP), as compared to the total fixed cations, is equal to or higher than 15% (Abrol *et al.*, 1988). This value corresponds to a sodium adsorption ratio (SAR) ≈ 13.

Along the River Guadiamar it was found a salinity gradient (increasing EC and Na<sup>+</sup> values) which shows that plant species are replaced according to their ability to endure such conditions. Consequently, this is an ideal scenario for the study of the limits of tolerance to salinity among the different groups of species. The most significant thresholds were the following:

a) EC < 2 dS·m<sup>-1</sup>; Na<sup>+</sup> < 2.3 mmol·L<sup>-1</sup>. Here it was found non halophilous species, such as *Alnus glutinosa*, *Nerium oleander*, *Salix salviifolia* or *Flueggea tinctoria*.

b) 2 dS·m<sup>-1</sup> < EC < 5 dS·m<sup>-1</sup>; Na<sup>+</sup> < 2.3 mmol·L<sup>-1</sup>. Here it was found non halophilous species, such as *Fraxinus an-*

*gustifolia*, *Populus alba* and *Ulmus minor*, able to tolerate moderate salinity.

c) EC > 5 dS·m<sup>-1</sup>; Na<sup>+</sup> > 2.3 mmol·L<sup>-1</sup>. The previous species disappear and are replaced by typically halophilous taxa, such as *Tamarix africana*, *T. mascatensis*, *Juncus acutus*, *Scirpus maritimus* subsp. *compactus*, *Phragmites australis*, *Suaeda vera*, *Spartina densiflora*, *Sarcocornia fruticosa* and *Arthrocnemum macrostachyum*, which compete successfully under these conditions. In the Almeriense wetlands, where the salinity values are, at least seasonally, much higher than those found along the River Guadiamar, it has been observed that some of these species tolerate much higher salinity. This is the case of *Sarcocornia fruticosa*, *Arthrocnemum macrostachyum* or *Phragmites australis*, which can survive with an EC of 200 dS·m<sup>-1</sup>, Na<sup>+</sup> values close to 4500 mmol·L<sup>-1</sup> and TDS values over 365 g·L<sup>-1</sup>.

#### Comparative analysis of the salinity conditions of an Atlantic wetland and a Mediterranean wetland

Along the River Guadiamar it was taken some samples with EC values varying from 0.46 to 55.50 dS·m<sup>-1</sup> and Na<sup>+</sup> concentrations in the saturation extract between 0.79 and 456.73 mmol·L<sup>-1</sup>. In the wetlands of the bay of Almería the EC values range from 1.74 to 200.00 dS·m<sup>-1</sup>. Na<sup>+</sup> concentration varies from 5.95 to 4868.29 mmol·L<sup>-1</sup>. The recorded TDS values lie between 2.46 and 368.71 g·L<sup>-1</sup>.

Few species are found both along the River Guadiamar (Atlantic wetland) and in the wetlands of the bay of Almería (Mediterranean wetlands). These are always halophilous species which, in the case of the River Guadiamar, are restricted to the marshes in the lower reaches

#### Conversion of salinity measurements

As already suggested by many authors (Abrol *et al.*, 1988; APHA, 1992), there is a close co-relation between the recorded EC values of the saturation extract and TDS (Tab. 2).

Tab. 2. Linear regression models, excluding interception, estimated for all the samples (general model) and for samples sorted by intervals. N indicates the number of samples used to adjust the model. TDS in  $\text{g}\cdot\text{L}^{-1}$  and EC in  $\text{dS}\cdot\text{m}^{-1}$

	N	Model	p value	R <sup>2</sup>	95% Confidence interval for slope
General model	402	TDS = 1.161·EC	<0.001	0.938	1.132-1.190
0<EC<100 $\text{dS}\cdot\text{m}^{-1}$	279	TDS = 0.954·EC	<0.001	0.967	0.934-0.975
100<EC<175 $\text{dS}\cdot\text{m}^{-1}$	100	TDS = 1.114·EC	<0.001	0.972	1.077-1.152
EC>175 $\text{dS}\cdot\text{m}^{-1}$	23	TDS = 1.490·EC	<0.001	0.954	1.345-1.635

of the river, especially *Juncus acutus*, *Phragmites australis*, *Suaeda vera*, *Sarcornia fruticosa* and *Arthrocnemum macrostachyum*. For all of them, the salinity values recorded in the Almeriense wetlands are considerably higher than those in the marshlands of the River Guadiamar. These differences reveal the general conditions of both wetlands. The Atlantic marshlands are open ecosystems undergoing a regular fresh water supply and the ebb and flow of sea tides. By contrast, the Mediterranean lagoons (*albuferas*) are relatively closed systems with little fresh water supply and sea water flooding their salt marshes. In the very dry summer season, these lagoons are almost completely dried up through evaporation, which dramatically increases the salt concentration in the soil. Less soluble salts ( $\text{CaCO}_3$ ,  $\text{MgCO}_3$  and  $\text{CaSO}_4$ ) precipitate and the soil solution is enriched with ions from the more soluble salts, such as  $\text{Na}^+$ ,  $\text{Cl}^-$  or  $\text{SO}_4^{2-}$ . The regular flooding and drying cycles keep supplying new salts to the soil with a progressive increase in the total concentration. In the Atlantic marshlands like those of the River Guadiamar, these flooding and drying cycles are very short as they are mainly affected by tidal influence and not only by seasonal effects. Consequently, salt concentrations higher than those of sea water are very rare. By contrast, in the typically open Almeriense *albuferas* and marshes, salt concentrations up to 4 times higher than those of sea water have been recorded.

Redondo Gómez *et al.* (2006, 2010), following Rubio Casal *et al.* (2001), found *Arthrocnemum macrostachyum* in the salt marshes of the Odiel and Tinto rivers, in soils with an EC between 1.6 and 85.8  $\text{dS}\cdot\text{m}^{-1}$ . Likewise, Sánchez *et al.* (1998), working in the marshes of the Rias of Ortigueira and Ladrado (Galicia, northwest Spain) found *Halimione portulacoides*, *Juncus maritimus*, *Spartina maritima*, *Scirpus maritimus* and *Phragmites australis* growing under EC conditions below 40  $\text{dS}\cdot\text{m}^{-1}$ . These EC values are similar to the records corresponding to the marshlands of the River Guadiamar, but are still well below the maximum values recorded in the Almeriense wetlands, which often reach values close to 200  $\text{dS}\cdot\text{m}^{-1}$ .

The application of a linear model to all the data recorded in the Almeriense wetlands has revealed the following co-relation:  $\text{TDS} (\text{g}\cdot\text{L}^{-1}) = 1.161 \text{ EC} (\text{dS}\cdot\text{m}^{-1})$ . The model shows high residues for high EC values, with the ensuing loss of predictive capability, so in order to improve the possibility of extrapolating it to other wetlands with lower saline concentrations (as in the River Guadiamar) it has been decided to calculate partial models according to the following intervals: 0<EC<100  $\text{dS}\cdot\text{m}^{-1}$ , 100<EC<175  $\text{dS}\cdot\text{m}^{-1}$  and EC>175  $\text{dS}\cdot\text{m}^{-1}$ .

With the models calculated in this manner it was made predictions of TDS and compared them with the data reserved for validation. This enabled to estimate the mean absolute error (MAE) and the root mean square error (RMSE) and to determine the accuracy of each of the models. The partial model developed for the lowest EC interval (Tab. 3) reduces by 45% the MAE and by 41% the RMSE as compared with the predictions made using the general model. This means a considerable increase in the global accuracy of the predictions. Similarly, in the highest EC interval the partial model reduces by 52% the MAE and by 51% the RMSE. Only in the middle interval of conductivity do both models behave in a similar way.

When reviewing scientific literature dealing with soil salinity one of the problems is the disparity of the units of measurement used. It can be often found salinity expressed as the salt content in weight divided by the unit of volume of the solution ( $\text{mg}\cdot\text{L}^{-1}$  or  $\text{g}\cdot\text{L}^{-1}$ ) or by the unit of weight of soil ( $\text{mg}\cdot\text{kg}^{-1}$  or  $\text{g}\cdot\text{kg}^{-1}$ ). Both units can also

Tab. 3. Mean absolute error (MAE) and root mean square error (RMSE) for the general model and for each of the partial models. N shows the number of samples used in the validation process

	N	General model		Partial models	
		MAE	RMSE	MAE	RMSE
0<EC<100 $\text{dS}\cdot\text{m}^{-1}$	70	11.009	13.977	5.988	8.254
100<EC<175 $\text{dS}\cdot\text{m}^{-1}$	25	21.391	26.61	20.349	26.878
EC>175 $\text{dS}\cdot\text{m}^{-1}$	7	83.929	93.592	40.274	45.804

be found expressed in terms of parts per million (ppm) or parts per thousand (ppt), either referred to weight per unit of volume ( $\text{ppm} = \text{mg}\cdot\text{L}^{-1}$ ;  $\text{ppt} = \text{g}\cdot\text{L}^{-1}$ ) or to weight per unit of weight ( $\text{ppm} = \text{mg}\cdot\text{kg}^{-1}$ ;  $\text{ppt} = \text{g}\cdot\text{kg}^{-1}$ ). Another usual form of expressing salinity records is in percentages (%), or in percentage per thousand (‰ or ppt). This last option derives from the traditional way of expressing sea water salinity, whose interpretation is similar to those previously mentioned ( $\% = \text{g salt} / 100 \text{ mL of solution}$ ;  $\text{‰} = \text{g salt} / \text{L of solution}$ ). The estimation of these units of measurement requires an exhaustive analysis of the ion content of the solutions, a procedure which is both time and money-consuming. Not surprisingly, methods have been developed to estimate solution salinity by means of indirect, quicker and cheaper measurements. Probably the most widely known of these methods involves the direct estimation of the electrical conductivity of the solution as a means to determine salinity. In the International Systems of Units the unit of measurement of electrical conductivity is the siemens (S), and to measure the electrical conductivity of the soil saturation extract the  $\text{dS}\cdot\text{m}^{-1}$  record at 25 °C is normally used. However, other units of measurement, such as  $\text{mS}\cdot\text{cm}^{-1}$ ,  $\text{mmho}\cdot\text{cm}^{-1}$  or  $\mu\text{mho}\cdot\text{cm}^{-1}$  ( $1 \text{ mmho}\cdot\text{cm}^{-1} = 1 \text{ mS}\cdot\text{cm}^{-1} = 1 \text{ dS}\cdot\text{m}^{-1}$ ), are also common practice. It can be estimate TDS ( $\text{g}\cdot\text{L}^{-1}$ ) by multiplying EC ( $\text{dS}\cdot\text{m}^{-1}$ ) by a empirically determined factor (APHA, 1992, standard method 2510) which varies from 0.55 to 0.9. One of the most commonly used values for this factor is 0.64 (TDS = 0.64EC), although this adjustment is only valid for EC < 5  $\text{dS}\cdot\text{m}^{-1}$  (Abrol *et al.*, 1988; USSLS 1954). The factor obtained from the samples taken in the Almeriense wetlands for much higher EC ranges is also higher, either close to or higher than 1 (Tab. 2).

However, in highly concentrated solutions the direct measurement of the electrical conductivity does not always provide a reliable estimation of the real concentration of salts. As a result, scientific researchers of saline environments often use the practical salinity unit (psu), which originated in oceanographic studies and is defined as the ratio of the conductivity of the sample (measured at 1 atmosphere and 15 °C) to the conductivity of a KCl solution containing 32.4356 g of KCl per kg of solution. The sample salinity (S), expressed in ‰, is estimated, according to Lewis (1980), as follows:

$$S = 0.008 - 0.1692K^{1/2} + 25.3851K + 14.0941K^{3/2} - 7.0261K^2 + 2.7081K^{5/2}$$

where K represents the ratio, mentioned above, between conductivities. The previous equation is valid for the range  $2\text{‰} \leq S \leq 42\text{‰}$ .

Other equations have also been published for estimating salinity values in % [ $\% (\text{w/v}) = 10 \cdot \text{TDS} (\text{g}\cdot\text{L}^{-1})$ ] from the EC and the moisture content at saturation (Hsat) (Simón *et al.*, 1980):

$$\% \text{ salt (w/v)} = 0.075 \cdot \text{EC} (\text{dS}\cdot\text{m}^{-1}) + 0.0261 \cdot \text{Hsat} (\%) - 1.264$$

If it is apply the models of Abrol *et al.* (1988), APHA (1992) with a factor of 0.9, that of Simón *et al.* (1980) and the present general model to the data reserved for validation, it can be observe in Tab. 4 and Fig. 7, that the least reliable predictions based on the estimation of the mean absolute error (MAE) and the root mean square error (RMSE) correspond to Abrol's model and the best are ours. On the other hand, the model by Simón *et al.* (1980) produces negative values for EC < 10  $\text{dS}\cdot\text{m}^{-1}$ .

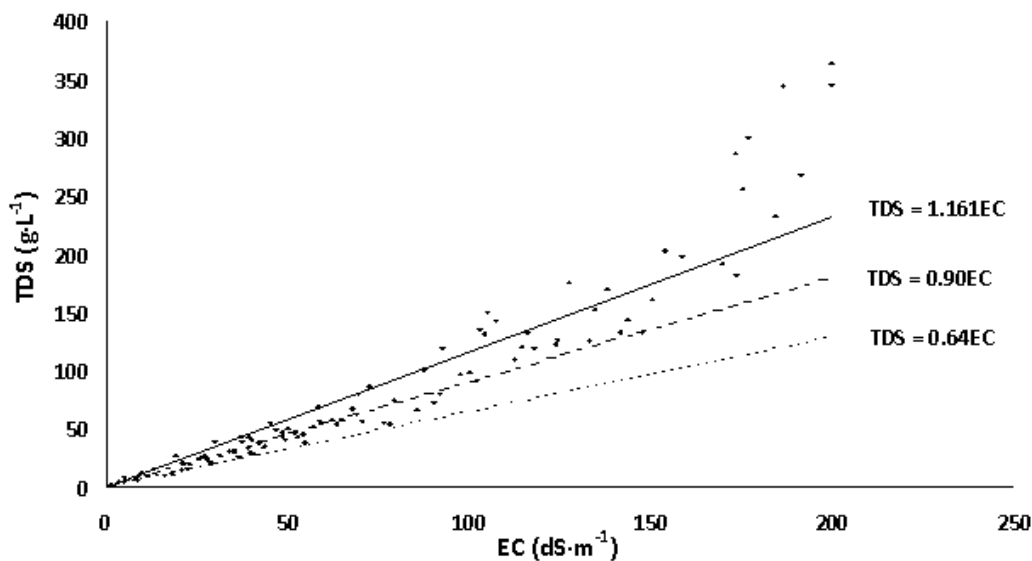


Fig. 7. EC-TDS dispersion graph of the samples used to validate the models. The lines shown in the Fig. belong to three of the four models under study, with their corresponding equations. The model by Simón *et al.* (1980) has not been plotted because it includes two predictive variables

Tab. 4. Mean absolute error (MAE) and root mean square error (RMSE) for four models. N shows the number of samples used in the validation process

Models	Equation	N	MAE	RMSE
Abrol <i>et al.</i> (1988)	TDS = 0.64·EC	102	37.20	6.17
Simón <i>et al.</i> (1980)	TDS = 0.75·EC + 0.261·Hsat - 12.64	102	29.75	5.19
APHA (1992)	TDS = 0.9·EC	102	20.72	4.23
General model	TDS = 1.161·EC	102	18.56	2.98

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