IMAGING THE EFFECT OF DYNAMIC INTERACTIONS BETWEEN FRESH AND SEA WATER ON THE SALINITY OF AN AQUIFER-COASTAL WETLAND SYSTEM: THE RESTORED LA PLETERA SALT MARSH LAGOONS (CATALONIA, NE SPAIN)

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Abstract

One important issue in restoration and management projects of coastal wetlands is the challenge of how to establish the environmental conditions under which the final saline status of the system ensures a fluctuation degree compatible with the ecosystem requirements. Monitoring salinity in pre-existing and new lagoons is a crucial tool before, during and after the intervention. Nevertheless, this task should also consider knowledge of the interactions between fresh and salt water in the surface water-groundwater interphase, since periodic fluctuations in the various water input and output vectors determine the whole balance, and hence, the salinity of the entire system or parts of it. During two LIFE$^+$ projects conducted with the aim of restoration of La Pletera coastal lagoons in Catalonia, NE Spain (http://lifepletera.com), a monitoring survey from 2016 to 2018 has been deployed in order to determine seasonal relative and accumulated variations in salinity of soil and lagoons. At a reference profile set perpendicular to the shoreline and located between a pre-existing lagoon and a newly created one, an electrical resistivity tomography profile has been measured and interpreted on a time-lapse basis. Complimentary data comprise near-surface soil sampling, measurement of water table levels and physicochemical parameters such as electrical conductivity in the lagoons, the groundwater and the sea, and compilation of daily meteorological and sea state data records. Discrete representation of the electrical resistivity section has allowed a detailed image of bulk salinity variations along space and time. This has also permitted precise delimitation of the subsurface extent of brackish groundwater and the interphase with the marine water intrusion wedge within the aquifer. Results evidence that the most pronounced fluctuations in salinity occur in the first 2 meters below the surface. This interval of depth comprises both the unsaturated zone and the upper part of the saturated zone, where flow interactions between the shallow aquifer and the lagoons occur. Here, soil undergoes strong resistivity changes reflecting the relative contribution of fresh, brackish and salty water for any given period of time, under the influence of the hydrodynamics of the system. While newly created lagoons show a seasonal pattern of variation intimately linked to that of soil, older lagoons maintain a different, higher salinity regime strongly conditioned by their low permeability muddy bottom long-time accumulated. The study has also identified the synoptic hydrometeorological scenarios that are responsible for the high- and low-salinity events affecting the ecosystem.

Keywords: Surface-groundwater interactions, coastal lagoons, salinity, electrical resistivity imaging, salinity monitoring

1. INTRODUCTION

Coastal wetlands play an important role in coastal defense and wildlife conservation, also acting as sinks or sources of a wide range of substances, such as nutrients, organic matter, and pollutants (Boorman, 1999; Costa et al., 2001, López-Flores et al., 2003; Salvadó et al. 2006). In these ecosystems, the structure and dynamics of biological communities are driven by water inputs, which may vary naturally or due to human pressures in their flow rates and biogeochemical characteristics. In particular, changes in water regimes produced by human activities may cause water quality degradation, lagoons and wetlands disappearance, or the establishment and expansion of invasive species (Crivelli, 1995; Pérez-Ruzafa et al., 2002; O'Connell, 2003; La Jeunesse and Elliott, 2004; Badosa et al., 2007).

La Pletera salt marshes are composed of several temporary and permanent coastal lagoons and wetlands in a region mainly dominated by agriculture and tourism activities in the Mediterranean coast of Catalonia (NE Spain; Figure 1). This area was affected by the incomplete construction of an urban development in 1987, and it has been the focus of two Life^{+} projects (http://lifepletera.com/es/life-pletera/), whose aim was to restore this protected area and to recover its ecological functionality. Therefore, the herein studied system is composed of two natural lagoons, Bassa del Pi and Fra Ramon lagoons, originated by the abandonment of a river channel; and five other lagoons excavated during the Life^{+} Restoration Projects, such as G02 lagoon which was created in 2002, and L04, M03, M04 and M05 lagoons, excavated in 2016 (Figure 1). These lagoons are associated to a shallow level of sediments with a thickness of 10-20 m, formed by the present prograding alluvial deposits, which near the coast line are substituted by marsh and coastal deposits, and act as unconfined aquifer (Montaner, 2010).

The most important water inputs in this zone occur suddenly during intense precipitations and cyclonic storm events (mainly in spring and autumn). Freshwater, as well as sea water, may enter these lagoons, especially when these cyclonic storm events are associated to strong easterly winds, and sea level rise more than 1m (Marquès et al., 2001). In these periods, sea waves with a height of at least 2 m may enter in some of the lagoons. Together with freshwater surface, subsurface and ground water inputs, this usually causes an increase of 0.3-0.9 m in their water level. Apart from these events, salinity of the lagoons also increases due to evaporation, up to values equivalent to those of meso-euhaline water bodies (i.e., López-Flores, 2014). Therefore, during dry seasons, La Pletera salt marshes lagoons are maintained thanks to groundwater contributions, which show a mix of freshwater and seawater in its composition. Moreover, different proportions of these two sources of ground water have been observed throughout the year, with higher percentages of seawater during dry seasons (Menció et al., 2017).

The La Pletera ecosystems have a strong degree of fluctuation on the salinity which is ruled by the environmental conditions occurring on them. As a main task of the restoration project, focus has been put in salinity monitoring of pre-existing and new lagoons in order to ensure a final status compatible with the requirements set by all the vectors that control the whole balance of the system or parts of it. In this two-year long study, a monitoring survey has been deployed with the aim to determine seasonal variations in salinity of soil and lagoons in a representative part of the area that remained undisturbed during the environmental restoration works. At a reference profile set perpendicular to the shoreline and located between a pre-existing lagoon (Fra Ramon) and a newly created one (L04), an electrical resistivity tomography (ERT) profile has been measured and interpreted on a seasonal time-lapse basis, giving a total of nine campaigns (C1 to C9) starting in February, 2016 and ending in January, 2018 (Figure 1). ERT data have been complemented with near-surface soil sampling for determination of grain size distribution and water content, and water electrical conductivity measurements in the lagoons, groundwater and the sea. Other data have been also compiled, such as topographical position of water level in the lagoons, daily meteorological and sea state data records, and descriptive soil profiles included in hydrogeological and geotechnical reports available from the area.

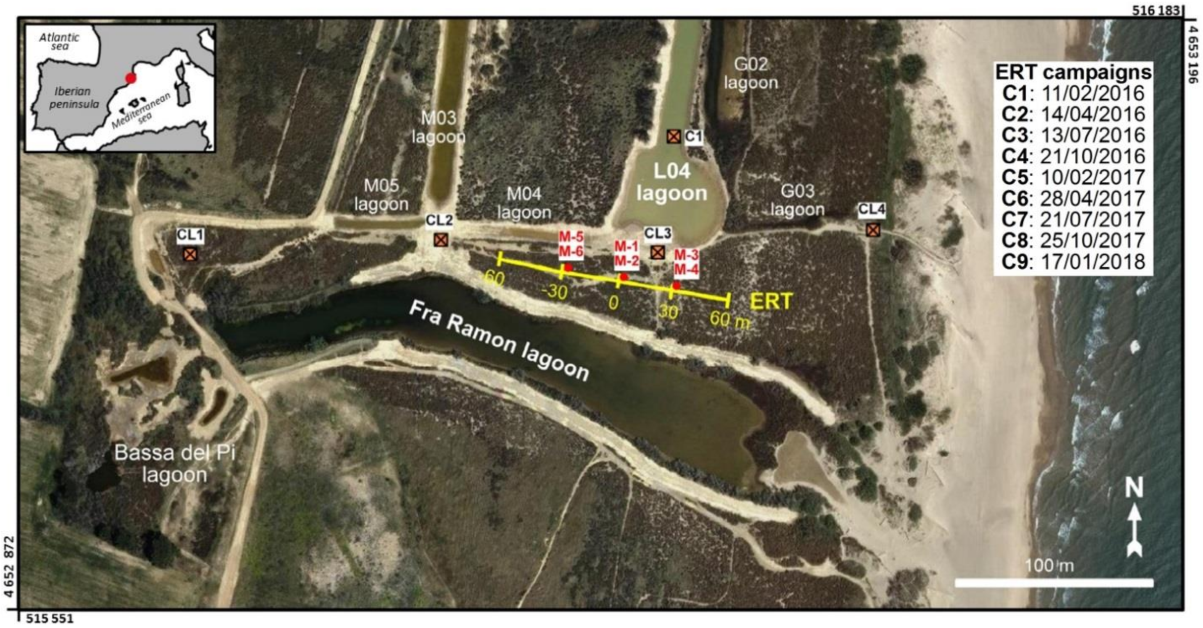

Figure 1. Geographical situation of the study area and location of the ERT profile, soil samples (red dots) and ground investigation trenches (orange squares). UTM coordinates, zone 31T, datum ETRS89.

2. METHODS

ERT is a direct current technique that uses multi-electrode arrays to image the electrical resistivity distribution of the ground along a section. The survey at La Pletera was implemented using a Lund Imaging System (ABEM, 2009). A profile 120 m long was set with four multicore cable coils connected in series, with 61 steel electrodes nailed to the ground regularly spaced 1.5 m in the two central coils and 3 m in the two external ones. Fixed reference bars were used to ensure exact location of the same measurement points in each campaign. Data acquisition followed a Wenner-Schlumberger protocol (Loke, 2014). Data inversion, model section graphical representation and results export were performed with Res2DInv software.

Surface water electrical conductivity (EC) from the lagoons and the sea was measured at each field campaign, using a portable Crison meter. Soil samples (M-1 to M-6) were obtained at 0.15 m and 0.45 m depth at the profile X coordinates of -30 m, 0 m and 30 m by manual boring with an auger sampler. When intersected, groundwater level was measured with a portable OTT piezometric probe (precision 1 cm). Relative height of each electrode position and water table in the lagoons was measured with a laser level meter, and then referred to the known topographical elevation of the ERT profile central point. Soil grain size distribution was determined by sieve granulometry. Gravimetric water content was determined by weighing moist samples and dry samples after storing them on a stove at 60ºC during 24-48 h; thereafter equivalent volumetric water content was calculated. Potential regression equations from relation between water content and measured electrical resistivity for each set of samples (e.g. same depth and campaign) allowed calculation of volumetric water content for the ERT data levels in the unsaturated zone. In order to evaluate influence of vegetation on the humidity retention of near-surface soil, these datasets were after compared on a qualitative basis to the surface coverage of *Salicornia* bushes (dense, sparse and none), the only vegetation along the study line. Groundwater electrical conductivity in the saturated zone was calculated according to Archie's law (Archie, 1942). Valid for clay-free granular materials, it links bulk soil electrical resistivity to saturation water resistivity as a function of soil porosity and saturation index, among other material constants. In this case, porosity values adopted for calculation ranged between 0.46 for the materials near the surface, and 0.30 for the deepest ones, while saturation index was always set equal to 1 and the other constants were set to values commonly used in the literature (Friedman, 2005).

Hydrometeorological data served to evaluate seasonal contribution of water inputs and outputs to the lagoon system. Precipitation was recovered from Torroella de Montgrí station, and evapotranspiration from La Tallada d'Empordà station (Servei Meteorològic de Catalunya, www.meteo.cat). L'Estartit station (www.meteolestartit.cat) provided records of sea state conditions: maximum and minimum daily sea level, daily wave heigh and sea storm episodes.

3. RESULTS AND DISCUSSION

Electrical resistivity distribution along the investigated section shows a pattern consistent with the geology of the area, mainly sand and silt saturated by very shallow brackish water and by deeper marine groundwater (Figure 2). The uppermost materials (unit 1, present-day floodplain and unit 2, ancient lagoons) extent from the surface (elevation 1 m) up to -0.5 m, having dominant resistivity values 1-4 Ωm that increase to 3-10 Ωm in the eastern part (degraded sandy dunes and washover deposits). Resistivity decreases downwards to 1-2 Ωm in unit 2 (up to elevation -3 m) and <0.5-2 Ωm in unit 4.

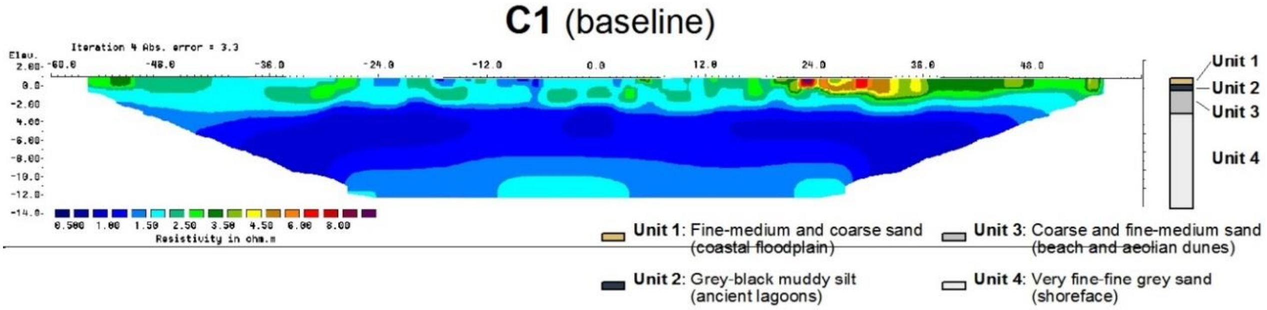

Figure 2. Baseline ERT model section (campaign C1) and synthetic vertical soil profile.

Representation of relative electrical resistivity variations between ERT campaigns are shown in Figure 3. Strongest variations take place in the first 2-3 meters from the surface, at depths where water interaction between lagoons and the ground occurs. Taking into account that soil is water-saturated below an elevation of 0.5-0 m, changes essentially imply differences in water electrical conductivity. An increase in electrical resistivity indicates a more saline water (e.g. 0 to -1 m in C2-C3 and C4-C5), while a decrease is related to fresher water (e.g. 0 to -1 m in C3-C4).

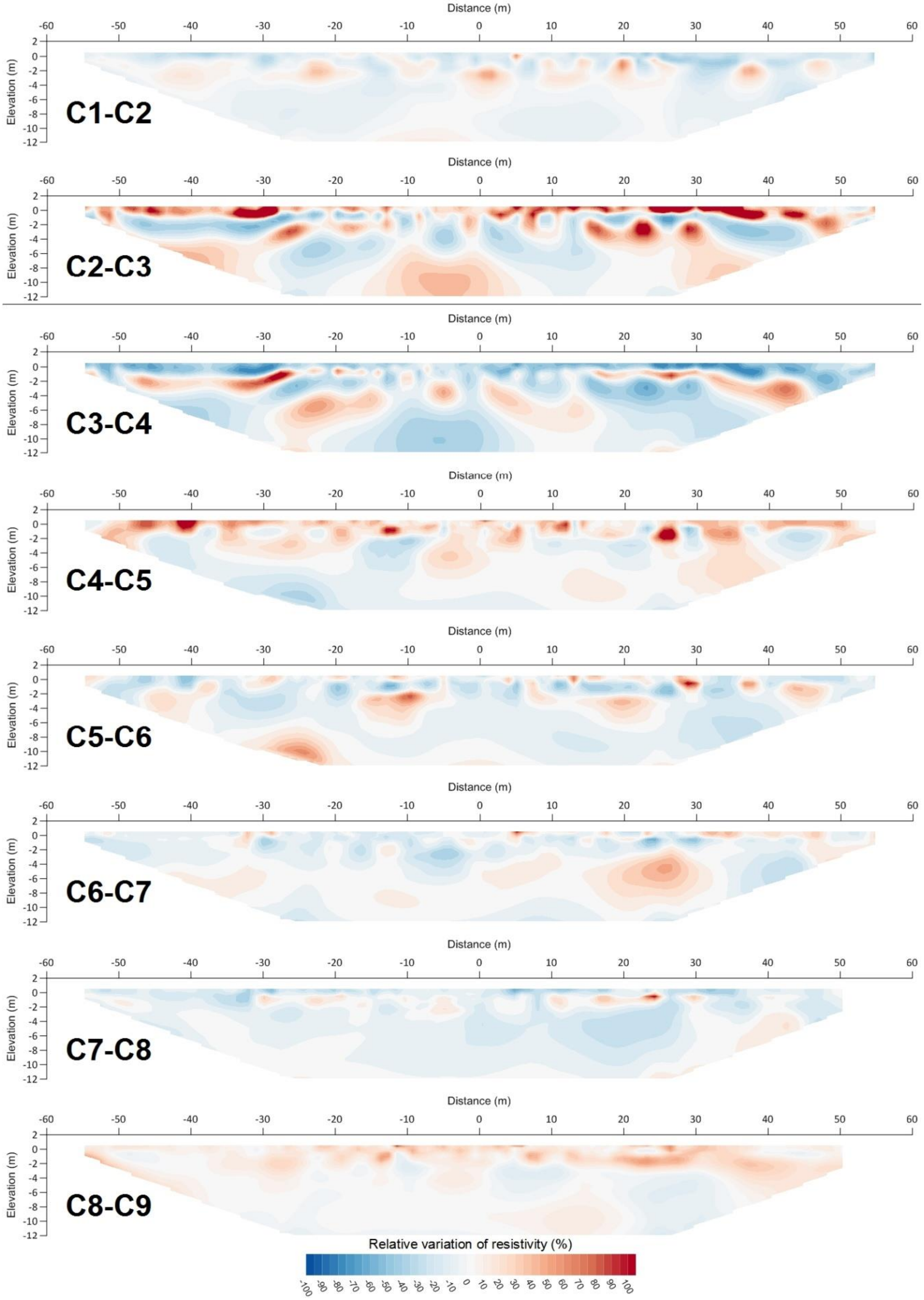

Figure 3. Time-lapsed variations of bulk soil electrical resistivity along consecutive ERT campaigns.

Bulk salinity at shallow depths is highly dependent on the infiltration related to environmental conditions, while deeper levels remain more stable along time. Among the main factors responsible for salinity variations are rainfall that provides freshwater, evapotranspiration that dries out unsaturated zone and forces groundwater ascent by capillarity, and entrance of seawater caused by storm waves that, depending on the sea level at the time, may overcome the littoral dune barrier even if they only reach 2 m height (Figure 4). Relative changes depend on the contribution of each vector and also on the previous state of salinity and water level at the lagoons and the soil. For instance, episode C3-C4 implied a marked raise in the water table of the lagoons because of a very rainy autumn after an exceptionally dry and hot summer. Nevertheless, subsurface resistivity dramatically decreased (salinity increased) due to the effect of several sea storm events coeval with a relatively high sea level that caused massive entrance of sea water into the lagoons. The following winter (C4-C5) abundant precipitations continued, but a lower mean sea level reduced sea water inputs, thus subsurface resistivity increased as a result of more diluted infiltration water. Time periods lacking such extreme environmental events (i.e. C6 to C9) reflect a smoother salinity variation pattern.

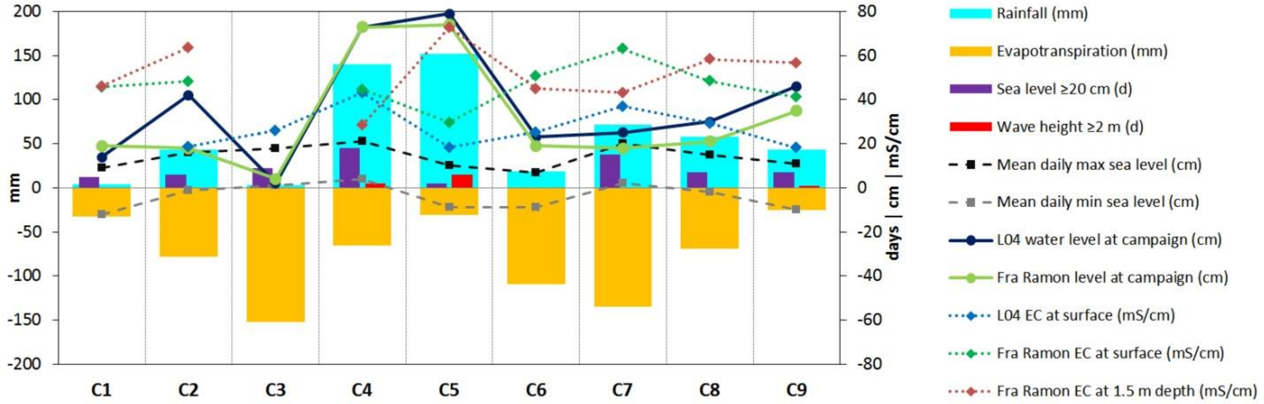

Figure 4. Hydrometeorological vectors influencing water availability and saline status of the lagoons and the subsurface soil. Plotted data comprise a span of one month previous to each campaign.

Given the high salt content of the ground, humidity in the unsaturated zone influences the mobility of the soil ionic load, even by lixiviation downwards to the aquifer or by upwards transport to the surface under summer arid conditions. Volumetric water content from ERT data is generally higher during the episodes of positive balance between surface water inputs and outputs. Marsh autochthonous vegetation, dominated by *Salicornia* bushes, plays also an important role in the lateral distribution of soil humidity, since it acts as an absorption focus for saline water (i.e. segments between X coordinates -40 to -10 m and 0 to 25 m). Patches free of vegetation tend to retain more water in the soil (i.e. -10 to 0 m) but are areas more prone to saline water infiltration. Nature of the ground is also crucial in the retention of humidity. Profile segment between 20 and 60 m has lower water content in all campaigns because the coarser clean sandy terrain with higher permeability that facilitates infiltration (Figure 5).

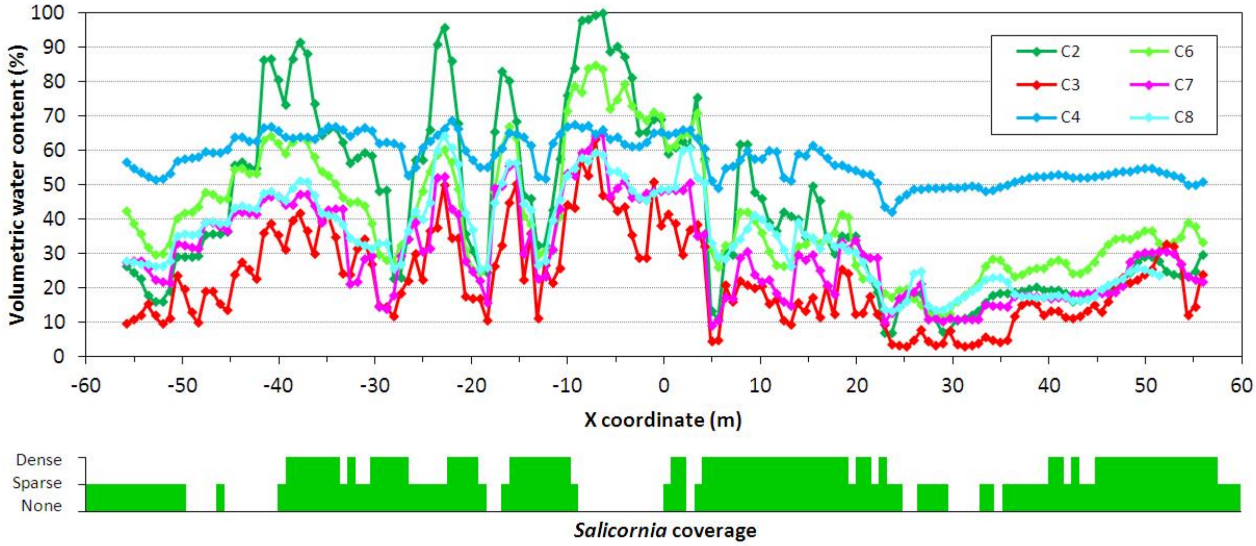

Figure 5. Soil volumetric water content at 0.15 m depth in spring, summer and autumn, compared to the relative density of *Salicornia* bushes.

Another important issue on the subject of salinity refers to the presence of sea water within the aquifer. Groundwater EC values calculated after ERT results coincide all along the studied period in that the uppermost part of the saturated zone hosts brackish waters (10-40 mS cm^{-1}), and the transition to sea water (>40 mS cm^{-1}) takes place at an elevation between -3 and -4 m. The interface is not sharp but progressive, and defines a slightly wavy contact that might reflect heterogeneities in the mixing zone due to sediment geometry and/or the flow dynamics. Higher EC values in depth tend to be present in the eastern side of the section, supporting the marine origin of the groundwater (Figure 6).

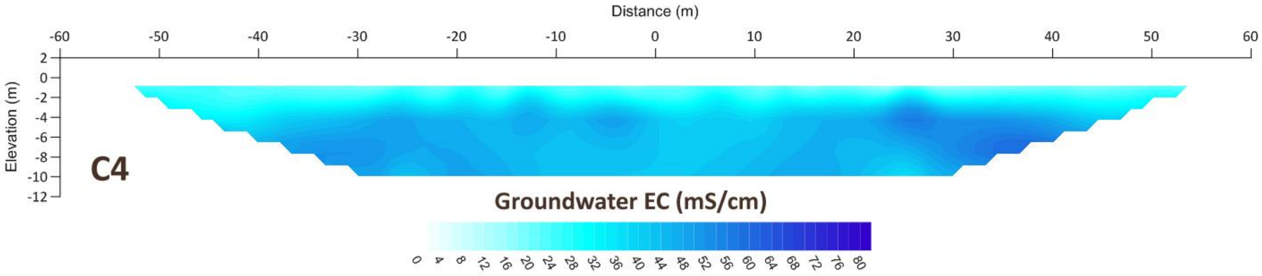

Figure 6. Example of calculated groundwater EC from ERT model section, campaign C4.

Vertical distribution of mean groundwater EC do not show substantial differences in the absolute values along time, being the described pattern quite constant, except for the first 1.5 meters below the surface, up to an elevation of -1 m (Figure 7a). Here, mean EC ranges always between 10-20 mS cm^{-1}, similar or slightly lower to that of L04 lagoon but significantly lower than that of Fra Ramon lagoon. The most pronounced EC variations between campaigns (declines up to -30% and increases up to 70%) take place at depths that coincide with the topographic extent of the bottom of lagoons L04 and the shallower Fra Ramon eastern lobe, while at elevations similar to that of deeper Fra Ramon western lobe EC temporal contrasts are lower (Figure 7b). These evidences support a direct connection between the newly created L04 lagoon and the aquifer, and the not-so-direct groundwater-surface water interaction in the pre-existing Fra Ramon lagoon, where evaporation processes have a crucial role on the salinity of the water body (Menció et al., 2017).

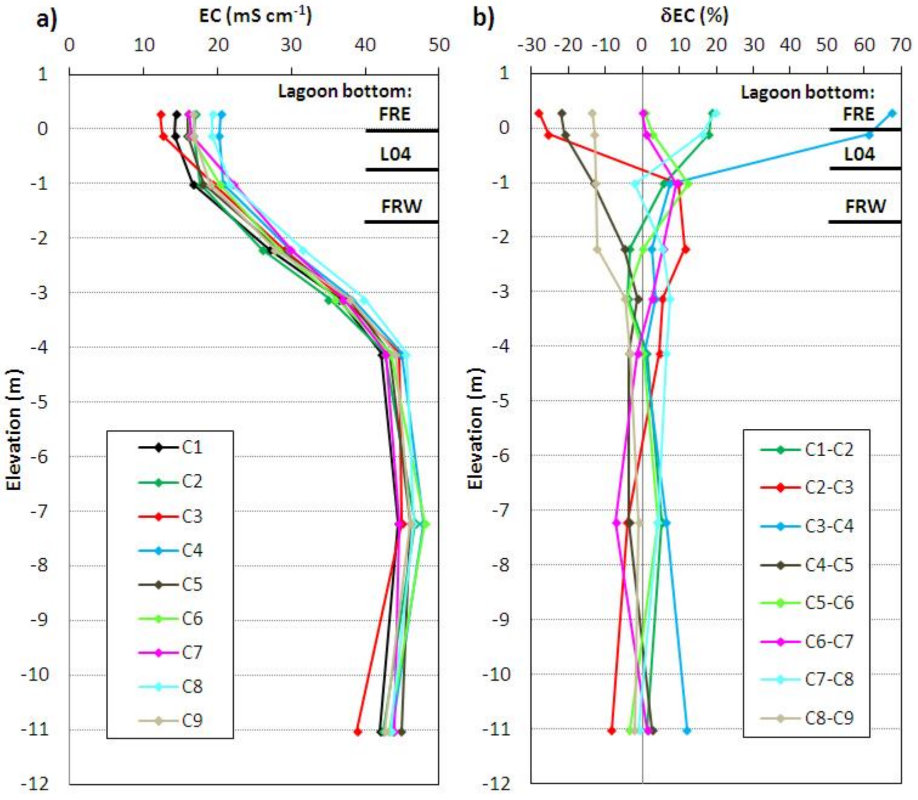

Figure 7. Mean groundwater EC values within the saturated zone (a), and EC variation percentage between consecutive campaigns (b). Also indicated is the topographic position of the bottom of lagoons L04 and Fra Ramon. FRE: Fra Ramon eastern lobe (shallower); FRW: Fra ramon western lobe (deeper).

4. CONCLUSIONS

The geoelectric geophysical survey carried out between 2016 and 2018 at the salt marsh of La Pletera has allowed seasonal monitoring of variations in bulk soil electrical resistivity of the sandy coastal wetland sediments and the aquifer related to newly created and restored lagoons. The imaged section, 120 m long and 13 m deep, has provided enough discrete data to reach a detailed and comprehensive visualization of electrical resistivity distribution and its variations that are consequence of the various hydrometeorological situations influencing the saline status of the ecosystems. Temporary balance between rainfall, evapotranspiration and sea water entrance due to sea storms, together with the previous water level and salinity of soil and lagoons, are the factors that control this multivariable system. The study has also led to evaluation of the effect that marsh vegetation has in the humidity of the near-surface sediments in the unsaturated zone of soil. Groundwater EC in the saturated zone has been calculated from ERT results, depicting a situation in which marine water is permanently present below an elevation of -4 m, and that strongest fluctuations in brackish groundwater take place at depths that coincide with the bottom of the shallowest lagoons (L04 and Fra Ramon eastern lobe). Moreover, salinity changes in the deeper Fra Ramon western lobe may not be explained only by groundwater-surface water interactions.

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