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# Salinity Spatial Patterns in Mediterranean Coastal Landscape: The Legacy of the Historical Water Management and Land Planning

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► **To cite this version:**

Laurène Marien, Armand Crabit, Benoît Dewandel, Bernard Ladouche, Perrine Fleury, et al.. Salinity Spatial Patterns in Mediterranean Coastal Landscape: The Legacy of the Historical Water Management and Land Planning. 2023. hal-04142626

**HAL Id: hal-04142626**

**<https://institut-agro-dijon.hal.science/hal-04142626v1>**

Preprint submitted on 27 Jun 2023

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1 **Salinity spatial patterns in Mediterranean coastal landscape: the legacy of the historical water**

2 **management and land planning**

3  
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14  
15 **ABSTRACT**

16 Mediterranean coastal areas have been occupied and developed intensively for a long time facing issues  
17 related to agricultural production, urbanization, tourism, preservation of natural resources often linked to  
18 salinity. This article explores the relationship between historical land planning and water management,  
19 and current soil and water salinity to gain insights into future projections.

20 Soil samples (1185) were collected in a coastal plain of 114 km<sup>2</sup> in the south of France and saturated paste  
21 extract Electrical Conductivity (EC<sub>sp</sub>) was deduced from 1:5 dilution. Soil salinity exhibits a wide range of  
22 variation (from 0.54 to 113.1 mS cm<sup>-1</sup>) and spatial patterns. EC<sub>sp</sub> is significantly different among soil types,  
23 higher at depth than at the surface (Kruskal Wallis and Wilcoxon tests) and influenced by the distance to  
24 ancient anthropogenic structures (Pettitt test). Surface water and shallow groundwater samples were  
25 collected for trace element concentrations and Oxygen (<sup>18</sup>O/<sup>16</sup>O) isotope ratio measurements. The  
26 geochemical signatures indicate a mixture between surface freshwater and seawater, with the presence  
27 of over-salted seawater and a stratification of salinity from the surface to the depth.

28 Results suggest that groundwater is the source of soil salinity, and illustrate the long-term impact of water  
29 management and land planning. Less saline soils are found near the freshwater supply channel  
30 (constructed from 15<sup>th</sup> to 18<sup>th</sup>), while more saline soils are located near drainage channels. The presence  
31 of over-salted water reflects temporal evolution of the plain over the last few centuries (initially under  
32 seawater, gradually filled in, presence of ponds and salt works that have now disappeared). The current  
33 soil salinity patches continue to be a visible reminder of this evolution. The trend towards desalinization  
34 of the plain over the last few centuries has been made possible by massive freshwater inflows, which are  
35 now under threat due to the general decrease of water resources availability.

36

37 **KEYWORDS**

38 Freshwater availability; soil fertility; anthropogenic structures; geochemical signature; ancient ponds; salt  
39 works

40

## 41 1. Introduction

42 Soil salinity is one of the main causes of soil degradation limiting its productivity (Epstein, 1980). 10% of  
43 arable land is affected by salinity and sodicity in more than 100 countries and on all continents (Szabolcs,  
44 1989). According to FAO in 2000, around 830 Mha of land worldwide contains salt-affected soil (SAS)  
45 (Martinez-Beltran & Manzur, 2005). Soil salinity refers to the accumulation of soil soluble-salts, from  
46 natural or anthropogenic origins, mainly in the form of chlorides, sulfates and carbonates of sodium,  
47 calcium and magnesium (Shrestha, 2006).

48 Soluble salts could be of environmental origin or result from inefficient or inappropriate human activities  
49 (Daliakopoulos et al., 2016; Shrestha, 2006; Szabolcs, 1992). Primary salinization is the development of  
50 salts by natural processes, mainly including physical or chemical weathering and transport from parent  
51 material, ecological deposits or groundwater (Daliakopoulos et al., 2016). Human interventions cause  
52 secondary salinization, primarily due to irrigation with brackish water or other inappropriate irrigation  
53 practices, often combined with poor drainage conditions (Stavi et al., 2021).

54 Whatever the origin, salinity threatens the sustainability of agriculture by affecting crop production  
55 through decreased yields and plant death (Feinerman & Yaron, 1982; Li et al., 2012; Maas & Hoffman,  
56 1977), according to processes summarized by Rengasamy (2010). Salt-affected soils occur in more than  
57 100 countries worldwide, with the exception of Antarctica, and are generally found in arid and semi-arid  
58 climatic zones (Rengasamy, 2006; Szabolcs, 1985). In Europe, soil salinity affects approximately 3.8 million  
59 hectares of land (Jones et al., 2012; Tóth et al., 2008), with coastal regions in southern Europe particularly  
60 facing especially severe agricultural challenges due to salinization (Daliakopoulos et al., 2016).

61 Coastal areas are particularly vulnerable because they are located at the interface between land and sea.  
62 As indicated in recent review articles, these areas concentrate many issues related to water (Tramblay et  
63 al., 2020) and soil resources (Ferreira et al., 2022), agricultural production (Jacobsen et al., 2012),  
64 remarkable natural spaces (Erostate et al., 2020; Martínez-Megías & Rico, 2022), urbanization and tourism  
65 (Mejjad et al., 2022). The preservation and development of these areas involves a balancing act between  
66 the needs and availability of resources and land for the various uses. This balancing act must be carried  
67 out under conditions of climate change and land use (García-Ruiz et al., 2011; Linares et al., 2020) and may  
68 be complicated by salinity conditions.

69 A conceptual model of the processes involved in water and soil salinization in Mediterranean coastal areas  
70 has been proposed by Bless et al. (2018). In the case of salinity issues related to proximity to the sea, this  
71 model highlights the need to understand the salt and water fluxes and mixtures between the soil, surface  
72 water and groundwater compartments. The model also indicates the importance of incorporating the  
73 consequences of hydro-agricultural management in these interactions (de Louw et al., 2011, 2013). Such  
74 models question the long-term dynamics when landscape conditions that influence salinization processes  
75 change. Mediterranean coastal landscapes are particularly at the center of this questioning because they  
76 have been occupied and managed for a long time. Since ancient times, land use patterns and hydro-  
77 agricultural management have changed significantly and interfered with water and soil (Gibling, 2018;  
78 Pieruccini et al., 2021; Wilkinson, 2005) and thus with the processes that cause salinity. While the current  
79 concern is to adapt Mediterranean coastal areas to climate change, it is crucial to analyze what the impacts  
80 of past land and water management may be on current salinity conditions.

81 This article aims to analyze the spatial patterns of soil salinity and surface and groundwater quality in  
82 relation to historical water management and land planning in a Mediterranean coastal landscape. The  
83 chosen study site shows a long history of land use and allows to discuss the consequences of long-term  
84 landscape management on water and soil salinity and the implications for the future in a climate change  
85 context.

## 86 **2. Study site**

87 The selected study area located in the department of Aude, in the south of France, includes the city of  
88 Narbonne and covers an area of 114 km<sup>2</sup>. It is the part of a low plains corresponding to the deltaic zone of  
89 the former southern branch of the Aude River. It is bounded to the North by the Aude River, to the South  
90 by the Mediterranean sea, ponds and lagoons, in the western part by the Corbières hills (maximum  
91 elevation 248 m a.s.l.) and to the east by the Clape massif (maximum elevation 214 m a.s.l.) (Fig.1A).

92

93 *[FIGURE 1: Study site maps (A) sampled points, (B) soil types, (C) land cover and (D) hydro-agricultural*  
94 *network]*

95

### 96 **2.1. Geological and soils characteristics**

97 The main stages of the geological history of the Narbonne coastline are part of the formation of the Gulf  
98 of Lion during the Tertiary era (Ambert, 1994; Guennoc et al., 2000). For nearly 10,000 years, the Narbonne  
99 coast has undergone a very important geomorphological evolution, changing from a ria to a lagoon under  
100 the combined influence of a rise in sea level and the process of progradation resulting from the

101 sedimentary contributions of the Aude (André & Ambert, 1998; Guilaine, 1995). The structure of the  
102 Narbonnaise plain results from the filling of two rias during the Holocene era, identified below as the  
103 South and East branches (Salel, 2018). The bedrock of the basin is composed of blue marls from the  
104 Miocene (Helvetian, -11-16 Ma). These formations were eroded during the last glacial period and now  
105 form the base of this sedimentary basin. After the ice age, the sea level rose and rias were filled in.

106 The course of the Aude in its deltaic zone was N-S 10,000 years ago following the ria of the southern  
107 branch. This area was then protected behind the Clape massif and an arm of the sea penetrated quite far  
108 inland. It was the same for the Eastern branch, with an ingress of the sea that rushed to the North of the  
109 Clape massif. Over the past two millennia, increased human activity has led to an intensification of  
110 agriculture and grazing. The important deforestation which resulted generated a strong erosion on the  
111 Aude basin and contributed to a massive sedimentary contribution. This contribution finished filling the  
112 South Branch in less than 1000 years, with several meters of alluvial sediments of fluvio-palustral origins  
113 which were deposited in the plain, deviating the direction of the river in the early 14<sup>th</sup> century to give it  
114 an E-W orientation comparable to the current one (Larguier, 2018). The lower Aude plain is then formed  
115 of ancient quaternary alluvium near the Clape massif and more recent one in the plain. Today, the Aude  
116 flows North of the Clape massif before reaching the sea.

117 Consequently, the study area is today essentially composed of a topographically flat sedimentary basin.

118 The northern part of the area is composed of recent alluvial sediments dating from the Quaternary period  
119 and originating from sediment transport by the Aude River. At the edge of the study area, the relief is  
120 characterized by higher elevations, related to older alluvial and colluvial sediments. In the southern part,

121 near the present Bages-Sigean pond, the alluvial deposits are substituted by fluvial and lacustrine  
122 deposits.

123  
124 By combining the BRGM geological map at a 1:50,000 scale (Lespinasse et al., 1982), the INRA soil  
125 landscape map of the Aude at a 1:250,000 scale (Barthès et al., 1999), and data from 393 auger bores at  
126 depths of 0-20 cm, 30-40 cm, 70-90 cm, and 90-120 cm, with recorded properties such as Munsell color,  
127 texture (using the FAO method), hydromorphy, HCl test,  $EC_{1:5}$ , pH,  $Na^+$ , and  $Ca^{2+}$ , a detailed soil map was  
128 elaborated (Fig.1B). The main characteristics of the five dominant soil types (WRB, 2015) represented in  
129 the study area are (see also Table 1):

- 130 ● Soil 1: Calcaric Cambisol developed in the current alluvial deposits and located at relief footslope  
131 positions with elevation ranging from 10 to 20 m a.s.l. and classified as Cambisol. This soil unit  
132 represents 20% of the study area;
- 133 ● Soil 2: Colluvic Cambisol mainly located in the northeastern part of the study area, with  
134 elevations ranging from 20 to 50 m a.s.l., characterized by a shallow soil depth (<80 cm). This  
135 soil unit represents 4% of the study area;
- 136 ● Soil 3: Fluvisol located in the northern part of the study area, in recent alluvial deposits from the  
137 Aude river at a medium elevation (5-10 m a.s.l.). They are characterized by medium to high soil  
138 depth (>1.2 m) and exhibit temporary waterlogging within the first meter soil depth. This soil  
139 unit represents 21% of the study area;



- 140 • Soil 4: Gleyic Fluvisol located in the central and low elevation part of the study area (<5m a.s.l.)  
141 and characterized by permanent waterlogging whatever the soil depth. It is the dominant soil  
142 unit, representing 40% of the study area;
- 143 • Soil 5: Solonchaks located at the edges of the present pond (Bages-Sigean) formed on lacustrine  
144 deposits, rarely cultivated. They are characterized by a high electrical conductivity of saturated  
145 paste ( $>4 \text{ mS cm}^{-1}$ ) and an ESP (Exchangeable Sodium Percentage) may exceed 15% and  
146 permanent waterlogging at low depth. They represent 14% of the study area.

147

148 *[TABLE 1 - Main characteristics of the five soil types.]*

149

## 150 **2.2. Agriculture, natural areas and water management**

151

152 The land use established in 2018 is composed of 24% of vineyards, 14% of wasteland, 4% of grasslands,  
153 18% of field crops, 18% of natural areas and 22% of urbanized areas (Fig.1C). The urban areas have been  
154 growing rapidly over the last 50 years. The natural areas, which are mostly protected, include  
155 Mediterranean scrubland in the higher elevations, wetlands and salt marshes in the lower elevations.  
156 Vines are the main land use and have been present in the area for a long time. Introduced by Greek settlers  
157 around 600 BC in Marseille, viticulture was initially limited to southern Gaul during the Iron Age (Boissinot,  
158 2001; Collin Bouffier, 2009). Viticulture then spread to Languedoc and particularly to the province of Gallia  
159 Narbonensis after the Roman conquest around 118 BC (Bernigaud et al., 2021). During the first millennium  
160 AD, Narbonne was the capital of the Roman province Gallia Narbonensis, one of the largest port cities in

161 the northwest Mediterranean (Faïsse et al., 2018). As related by Martínez Ferreras et al. (2013), the city  
162 of Narbonne, then capital of the province of Narbonensis, played a very important role in the commercial  
163 redistribution of Tarraconensis wine (one of the three roman provinces in Hispania) to other regions of  
164 the Empire. Later, from the 9<sup>th</sup> century to the 16<sup>th</sup> century, if wine production was still important (Larguier,  
165 1996), the salty land in this area was also exploited in the form of salt ponds for the production of salt.  
166 Salt then became one of the most characteristic products of the medieval Mediterranean economy  
167 (Dupont, 1958). The use of ancient data in geography allowed to study the paleogeography of Narbonne's  
168 ponds. Based on the georeferencing of ancient maps published since the early 18<sup>th</sup> century, and extensive  
169 work in archaeology, Cavero (2010) suggests a representation of the historical contours of the ancient salt  
170 ponds located in the study area.

171 The production of salt coincided with the onset of significant drainage operations in the plain, leading to  
172 the construction of large canals that are still visible on the map D in Figure 1. This land drainage progress  
173 was instrumental in establishing and diversifying agriculture. The Robine canal, built over several centuries  
174 from the 15<sup>th</sup> to the 18<sup>th</sup> century, serves as a navigable waterway and a source of freshwater for the  
175 lowlands. It runs along the former course of the southern branch of the Aude river and flows into the  
176 Bages-Sigean pond (Ambert, 1993). This canal supplies a network of channels and ditches, as depicted in  
177 map D of Figure 1. The water is managed collectively by Authorized Syndical Associations (Dallmayr, 1961)  
178 and allows for artificial flooding (Alaghmand et al., 2016). This practice is water-intensive as it requires  
179 about 300 mm one to three times a year. During the winter, water is supplied for several days on the plots  
180 and then drained via artificial subsurface and open drainage networks to downstream ponds and lagoons,  
181 which serve as the general outlet of the network. The primary objective of these winter inputs is the soil

182 desalinization through leaching. Water can be reapplied in the spring to fight against freezing of the  
183 vineyards and replenish the soil's water content before the vineyards' budburst. A third application can be  
184 made at the beginning of summer to prevent water stress in crops. Some of the natural areas on the plain  
185 have taken place over formerly cultivated areas, particularly around the ponds and lagoons. The hydro-  
186 agricultural networks' maintenance ensures that water is added to these natural areas to promote  
187 variously saline grasslands and reed beds, serving as a refuge for numerous animal species.

188

### 189 **3. Materials and Methods**

#### 190 **3.1. Soil measurements**

191 Soil sampling was done randomly, taking into account the accessibility of the plots and ensuring that all  
192 soil types were well represented. Soil samples (N = 1185) were collected at different depths (0-120 cm)  
193 using an auger during two different periods: dry season (end of September) and wet season (April-May)  
194 from 2018 to 2022 (Fig.1A). Each auger survey was conducted in accordance with FAO rules for soil  
195 description (Jahn et al., 2006). All soil samples were air-dried and measured for  $EC_{1/5}$  according to the U.S.  
196 Salinity Laboratory protocol (Rhoades et al., 1999).

197 Soil salinity was estimated by measuring the electrical conductivity (EC), which is determined by the  
198 electrical conductivity of the saturated paste extract ( $EC_{sp}$ ) and total dissolved salts, as calculated by  
199 Richards' equation (Richards et al., 1954). To analyze a large number of samples, EC measurements were  
200 conducted on soil solution extracts diluted in demineralized water at a 1:5 ratio ( $EC_{1:5}$ ). The soil samples  
201 were treated using the United States Salinity Laboratory protocol (Rhoades et al., 1999), and  $EC_{1:5}$  was  
202 measured using a conductivity meter (WTW model 2CA301 Cond 3310).

203 Soil salinity is often estimated using the electrical conductivity of soil saturated paste extract ( $EC_{sp}$ ).  
204 However, this method can be time-consuming and laborious. As a result, alternative methods that involve  
205 different soil/water ratios, such as 1:5 ( $EC_{1:5}$ ), are often used to estimate the  $EC_{sp}$  (Kargas et al., 2022).  
206 These alternative methods are generally faster and easier to implement. As highlighted by Sonmez et al.  
207 (2008), the findings revealed a strong correlation between the values of electrical conductivity measured  
208 in saturated paste extracts and those measured in extracts of varying soil to water ratios. A specified  
209 relationship between  $EC_{sp}$  and  $EC_{1:5}$  was then established for the study area, considering  $EC_{sp}$  and  $EC_{1:5}$  on  
210 32 subsamples (16 points at two different depths), both measured at the CIRAD laboratory in Montpellier.  
211 The specific relationship ( $R^2 = 0.98$ ) found was:

$$212 \quad EC_{sp} = 11.35 EC_{1:5} \quad \text{Eq. 1}$$

213 Laboratory analysis was done on 32 subsamples in order to quantify the main characteristics of the five  
214 soil types and the results are given in Table1.

215 Inverse Distance Weighted (IDW) method was employed for interpolating Electrical Conductivity with the  
216 power value  $p = 4$ , at a resolution of 20 meters. Two visual representations were generated, one for the  
217 spatial distribution of surface salinity data (0-40cm) and the other for depth salinity (90-120cm).

218 The study involved three levels of statistical analysis: i) the variability of the salinity in the soil profile was  
219 examined by comparing  $EC_{sp}$  at the surface and  $EC_{sp}$  at depth using non-parametric one-way ANOVA test  
220 (Kruskal Wallis); ii) the spatial distribution of salinity across the study area was analyzed in relation to the  
221 various soil types encountered, by comparing  $EC_{sp}$  with soil types using both one-way and pairwise  
222 comparison tests (Kruskal Wallis and Wilcoxon); iii) the impact of anthropogenic structures on salinity was

223 investigated by comparing  $EC_{sp}$  with the distance to the Robine canal and  $EC_{sp}$  with the distance to  
224 drainage channels.

225 An important issue was to delineate the zone of influence of anthropogenic structures e.g. Robine canal,  
226 drainage channels, and to quantify their respective impacts on soil salinity in order to answer the question  
227 of whether conductivity increases or decreases with distance from this structure. For this purpose, a  
228 statistical analysis based on spatial soil electrical conductivity dataset and a statistical method for  
229 analyzing points of change in a continuous series of points, was performed. As defined by Chandler &  
230 Scott (2011), a change point can be defined as a point in series when any parameter of the data  
231 distribution (mean, median, variance) undergoes an abrupt change. Pettitt test is a non-parametric test  
232 derived from the Mann-Whitney test to find a single change point in the mean of a series and returns a p-  
233 value for the change point (Pettitt, 1979; Pohlert, 2023). The non-parametric Pettitt test is robust to  
234 outliers and skewed distributions (Sagarika et al., 2014), usually used for evaluating the occurrence of  
235 abrupt changes in climatic records (Gao et al., 2011; Verstraeten et al., 2006; Zhang & Lu, 2009) and  
236 hydroclimatological studies (Conte et al., 2019). It applies to non-stationary data sets with at least 3 data  
237 and a non-normal distribution. To detect a change point in our dataset, we then applied Pettitt's test. In  
238 this analysis, the variable under consideration is the electrical conductivity of the saturated paste extract,  
239 while time was substituted by the minimum euclidean distance of the point from the anthropogenic  
240 structure being analyzed.

241 The statistical analysis focuses on the soils with the highest salinity (Fluvisol, Gleyic Fluvisol and Solonchak)  
242 and does not include the least saline soils 1 and 2. The minimum distance between the measurement

243 points and the anthropogenic structures, including the Robine canal and drainage channels, were  
244 calculated using QGIS and statistical tests were realized using R Software.

### 245 **3.2. Water measurements**

246 Water samples were collected in early summer for the years 2021 and 2022 in 14 locations for  
247 groundwater and 2 locations for surface water (Robine canal Sw1, and Aude river Sw2). Among the 14  
248 groundwater sampling locations, 3 locations are boreholes (Gwb1, Gwb2, Gwb3), 2 are wells (Gww1,  
249 Gww2), 2 are springs (Gws1, Gws2), 5 are shallow piezometers (between 2 and 4 m depth, Gwp1 to Gwp5)  
250 and 2 are locations where piezometers have been installed at 3 depths (2, 4 and 8 m depth, Gwp6 to  
251 Gwp8 and Gwp9 to Gwp11).

252 Water samples for major and trace element analysis were filtered on-site with a 0.45 µm PVDF filter.  
253 Chemical analyses were performed in the HydroSciences Montpellier laboratory at the University of  
254 Montpellier. Major ions were analyzed by ion chromatography (ICS 1000 Dionex®, precision error is  $\pm$   
255 5%). Oxygen ( $^{18}\text{O}/^{16}\text{O}$ ) isotope ratio measurements were performed at BRGM Laboratories by gas  
256 equilibration method ( $\text{CO}_2$ ) using a Finnigan MAT 252 mass spectrometer. Results are expressed in parts  
257 per thousand (i.e. ‰) in the familiar  $\delta$  notation relative to the Vienna Standard Mean Ocean Water  
258 (SMOW) standard, where  $\delta = ([R_{\text{sample}}/R_{\text{standard}} - 1] \times 1000)$ , the uncertainty of measurement for oxygen  
259  $^{18}$  is  $\pm 0.1\text{‰}$ .

260  
261 The examination of the relationships between the ions and trace elements and the chloride contents by  
262 the binary diagrams made it possible to characterize the geochemical context of the study area.  
263 Geochemical signature of groundwater has been compared to values measured in Mediterranean sea

264 (Petelet-Giraud et al., 2016). Geochemical signatures were used to compare the different types of water  
265 (e.g., freshwater of different origins and Mediterranean seawater (Petelet-Giraud et al., 2016)) and their  
266 mixing conditions. A binary diagram showing the  $\delta^{18}\text{O}$  values and chloride concentrations was built to  
267 position the water samples and curves that represent different mixing conditions between river  
268 freshwater and seawater or seawater that has undergone an evaporation process with concentration  
269 factors (F) between 4 and 10.

270

## 271 **4. Results**

### 272 **4.1. Soil salinity pattern**

273 Maps of soil salinity with depth produced with the IDW method are shown in Figure 2. Overall salinity is  
274 higher in the South of the study area. However, the patterns do not show a systematic increase in values  
275 with proximity to the present ponds connected to the sea. Salinity patches appear in the north of the area  
276 near the town of Vinassan, several kilometers from the present sea coastline. Striped patterns of salinity  
277 are also visible. Lower values appear near the Robine canal and higher values near the drainage channels  
278 in their downstream part. Salinity values increase with soil depth and adopt similar spatial patterns  
279 whatever the considered soil depth.

280 *[FIGURE 2: Soil salinity interpolation using the Inverse Distance Weight method (IDW)]*

281

282

283 The Kruskal Wallis test highlights that soil salinity of the 0-40 cm top layer is significantly different than  
284 soils salinity of the 90-120 cm deeper layer (p-value = 0.0016), with  $EC_{sp}$  mean values equal to 6.76 and  
285 10.2  $mS\ cm^{-1}$  respectively. When analyzing the difference in salinity between surface and depth by soil  
286 type, this trend is also found for Gleyic Fluvisols (p-value = 0.0064).

287 [ **TABLE 2:** Descriptive statistics of  $EC_{sp}$  per soil type]

288

289 According to Table 2, the descriptive statistics for soil salinity indicate that the results vary depending on  
290 the soil type. Solonchaks are, as expected, much more saline than the other types of soil (mean  $EC_{sp}$  =  
291 27.7  $mS\ cm^{-1}$ ). These soils closest to the coastline are constituted with fine-textured alluvial deposits in  
292 lacustrine or fluvio-lacustrine paleo-environmental conditions. The Gleyic Fluvisol and Solonchack exhibit  
293 the highest range of salinity values among the studied soils, with the minimum and maximum values  
294 ranging from 0.54 to 98.72  $mS\ cm^{-1}$  and 2.36 to 113.43  $mS\ cm^{-1}$ , respectively. Moreover, the standard  
295 deviation of these soils is also considerably high, at 10.79  $mS\ cm^{-1}$  and 19.96  $mS\ cm^{-1}$ , respectively. The  
296 statistical analysis using the Wilcoxon test indicates a significant difference (p-value < 0.05) between these  
297 two soil types and the other three, highlighting their distinctiveness. The Colluvic Cambisols have the  
298 lowest salinity, with a mean electrical conductivity ( $EC_{sp}$ ) of 2.34  $mS\ cm^{-1}$ . These soils are developed on  
299 sloping faces of the Clape massif.

300 [ **TABLE 3:** Pettitt test results  $EC_{sp}$  per soil type]

301



302 Table 3 shows that the Robine canal has a substantial decreasing effect on the salinity levels observed  
303 across the three soil types: Fluvisol, Gleyic Fluvisol, and Solonchak. The salinity levels decrease with spatial  
304 proximity to the Robine canal. The impact of the Robine canal on soil salinity across the entire soil profile  
305 is substantial and statistically significant ( $p$ -value  $< 0.05$ ), particularly in the most saline soil types  
306 (Solonchak and Gleyic Fluvisol). Salinity levels in Solonchak range from 14.3 to 34.88  $\text{mS cm}^{-1}$ , while those  
307 in Gleyic Fluvisol range from 5.09 to 12.33  $\text{mS cm}^{-1}$ . The results also suggest that this effect is comparatively  
308 weaker in the least saline soil (Fluvisol), where the electrical conductivity values range from 2.38  $\text{mS cm}^{-1}$   
309 to 3.43  $\text{mS cm}^{-1}$  throughout the soil profile. When considering soil salinity of the entire soil profile, the  
310 distance of influence of the Robine canal is then estimated to 437 m and 560 m for the Gleyic Fluvisol and  
311 Solonchak respectively. When looking at the results by separating the two depths, Pettitt test shows that  
312 salinity decreases with proximity to the Robine Canal for Gleyic Fluvisol with a change point between 208  
313 and 285 m for the surface samples and between 431 and 544 m for the deep samples.

314 According to Table 3, there is a significant increasing effect near drainage channels, which is particularly  
315 evident when analyzing the salinity levels across the entire soil profile for Gleyic Fluvisol. The mean salinity  
316 level decreased by almost half between the points before and after the change point (10.84 to 5.80  $\text{mS}$   
317  $\text{cm}^{-1}$ ), indicating a considerable impact on soil salinity. The effect appears to be limited to the deepest  
318 layers of the soil, as evidenced by the significant results of the Pettitt test ( $p$ -value =  $4.89\text{e}^{-3}$ ) for the deep  
319 samples (90-120 cm), while the surface samples (0-40 cm) showed no significant effect ( $p$ -value =  $4.09\text{e}^{-1}$ ).  
320 Results from the Pettitt test show that the estimated distance of influence for Gleyic Fluvisol on the overall  
321 soil salinity profile due to the drainage channels is approximately 450 m. The lack of data for Solonchaks

322 has made it impossible to estimate the impact of drainage channel distance on its soil salinity. Regardless,  
323 since this type of soil is already highly saline, the concentration effect would have been less pronounced.

324

#### 325 **4.2. Water quality**

326 The concentrations of chlorides and bromides locally present higher values than those of seawater (Fig.3A)  
327 which indicates that the waters of marine origin have undergone phenomena of evaporation. The  
328 evaporation of seawater initially leads to enriching the water with dissolved ions and the  $\delta^{18}\text{O}$  signature  
329 of residual seawater until the concentration factor (F) reaches approximately 4, which globally  
330 corresponds to the beginning of the precipitation of anhydrite (gypsum) and celestite (Fontes & Matray,  
331 1993). According to Holser et al. (1979), the precipitation of anhydrite (gypsum) is also accompanied by a  
332 slight depletion of the isotopic signature ( $\delta^{18}\text{O}$ ) of the evaporated residual seawater. The Cl/Br ratio in the  
333 residual seawater remains stable during the precipitation of calcite and anhydrite (gypsum). It starts to  
334 decrease when halite precipitates when F reaches 10. Surface water (Robine canal, Aude river) represents  
335 the first freshwater end-member that recharges the alluvial aquifer. Groundwater of the Clape massif  
336 karstic system represents the second freshwater end member that can recharge the aquifer formation of  
337 the alluvial plain. Several end members for evaporated seawater trapped in alluvial plain have been  
338 defined depending on whether the seawater has undergone evaporation or not (Fig.3B).

339 The bromide and chloride concentrations plotted in Figure 3A show a linear alignment of points on a mixing  
340 line between freshwater and seawater. It is possible to distinguish between freshwater (chloride  
341 concentration  $< 1 \text{ g L}^{-1}$ ), brackish water (chloride concentration between 1 and  $10 \text{ g L}^{-1}$ ), saltwater (chloride  
342 concentration between 10 and  $35 \text{ g L}^{-1}$ ), and over-saltwater (chloride concentration  $> 35 \text{ g L}^{-1}$ ). Freshwaters

343 include surface water samples (Sw1, Sw2), water samples from boreholes in the alluvial aquifer of the  
344 Aude river (Gwb1, Gwb2, Gwb3), water samples from springs in connection with the limestone karstic  
345 Clape massif (Gws1, Gws2), water samples from shallow wells (Gww1, Gww2) and from shallow  
346 piezometers (Gwp6, Gwp9 placed at 2 m depth). For the shallow wells and piezometers Gwp6 and Gwp9,  
347 the geochemical signature is strongly influenced by nearby artificial flooding practices. Brackish water  
348 includes samples from the deeper piezometers (4 m and 8 m depth) installed at two locations (Gwp7,  
349 Gwp8 and Gwp10, Gwp11). For these two corresponding locations, a stratification of salinity is observed  
350 that increases with the depth of the piezometers and a geochemical signature that indicates a mixture  
351 evolving from freshwater to saltwater. The salty and over salty waters include samples Gwp1 to Gwp5 and  
352 indicate the presence of seawater in the groundwater that must have undergone evaporation (Fig.3A and  
353 3B).

354 The results indicate the presence of over-salted water in the subsurface layers for all piezometers with  
355 brackish and salty water in addition to piezometers Gwp1 and Gwp5. In this case, the concentration factor  
356 of the evaporated seawater is between 5.8 and 10. For these samples, the percentage of mixing is between  
357 0.5% for Gwp10 (which is now at the boundary between fresh and brackish water) and 30% for Gwp1  
358 (which is now still in an over-salted condition). These results therefore indicate that the saltier  
359 groundwater contains a percentage of formerly over-salted seawater that has been diluted over time.

360

361 *[FIGURE 3: Binary diagrams bromide vs. chloride (A) and  $\delta^{18}O$  vs. chloride (B)]*

362

## 363 5. Discussion

364 **5.1. Long term landscape management impacts on soil and water salinity**

365 Soil and water salinity is highly variable over the study area and increases with depth (see Figure 2). This  
366 observation confirms that the general origin of salinity is from the subsurface compartment and is not due  
367 to surface salt accumulation related to irrigation practices for example.

368 Salinity is first spatially structured according to soil formation conditions. The soils formed from the finest  
369 material deposits, in brackish or salty lacustrine/lagoon conditions are currently the most saline soils. They  
370 are found today near the edges of the present lagoons and are rarely cultivated. Soils formed from the  
371 deposition of silty fluvial materials are very variably saline. Gleyic Fluvisol and Fluvisol are very similar soils  
372 and are distinguished by the presence of temporary or permanent hydromorphy in the first meter. The  
373 Fluvisols, which are higher in elevation and closer to the current river course, are only slightly or not at all  
374 saline. The greatest variations in salinity are found on the Gleyic Fluvisols.

375 The results show that the current salinity is strongly structured in space by long-term water management.  
376 The Robine canal reached the southern end of the selected study area at the end of the 17<sup>th</sup> century from  
377 the first constructions dating from the 15<sup>th</sup> century. This canal, which takes water from the main river  
378 (Aude river), was initially intended to serve as a waterway for the transport of goods. Over time, it has  
379 been used to transport water for agriculture and desalinization practices by artificial flooding of the plots.  
380 Salinity is significantly lower near this canal for all soil types that can have high salinity levels. This can be  
381 interpreted as the proximity of the canal making water use easier and therefore desalinization of soils  
382 more efficient. It is also possible at the same time that leakage through the canal bed feeds fresh water  
383 into the subsurface compartment. It is therefore possible that this deep desalinization of the subsurface  
384 compartment reduces the saline pressure on the soils due to capillary rise during dry periods. These

385 results support the need to integrate surface and groundwater interactions to understand soil salinity  
386 (Bless et al., 2018). Artificial flooding practices consist of massive water inputs between one and three  
387 times per year to a large portion of the plots. These water inputs are then drained through a network of  
388 canals to downstream ponds. Near the larger drainage channels, salinity levels are higher. These results  
389 suggest a serial movement of salt masses over long times (Duan et al., 2022; Wang et al., 2018).

390 To further explore the relationship between landscape evolution and current salinity, we can examine the  
391 visible patches on the interpolated soil salinity maps. Geochemical analysis of groundwater within these  
392 high salinity patches has revealed the mixture between fresh and over-salinity water, a phenomenon that  
393 is not observed outside of these patches. Figure 4 illustrates the overlap of the interpolated salinity  
394 patterns with historical maps such as the Etat Major map from 1852 and the Jean Nicolas Bellin map  
395 published in 1764 in Cavero (2010). This overlap shows that the salinity patches are situated in areas that  
396 were previously ponds in the 19<sup>th</sup> century or designated as wetlands or swamps in the 18<sup>th</sup> century.

397 During the phase of sea recession and the establishment of the plain, salt water may have become isolated  
398 in ponds or marshes. The salt content may have become over-concentrated naturally due to the lack of  
399 fresh water from upstream or through anthropogenic means, such as the exploitation of these areas by  
400 salt works (Descadeillas, 1959; Dupont, 1958). Over time, these over-salted waters could have infiltrated  
401 into the groundwater compartment and been diluted by rainwater percolation and artificial flooding of  
402 the plots. As a result, higher salinity patches may still exist in the subsoil, contributing to areas of higher  
403 soil salinity today.

404

405 **[FIGURE 4:** (A) *Etat Major* map, surveyed in 1852, Narbonne sheet no. 244, published by the *Dépôt de la*  
406 *Guerre* in 1860 (Cavero, 2010), (B) Map by Jean Nicolas Bellin published in 1764, taken from the *Neptune*  
407 *François*, a work intended for navigation, commissioned by Colbert and published by La Favolière in 1693  
408 (Cavero, 2010) (C) overlap of map A and soil surface salinity map and (D) overlap of map B and soil  
409 surface salinity map.]

410

## 411 **5.2. Implications for the future land and water management**

412 The insights provided by this work provide perspective on an apparent paradox. The consequences of  
413 climate change through increased climatic water deficit and rising sea levels indicate a prospect of  
414 increased water and soil salinity problems in the coastal zone (Bless et al., 2018). Long-term perspective  
415 shows for this coastal zone that despite the sea level rise since the beginning of the Holocene, the influx  
416 of sediments by the river has allowed the establishment of a plain on formerly marine or lagoon areas. It  
417 also shows that over the last few centuries, the evolution is that of a global desalinization of water and soil  
418 of the plain.

419 This soil and water desalinization has been made possible in large part by land planning and water  
420 management. The freshwater inflow benefits all land uses with (i) agricultural areas, with high value crops  
421 such as vineyards and (ii) natural areas with rich and specific environments associated with multiple  
422 ecosystem services (*ie* salt marshes, Ermgassen et al., 2021; Himes-Cornell et al., 2018). The current land  
423 management strategy involves the use of large amounts of water for soil desalinization, maintenance of  
424 freshwater lens (de Louw et al., 2013) and mitigation of water stress accentuated by the presence of salt  
425 in the soil solution (Rengasamy, 2010). This strategy is now very strongly questioned. The water used for

426 artificial flooding practices comes from a withdrawal from a coastal river. The acceptability of this  
427 withdrawal depends on the river flows and other competing uses of water (drinking water, water for river  
428 aquatic ecosystems, water for coastal marine ecosystems). The European (WFD, 2000), national (LEMA,  
429 2006), and regional (Rhône Méditerranée & Corsica Water Agency policy) regulatory frameworks aim to  
430 achieve a quantitative balance between withdrawal and an available resource that is decreasing due to  
431 climate change. In this context, the encouragement to reduce withdrawals for agricultural use is very  
432 strong. With this issue of trade-offs on the use of water resources, the studied lowland area is probably  
433 beginning a new phase of transition as it has experienced in the past.

434 All Mediterranean coastal areas are concerned in the same way as for the lowland area studied.  
435 Adaptation strategies concern an overall reduction in freshwater withdrawals from rivers, concentration  
436 of water inputs in priority areas and for priority land uses, management of soils and groundwater levels to  
437 limit salinization processes, adaptation of plants (new resistant varieties and new crops) and planning of  
438 the spatial organization between natural and cultivated areas. As was done for the study area, a spatialized  
439 diagnosis of water and soil salinity is required to make the appropriate strategic choices. Supporting  
440 choices for a sustainable transition implies having a metrological logic to evaluate the evolution of water  
441 and soil salinity and put it into perspective on different time scales, including long time scales.

442

## 443 **6. Conclusion**

444 The current spatial distribution of salinity is mainly inherited from sedimentary processes over the last  
445 two millennia and land planning and water management over the last few centuries. In the short term,  
446 the soils are subject to salinization processes from salty groundwater through variations in water table

447 levels and capillary rise. In the long term, desalinization is observed by massive use of water inputs. The  
448 current spatial patterns ask questions for the future. Stakeholders have therefore to decide where to  
449 continue to fight against salinization. In a situation of decreasing available water resources, three  
450 directions are emerging: fight against salinization on the whole area with less water, choose to fight on  
451 the most impacted areas or, on the contrary, to concentrate desalinization efforts on the areas that are  
452 currently the least salty in order to create non-salted patches surrounded by other areas where  
453 salinization is accepted. In a way, salinity raises the question of the trade-off between water and soil  
454 resources in the medium to long term: is it preferable to use large amounts of water to maintain soil  
455 fertility? Or should water use be reduced with the risk of degrading soils and losing agricultural land and  
456 the conditions required for diversified coastal ecosystems?

457 Mediterranean coastal areas are particularly sensitive to climate change and the impacts of water and soil  
458 salinization. Salinity has a strong impact on plant water availability and requires to be mitigated by water  
459 inputs. Climate change in the Mediterranean regions already shows a greater interannual variability of  
460 precipitation that is concentrated on more extreme events while climatic water deficits are increasing.  
461 The consequence is a decrease in the amount of water available for societies and ecosystems. Salinity is  
462 therefore a prism that allows to perceive in an accelerated way the impacts of climate change related to  
463 the decrease of available water resources. This prism can be particularly interesting to analyze the  
464 trajectories of a large number of regions in the world.

465

466 **Acknowledgements**



467 The authors thank the SALIN collaborative project associating BRGM, the Institut Agro Montpellier, the  
468 Regional Nature Park (PNR Narbonnaise en Méditerranée) and the Communauté d'Agglomération du  
469 Grand Narbonne with the financial support of the Rhone-Mediterranean and Corsica Water Agency and  
470 the Occitanie Region.

471

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