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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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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 km² in the south of France and saturated paste
21 extract Electrical Conductivity (EC_{sp}) was deduced from 1:5 dilution. Soil salinity exhibits a wide range of
22 variation (from 0.54 to 113.1 mS cm⁻¹) and spatial patterns. EC_{sp} 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 (¹⁸O/¹⁶O) 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 15th to 18th), 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 km². 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 14th 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;

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 9th century to the 16th 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 18th 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 15th to the 18th 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 (CO_2) using a Finnigan MAT 252 mass spectrometer. Results are expressed in parts
257 per thousand (i.e. ‰) in the familiar δ 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 mS cm^{-1} , while those
307 in Gleyic Fluvisol range from 5.09 to 12.33 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 mS cm^{-1}
309 to 3.43 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 mS
317 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 = 4.89e^{-3}) for the deep
319 samples (90-120 cm), while the surface samples (0-40 cm) showed no significant effect (p -value = 4.09e^{-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 g L^{-1}), saltwater (chloride
342 concentration between 10 and 35 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 17th century from
377 the first constructions dating from the 15th 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 19th century or designated as wetlands or swamps in the 18th 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

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471

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