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Combining multiple geostatistical analyses to assess the past, present, and future of fragile Mediterranean deltaic environments

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ABSTRACT

Littoral plains in general and those of the Mediterranean rivers and ramblas, are highly vulnerable territories. Understanding the past and present conditions of these areas is the best strategy to design efficient land management plans to prevent degradation such as pollutants, soil sealing, erosion, etc. in the near and medium future. In this research, different mapping techniques (land-use changes in twelve different years using manually digitalisation and field observations, from 1956 to 2019, and pattern analysis using ecological landscape indexes), multivariate statistical analyses (Spearman rank coefficient and Principal Component Analysis), and predictive models (Markov chain) are combined to assess the past, current, and future status of the Vélez River delta (Málaga province, Southern Spain), a representative vulnerable territory situated in the popular touristic area of Costa del Sol. We also included a demographic analysis using annual population census data (current inhabitants and projections) and a climate trend analysis (Mann-Kendall test) considering temperatures, precipitations and wind data. Our results demonstrate that the drastic urbanization, including new settlements, roads, and ways, has negatively impacted the delta area, even the alluvial plain, beaches, and natural sand deposits. From 1956 to 2019, >70 ha of deltaic area have been lost. The largest category of land-use, cultivated fields, accounted for up to 72.4 % of the total delta area in 1984. However, this was reduced to 41.1 % by 2019. The alluvial plain and beaches/sand deposits started from 9.3 and 11.8 %, and decreased to 5.2 and 5.9 %, respectively. Also, climate change (especially in temperature) could affect some spatial patterns. Predictive models reveal that it is likely that abandoned spaces, sand deposits, and beaches, will be transformed into new urban areas and, to a lesser extent, into cultivated fields. We concluded that the conservation of the cultivated lands, although decreasing in the area over the studied period, obtained the highest correlation with the delta conservation. Therefore, we affirm that efficient plans, which promote specific changes in land use, would contribute to stopping the degradation of the delta such as pollution of natural areas or soil sealing. Specifically, a plan should be developed to preserve sustainable agriculture and control urban sprawl.

1. Introduction

Deltas are surface geomorphological features associated with coastal wetland areas and are characterized by an elevated richness of biodiversity and fertile soils (Baskaran et al., 2022; Holzhauer et al., 2022). For millennia, humans have exploited deltaic territories to provide their settlements with vital resources such as food and energy (Dang et al., 2021; Rodríguez-Santalla and Navarro, 2021). Consequently,

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deltas are suffering land degradation related to the loss of biological functionality, especially because the coast is moving inland due to pollutants or soil sealing (Parrinello et al., 2021). Recent investigations claim that this situation will be even worse due to the effects of imminent climate change such as the sea-level rise and weather pattern changes (Dang et al., 2021; Dawson et al., 2003) and the rapid urbanization of coastal areas (Canfora et al., 2017; Colantoni et al., 2015). Therefore, understanding the connection between deltas and land-use changes over time will allow us to carry out successful assessments of the past, present, and future status of these vulnerable deltaic ecosystems against irreparable negative impacts such as pollutants, soil sealing or soil erosion (Liu et al., 2019; Minderhoud et al., 2018).

An increasing number of publications emphasize that big rivers and associated deltas on the coasts are mismanaged, causing increasing degradation, contamination, and loss of water quality. Examples include the Nile (Bakr and Afifi, 2019; Elagouz et al., 2020), Mekong (Liu et al., 2020; Ogston et al., 2017), and Niger (Ayanlade and Howard, 2019; Dan-Jumbo et al., 2018) deltas, among others. Soils on deltas are characterized by high fertility due to their location, formation, and development near the rivers (Wang et al., 2018; Wu et al., 2019). They are azonal soils, whose development and quality are closely related to the surrounding geospatial variations and character of rivers (Dolobeshkin et al., 2021; Polyakov et al., 2018). From this point of view, they are spatially heterogeneous, implying that they must be carefully evaluated for their sustainability and quality, so as not to lose their fertility due to pollution or soil sealing (Rodríguez et al., 2021).

In Spain, 80 % of coastal urban areas and 90 % of the population are associated with coastal ecosystems, which is of special interest for the integrated management of coastal zones (de Andrés et al., 2017). In the south, many deltas, such as those of the Vélez River, Guadalfeo or Adra, are highly affected by human activities (Bergillos and Ortega-Sánchez, 2017; Gallegos Reina and Perles Roselló, 2021; Sánchez et al., 2008). In general, the Mediterranean coast in Andalusia is undergoing a double process of transformation, due to both urbanization and the extension of intensive agriculture. Both are processes associated with tourism and second residences as the main explanatory factors of land consumption and the rapid deterioration of environmental conditions (Cumbrera and Lara, 2010; Zújar and Lama, 2007). Urbanization, forest exploitation, and intensification of agriculture have polluted and sealed the original ecosystems to the extreme (Malvárez García and Senciales González, 2003; Molina et al., 2019). On the other hand, in recent decades these lands have also seen the expansion of two new modalities of highly profitable crops, namely, in greenhouses and subtropical fruit trees, in more thermally benign areas (Rodrigo-Comino et al., 2022; Rodríguez, 2019).

Previous studies indicate that in the Vélez River Delta, land degradation processes (water and soil pollution, soil erosion, soil compaction, soil sealing, soil and water salinization, and floods) are disturbing this vital relationship between rivers and soils, and a constant retreat is recorded (Malvárez García and Senciales González, 2003). The floods also became one of the biggest concerns of the municipality after detecting that the mountains on the top of the catchment are affected by serious soil erosion and drastic land-use changes (Rodrigo-Comino and Senciales González, 2015; Senciales González and Perles Roselló, 1994). However, few studies present a long-term monitoring strategy to detect the current land-uses affecting the delta degradation and to design sustainable solutions that could prevent irreparable future contamination and sealing. In addition, some coastal protection initiatives by the Regional Government (Junta de Andalucía), such as the Protection Plan for the Andalusian Coastal Corridor, have barely had an effect due to their short application period (2015–2018).

To achieve this goal, it is necessary to combine multiple geospatial analyses to understand the past and the present, and to assess possible future changes within the deltaic areas. However, this aim is not possible without considering climate trends related to temperatures, wind speed, or precipitation and the variation of the population close to the delta. Therefore, the main aims of this research are: i) to conduct a delta and land-use changes analysis considering 12 different periods from 1956 to 2019 through mapping and multivariate statistical techniques (correlation and principal component analysis); and ii) to model climate, demographic, and land-use changes to understand the potential status of the delta of the Vélez River in the next decades. We want to highlight that this is interdisciplinary research which pretends to bring together insights from different fields (regional geography, ecology, land and coastal management and cartography). These kinds of holistic studies are limited in the literature due to the large datasets required and the investment of time needed to analyse the data. We intend for this research to demonstrate: i) how to integrate different datasets to assess a vulnerable deltaic ecosystem, broad environmental and societal challenges such as climate change and population growth; ii) and to inform policymakers and stakeholders about the mismanagement of this area. The characterization of the status of the delta and its evolution from a holistic perspective will determine whether this degradation is due to human impacts (pollution, soil sealing or erosion) or climate change effects (or both).

2. Materials and methods

2.1. Study area

The Vélez River delta is located in a basin in south-eastern Spain, within the province of Málaga, on the Mediterranean coast of the Alboran Sea (Fig. 1). The river flows along a short but very steep route (Senciales-González et al., 2018). The length of the main channel reaches about 68.39 km in a valley of 43.12 km and a maximum altitude of 2065 m, located asymmetrically in one of the vertices of the basin closest to its mouth (Senciales González, 1996). The total projected area is 610 km^2. Located in a semi-arid, sub-humid transitional environment, the annual average precipitation in the basin is 629 mm, with an annual climatic regime of marked seasonality: the almost total absence of rains in July and August, especially in the coastal stations, compared to rainy autumn, of up to 200 mm/month in the interior stations (Senciales González and Perles Roselló, 1994). The parent material in the mountains is characterized by karstic sediments and metamorphic materials, which define the composition of the fine sediments that reach the coast (Malvárez García and Senciales González, 2003). The municipality of Vélez-Málaga (composed of the settlements of Vélez-Málaga and Torre del Mar) has a total of 82,365 inhabitants (2020) and the most relevant economic sectors are coastal tourism, predominantly based on residential apartments and second homes (Almeida-Garcia and López Cano, 2003), and farming, which has focused especially on subtropical species (mango, avocados, etc.) and horticulture over the past decade.

At the mouth of the river, the wetland contains a coastal lagoon, which is separated from the sea by a sandy bar that breaks up with river floods and is restored with coastal storms (Suppl. Material 1 generated from the official information updated by the regional government of the Junta de Andalucía). In this last section of the river, pieces of riverside forest with *Populus alba, Rubus ulmifolius* and *Vinca minor* are preserved. Near the lagoon, a dense cane-grove of *Arundo donax* dominates, associated with the anthropic alteration of the environment. Moreover, various marsh formations can be found on the flooded shores and peripheral lakes along with a lagoon area with permanent flooding. As for birds, the larid and the waterfront are outstanding, and this space is also a wintering place for the green-headed and audouin gulls. There is a list of 30 endangered species living in this wetland, as documented in a regional report by the Andalusian government. In Suppl. Material 2, a gallery of general pictures of the wetland, cultivated and abandoned fields, urban areas and beaches was included.

2.2. Land-use changes and delta borders

The delimitation of the borders of each land use in the delta was

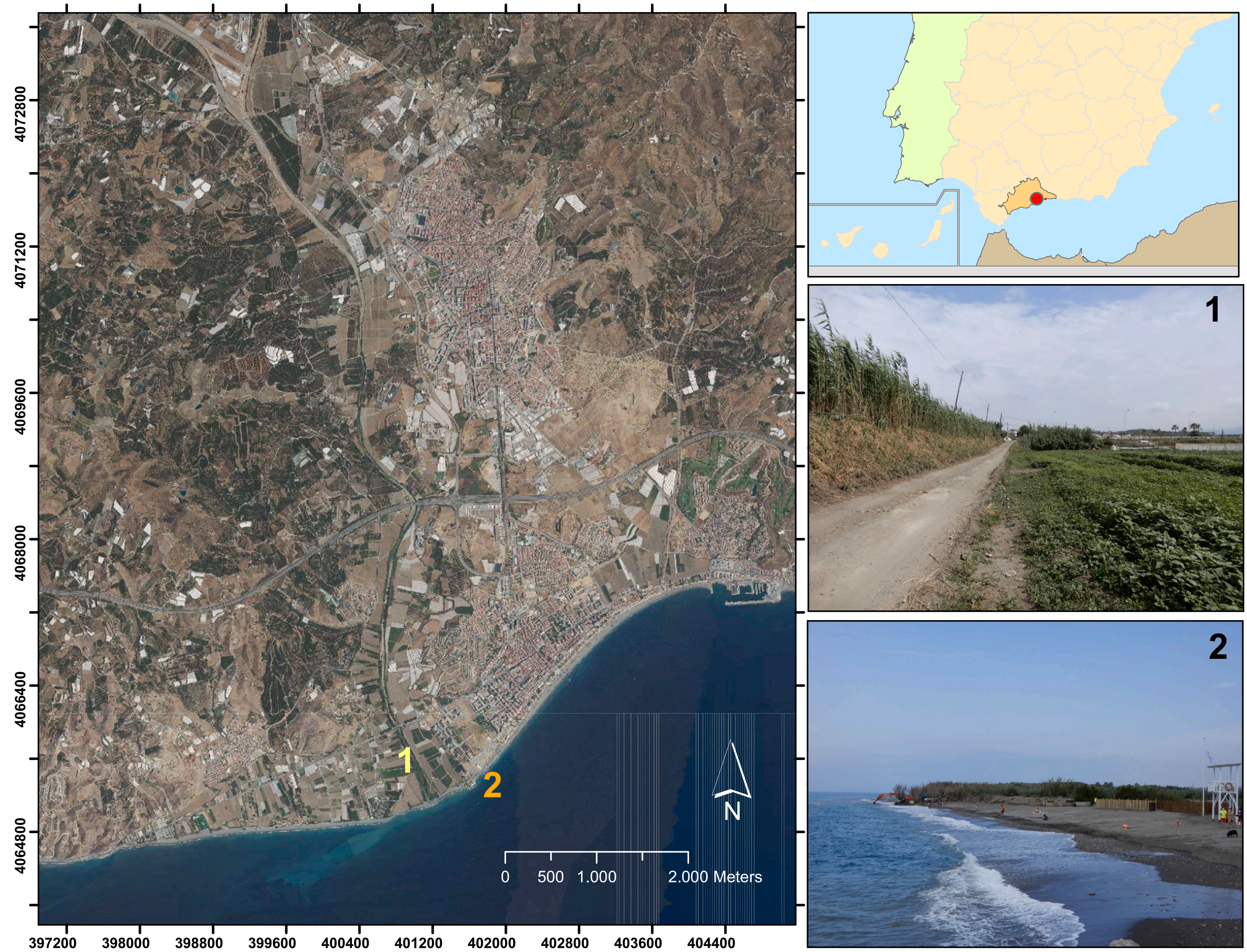

Fig. 1. Localisation of the study area, topographic map and examples of land uses.

conducted using digitized aerial photographs from 1956, 1977, 1984, 1998, 2001, 2004, 2006, 2007, 2008, 2013, 2015, and 2019 stored in the Department of Geography (University of Málaga, Spain) and downloaded from the official geovisor of the Spanish Geographic Institute (IGN), which are available for free. It was not necessary to preprocess the images because they are georeferenced (ETRS89) and the mosaics joined.

2.2.1. *Coastal change analysis*

To establish the borders of the delta and the coast and to reconcile the different sources (Leatherman, 2003; Tobias, 2008), we confirmed with field visits using a GPS (EMLID) the delimitation realized by Malvárez García and Senciales González (2003), who used stereo models of the years 1957 (American flight, 1:33,000), 1968 (municipality of Vélez, 1:33,000), 1976 (Interministerial flight, 1:18,000), 1981, 1982, 1984, 1990, and 1992 (Junta de Andalucía, 1:33,000), 1995 (Junta de Andalucía, 1:20,000), 1998 (Junta de Andalucía, 1:33,000), and 2000 (Junta de Andalucía, 1:8000), as well as oblique aerial photos of the years 1987 and 1989 (Aerial Landscapes of the South, S.A.) All measurements used in our study were based on the 1956 map, conserving as these authors suggested the Western (sedimentary cone) and Eastern (Pliocene materials) limits because of the lithological changes and human interventions (roads). The collected points were collected and sent in points as georeferenced vectorial format.

2.2.2. *Land-use change analysis*

Using the above-mentioned aerial photographs, two types of methods were used to quantify land-use changes per year. We conducted a manual digitization of the land-uses within the delta using the ArcGIS 10.5 (ESRI, USA) software package, because of the generalization done by other land-use and land-cover datasets such as CORINE land cover or SIOSE (Sistema de Información sobre Ocupación del Suelo de España) (García-Álvarez and Camacho Olmedo, 2017). Moreover, to verify and validate the data in 2019, a supervised classification was conducted using the functions DIGITIZE (to select the training and representative polygons), MAKESIG (to generate a spectral signature), and MINDIST (to observe the final map) using TerrSet 2020 Geospatial Monitoring and Modeling Software (Clark Labs, USA). The total area was calculated for each year and land use category using the area function in the attribute table after classifying and homogenizing all the categories. We considered it worthwhile to group different types of agricultural uses (horticulture, greenhouses, woody irrigation, subtropical, etc.) even though each of them plays a very different role in terms of water needs, soil erosion, etc. The main reason is the difficulty of distinguishing each of those types using the above-mentioned currently available information.

Moreover, considering all the land-use maps digitized per year by the Toolbox Raster Analysis, the Pattern Analysis function in SAGA (in QGIS, version Las Palmas) was used to calculate a set of indices and measures of variability, which are used, among others, in landscape ecology studies (Acharya and Bennett, 2001; Fu and Chen, 2000;

Hessburg et al., 1999), namely: relative richness, diversity, dominance, fragmentation, different number of classes (NDC), and different vicinity classes (CVN). These techniques are applied to 3 * 3, 5 * 5, or 7 * 7 matrices. This allows us to measure the local variability while moving successively through the raster file. It is also necessary to indicate the maximum number of classes, resolutions, and to transform the original vector data into raster data.

2.3. Climate and population trend analysis

2.3.1. Climate data and analysis

Climate parameters were also calculated using the temperature (average, maximum, and minimum), precipitation (total), and wind speed (km/h) from two different meteorological stations. The climate trend was then estimated using the Mann-Kendall Test and Sen's method (Alemu and Dioha, 2020; Sen, 1968). The IFAPA (Andalusian Agricultural and Fisheries Development Institute) weather station in Vélez Málaga is part of the Andalusian Agroclimatic Information Network (RIA) and offers a series of daily data from October 2000 to the present. Its coordinates are UTM: X: 399039, Y: 4072850. It is located at an altitude of 33 m a.s.l. at the bottom of the Vélez River valley, right at its confluence with its main tributary, the Benamargosa River. The data series covers from 2001 to the present time. The Vélez-Clause meteorological station (Semilleros Clause) in Vélez-Málaga forms part of the AEMET (Spanish State Meteorological Agency) secondary network and provides data since January 1992 (almost 30 continuous years). Its coordinates are UTM: X: 399962, Y: 4072833. It is only 923 m to the east of the Vélez-IFAPA station. It is located at 38 m a.s.l. on the left (eastern) bank of the Vélez river, a few meters above its confluence with the Benamargosa river.

2.3.2. Current and future population using linear regression

From 1996 to 2020, the total numbers of annual inhabitants were obtained from the Municipal register at the city hall of Vélez-Málaga. Also, we included demographic data from 1950 obtained from the national census approximately every 10 years. The demographic projection was calculated using a linear regression model considering the above-mentioned time series and the previous linear trend observed in this settlement. According to this model, the projection is based on the calculation of a configured regression equation, using SigmaPlot 12.1, from the available demographic annual data for a given time series. In this case, the starting data period was 1998–2020.

2.4. Multivariate statistical analysis and land-use change prediction

First, using IBM SPSS Statistics v23 software (IBM, USA), we performed a Spearman rank coefficient to evaluate which factors (land-uses, delta area, climate and demography) could directly influence the delta area changes during the studied period. Then, we carried out a principal component analysis (PCA) to identify the group of variables that could explain the current research topic (Karadzic and Popovic, 1994; Li et al., 2016). The PCA groups similar variables into dimensions, without distinguishing between independent and dependent variables. Before starting, all variables were centred and normalized and we verified the assumptions by including a Kaiser-Mayer-Olkin (KMO) test of sphericity and estimated the coefficients and determinants. A PCA, with an orthogonal rotation method (Varimax) and a correlation matrix, using factors with eigenvalues >1, was carried out. Our dataset included seventeen variables, which were classified into three different groups: i) land-uses and delta; ii) population; and iii) climate. The resulting principal components (considering the variables > 0.5) also allowed us to detect the factors that determine the different effects of human or climate impacts on the delta area.

Finally, to project land-use changes for a hypothetical future of 10 years, we used the CA_MARKOV function of Terrset (Camacho Olmedo et al., 2015; Mas et al., 2014; Shirley and Battaglia, 2008). That allowed us to calculate the Markov chain matrices and to determine the quantity of change along with suitability maps and cellular automata to spatially allocate those changes in the future. A Markov chain can be defined as a stochastic process, but differing from a general stochastic one since it uses "memory-less." The probability of future situations are independent upon the steps that led up to the current state. We tested these changes considering each land-use map from 1956 to 2013 (t_0) as the earliest scenario and fixing 2019 as the latest one (t_1). We depicted this information for each year simulated and according to the probability change between pixels (Adhikari and Southworth, 2012; Eastman and Toledano, 2018; García-Álvarez et al., 2019).

3. Results

3.1. Climate trends

In Fig. 2, the average temperatures in Vélez-IFAPA (station 1) ranged between 17.35 °C in 2013 and 18.48 °C in 2020, implying an annual average of 17.89 °C. Although an increasing temperature trend of 0.2 °C/decade can be noted, the Mann-Kendall test does not show a significant trend for any thermal variable at the IFAPA-Vélez station. The statistical estimators (standard deviation, coefficient of variation, bias) do not reveal any anomaly that leads one to infer any error in the series, with values of the coefficient of variation lower than 10 % in all months. Vélez-Clause (station 2), having a longer series, not only shows a greater interannual temperature range, but also a different dynamic. Thus, the lowest value of the annual averages of the series is shown in 1993, at 17.29 °C, while 2016 had the highest value, with an annual average of 19.42 °C. Meanwhile, the average temperature of the full series was 18.34 °C (almost half a degree higher than Vélez-IFAPA). Analysing the trends according to the Mann-Kendall test, the Z value of 3.66 (>1.96), shows a highly significant trend of the means. As can be seen in Fig. 2a and b, these trends translate into an estimated increase of 0.39 °C/decade. The statistical estimators show similar characteristics to those of Vélez-IFAPA in terms of deviation from the average values. The minimum and maximum temperatures show similar sequences in both seasons, although the Mann-Kendall test shows significant positive trends in Vélez Clause, but not in Vélez-IFAPA.

3.2. Population changes

Fig. 3a shows the de jure population of Vélez Málaga according to Census 1950–2011 (conducted every ten years). The parameters necessary to apply the linear eq. $Y = A + BX$ were obtained, resulting in $A = 53{,}217.01581$ (free parameter) and $B = 1421.321146$ (slope or conversion rate) using a total of six decimal points. The degree of correlation (R^2) between the variables X and Y was 0.934063 (the optimal range for demographic projections being between 0.9 and 1), with X being a given year and Y the following year.

In this period, the population more than doubled, increasing from 31,948 to 76,922 inhabitants. The de jure population according to the Municipal Register 1998–2020 (published on a yearly basis) rose from 53,816 to 82,365 inhabitants (Fig. 3b) (SIMA, 2021; Sistema de Información Multiterritorial de Andalucía (SIMA). Junta de Andalucía; https://www.juntadeandalucia.es/institutodeestadisticaycartografia/badea/informe/anual?CodOper=b3_151&idNode=23204). This increase in population has been almost constant during this period, with two exceptions: (i) during the 1970s, when the predominant trend in Southern Spain was emigration to North and Central Europe as well as to industrialized areas of Spain; and (ii) in the year 2013, marked by a strong reduction of international immigration, which was at its lowest on the national level in that period (González, 2020; González-Leonardo, 2020), together with an increase in emigrants from the municipality. Some of the databases allude to the dynamic populations of the province of Malaga in general. In Vélez-Málaga and since 2008, there have been fluctuations in immigration, with some peaks in 2012–2013.

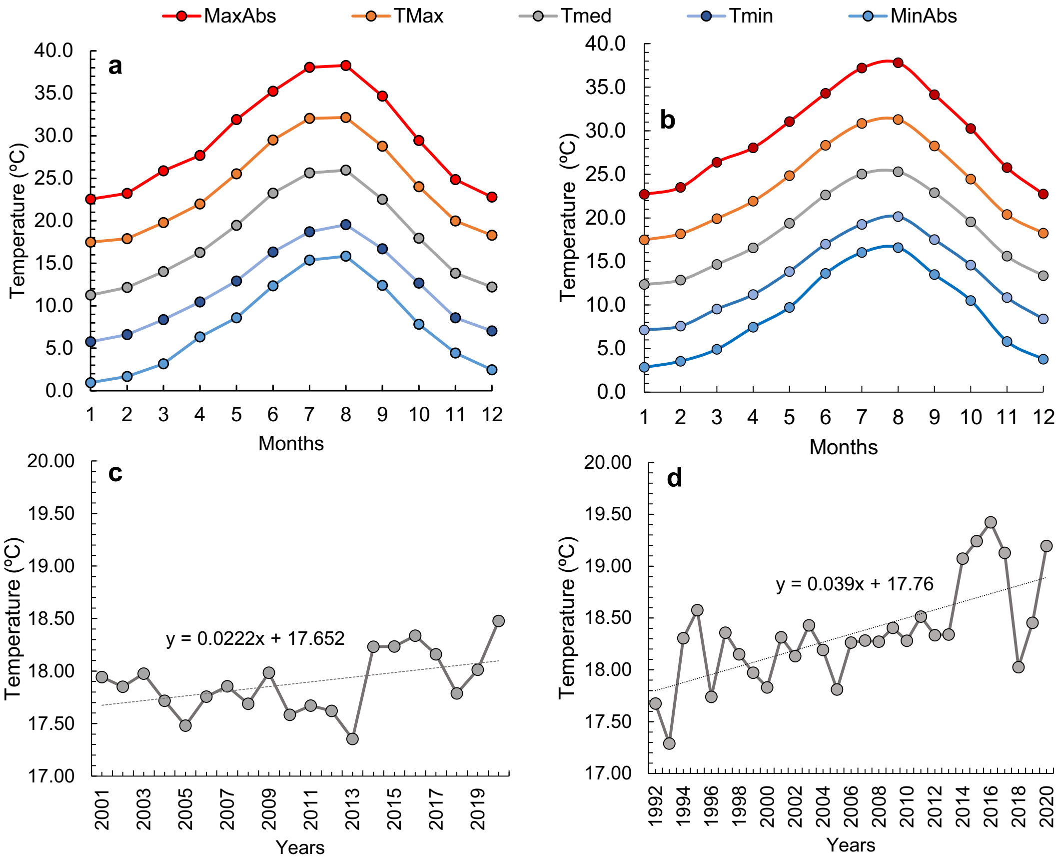

Fig. 2. Maximum, mean and minimum temperatures, and trends. Results of Climate station 1 are depicted in a and c, and Climate Station 2 in b and d.

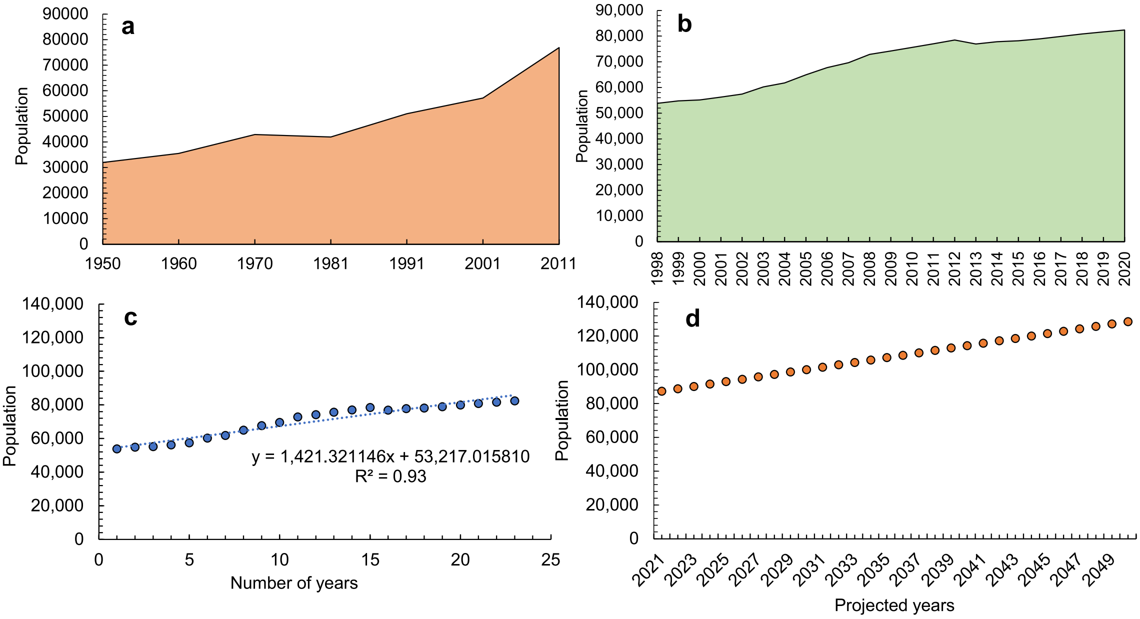

Fig. 3. Current total inhabitants and future expected population. a. Data derived from the Spanish Census; b. Data obtained from the municipal register.

Looking at the total population, the foreign population fell in that year (countries of origin: Romania, Germany and United Kingdom). With these migration patterns, emigration must also be taken into account to understand the constant net population growth at the rate of almost 800 inhabitants per year.

In the analysis of demographic projections, it must be emphasized that it is a mathematical estimation (Fig. 3c) based on the evolution of the population (Sarmiento, 2008) in a specific period (in this case 1998–2020). This projection (Fig. 3d) can reflect the real evolution of the population if the existing demographic and socio-cultural trends are maintained over time. Our results show that the population of the municipality of Vélez Málaga will increase, reaching a theoretical population of 128,547 inhabitants in 2050, a rise of 56 % since 2020.

3.3. Delta and wetland areas, land-use changes and pattern analysis

In Fig. 4, the evolution of the total area occupied by the delta in the Vélez-Málaga municipality along the wetland coast is presented. In 1956 and 1977, the delta registered a total area of 277 ha, decreasing to 222 ha in 1984 and 216 ha in 1998. During the present century, the total area of the delta registered a decrease from 215 (2001) to 207 ha (2019). In total, >70 ha have been lost.

Fig. 5 illustrates the land-use changes in map form per year, while Fig. 6 shows the changes in each category (as a percentage of the total) in graph form. Our results show that the largest category of land-use, cultivated fields, accounted for up to 72.4 % of the total delta area in 1984. However, this was reduced to 41.1 % by 2019. The alluvial plain and beaches/sand deposits started from 9.3 and 11.8 %, and decreased to 5.2 and 5.9 %, respectively. The first data that measured abandoned areas showed them covering 3.3 % of the total area. In 2008, these areas reached a maximum of close to 23 %, after which they were reduced to 13.8 % by 2019. In contrast, the settlements and roads/ways registered the more drastic increases, from 2.9 and 5.9 % to 23.6 and 10.4 %, respectively.

Finally, in Table 1, we transformed the digitized land-uses into a raster format in order to calculate indexes that could assess the differences among the various land-uses for each period. The average relative richness increased from 14.76 to 15.88. However, similar to the diversity index (from 0.21 to 0.26), this pattern did not follow an exactly linear trend. The maximum values were reached in 2007 and 2008, and then, a decrease was recorded. Also, the different number of classes (NDC) and different vicinity ones (CVN) reported the lowest values in 1956 (1.48 and 1.46), and reached their maximum values in 2008 (1.6 and 1.81), remaining relatively unchanged thereafter out to 2019. The dominance and fragmentation indexes did not show significant changes over the years.

3.4. Multivariate statistical analysis

First, we conduct a Spearman rank coefficient to show which factors are correlated with the above-mentioned changes in the delta (Table 2). Considering the land-uses, negative correlations between delta area and abandonment (−0.827), roads and ways (−0.955), and settlements (−0.964), were registered. These correlations were also confirmed by the negative correlation between population and delta (−0.955). On the other hand, an increase in cultivated areas would demonstrate the conservation of the delta (0.936). Moreover, the conservation of beaches and sand deposits (0.818), and the alluvial plain (0.927) would also imply a reduction in the delta degradation, although these areas never grew. The climate variables did not register a significant correlation with the delta area.

Table 3 shows the extraction and rotation sums of the results related to the Principal Component Analysis (Fig. 7). Table 4 and Fig. 6 display the final results. We obtained five components to explain 97.8 % of the total variance. Component 1 explains 36.1 % of the total variance, grouping variables related to land-uses, delta area, population, and climate (temperatures of climate station 2). We identified a relationship between the delta degradation and the increased area in settlements, roads and ways, and population. It could be understood as a causal relationship. However, it should be specified that the retreat of the delta may also be related to the hydrological regulation of the basin and, especially, to the regulation supplied by the Viñuela dam in the headwaters. Again, note that a decrease in cultivated areas, beaches and sand deposits, and alluvial plain corresponds to a delta retreat. Also, we registered a significant relationship between an increase in temperatures (minimum and average) and the delta retreat. The second and third components explain 16.6 % of total variance each, which accumulates to almost 70 % of the total variance. These are related to climate (temperatures and precipitations), like component 5, which considers wind speed and temperatures. Finally, component 4 explains the negative relationship between the conservative land-uses of the delta (cultivated areas, beach and sand deposits, and alluvial plain) and abandonment.

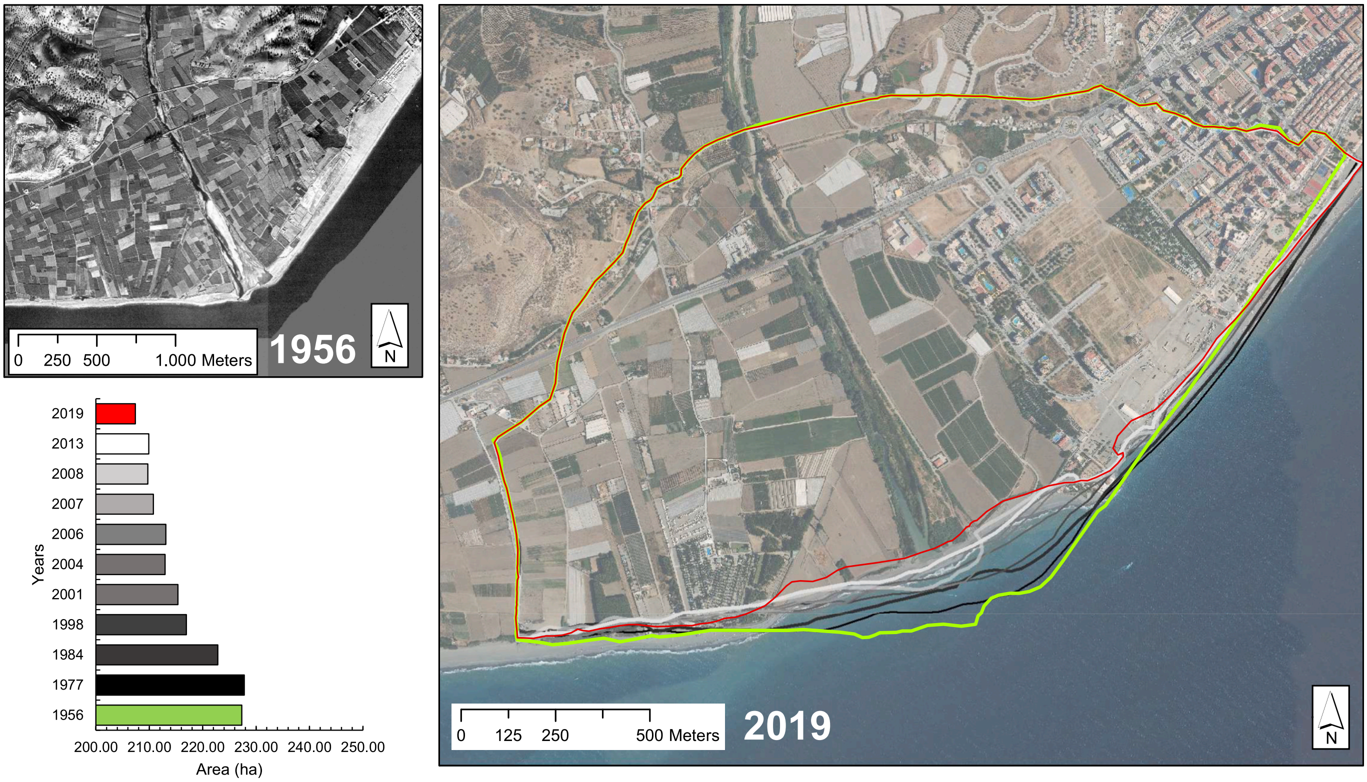

Fig. 4. Total area and changes over the studied periods in the delta of Vélez River.

Fig. 5. Land-use maps per studied year in the delta of Vélez River.

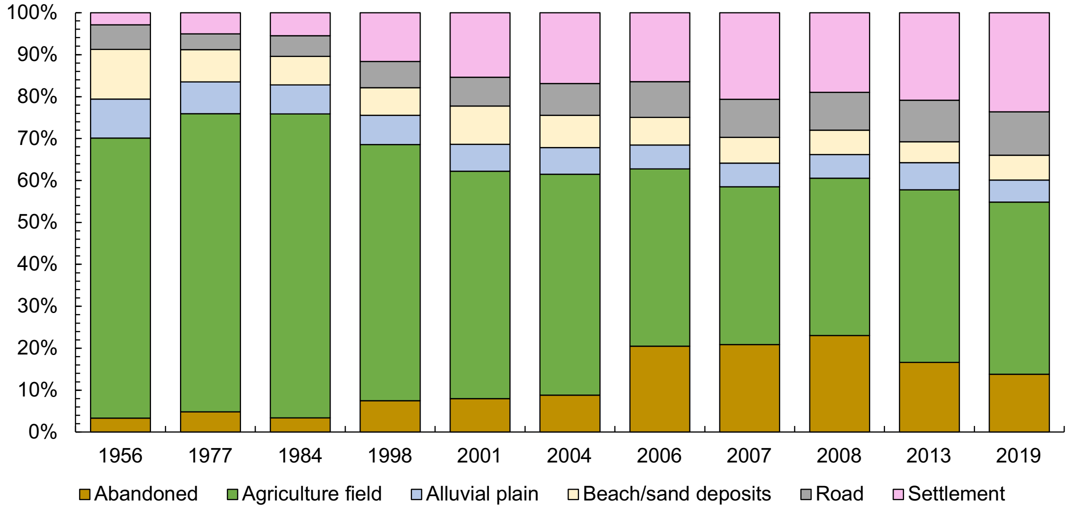

Fig. 6. Total area (%) of each land use per studied year in the delta of Vélez River.

Table 1
Performance of raster analysis indexes to assess differences among land-uses per time period.

		1956	1977	1984	1998	2001	2004	2006	2007	2008	2013	2019
Relative richness	Min	10	10	10	10	10	10	10	10	10	10	10
	Max	50	50	50	50	50	50	50	50	50	50	50
	Av	14.76	14.56	14.64	14.61	15.13	15.45	15.49	16.02	16.04	15.94	15.88
	St	6.37	6.93	6.7	6.82	7.05	7.35	7.45	7.78	7.7	7.74	7.61
Diversity	Min	0	0	0	0	0	0	0	0	0	0	0
	Max	1.56	1.49	1.52	1.37	1.56	1.53	1.59	1.56	1.57	1.52	1.52
	Av	0.21	0.19	0.2	0.21	0.23	0.24	0.25	0.27	0.27	0.27	0.26
	St	0.3	0.31	0.3	0.31	0.32	0.33	0.34	0.35	0.35	0.35	0.34
Dominance	Min	0	0	0	0	0	0	0	0	0	0	0
	Max	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59
	Av	0.10	0.09	0.10	0.08	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	St	0.15	0.15	0.16	0.14	0.16	0.16	0.15	0.15	0.15	0.15	0.15
Fragmentation	Min	0.08	0.08	0.07	0.08	0.08	0.12	0.08	0.08	0.08	0.08	0.08
	Max	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38
	Av	0.11	0.11	0.11	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.12
	St	0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.06	0.06
Different number of classes (NDC)	Min	1	1	1	1	1	1	1	1	1	1	1
	Max	5	5	5	5	5	5	5	5	5	5	5
	Av	1.48	1.46	1.46	1.46	1.51	1.54	1.55	1.60	1.60	1.60	1.60
	St	0.64	0.69	0.67	0.68	0.71	0.73	0.74	0.77	0.77	0.77	0.76
Different vecinity classes (CVN)	Min	0	0	0	0	0	0	0	0	0	0	0
	Max	12	12	12	12	12	12	12	12	12	12	12
	Av	1.43	1.30	1.32	1.38	1.50	1.58	1.66	1.78	1.81	1.77	1.78
	St	2.50	2.41	2.42	2.43	2.51	2.59	2.63	2.7	2.7	2.71	2.72

Table 2
Spearman rank coefficient considering related values of the total delta area.

Variables	Delta
Abandoned	−0.827**
Cultivated land	0.936**
Alluvial plain	0.927**
Beach/sand deposits	0.818**
Roads and ways	−0.955**
Settlements	−0.964**
Tmax1	0.107
Tmin1	0.536
Tmed1	0.107
Pp1	0.036
Wind speed 1	−0.179
Tmax2	−0.238
Tmin2	−0.643
Tmed2	−0.643
Wind speed 2	−0.321
Population	−0.955**

** Correlation is significant at the 0.01 (2-tailed). Tmax1: Average maximum temperature climate station 1; Tmin1: Average minimum temperature climate station 1; Tmed1: Average temperature in climate station 1; Pp1: Precipitation (mm) climate station 1; Wind speed 1: Wind speed in climate station 1; Tmax2: Average maximum temperature climate station 1; Tmin2: Average minimum temperature climate station 2; Tmed2: Average temperature in climate station 2; Wind speed 2: Wind speed in climate station 2.

3.5. *Future (MARKOV chain prediction)*

In Fig. 8, six different graphics depict the probability of changing from one specific land use to another one over a ten year period. This figure also shows this probability as a function of a calendar year (t_0: 1956, 1977, 1984, 1998, etc.), considering 2019 (t_1) as the final date. In Fig. 8a, the abandoned areas show a reduced probability, in almost all the years, that they will continue to have the same land use in 2029. Depending on the years used for the simulation, the model predicts that there are some finite probabilities to change into cultivated lands or settlements. Considering the model, the cultivated lands have a high probability to continue in the delta, confirming that they will still be the main use of land. The alluvial plain is a land-use category with a high probability to continue unchanged, with fewer variations that show changes in ten years. Only some interchanges with sand deposits and beaches might be contemplated. On the other hand, these sedimentary deposits are less likely to be conserved because the models project that they could be changed by settlements. Finally, the land-uses related to urban sprawl, such as roads and ways, and settlements, showed the highest probability to continue unchanged after ten years.

4. Discussion

During the interval 1998–2020, Spain was in a historical-demographic moment corresponding to an already completed Demographic Transition, but in which the Demographic Momentum was still active. In the period considered for the projection (2020–2050) and the Markov chain (2019–2029), these features could be weaker or could disappear, being able to alter, or even reverse, the trends present in the base period (Mosakova, 2019; Verdú, 2021). The real evolution of the population is conditioned by different factors, fundamentally those linked to the migratory balance resulting both from internal migrations and the migrations of populations of foreign origin (Carlucci et al., 2018; Serra et al., 2014). The study area is already a destination for internal flows, as a coastal place or reception centre for people from nearby rural areas (Rodríguez et al., 2021). It also filters strong and highly consolidated international flows, especially those from other EU countries.

Superficially, the wetland zones may appear to have little relevance, but they constitute a high-value space subject to important transformations during the studied period. Especially since 1986, with the construction of the Viñuela reservoir and the diversion of springs downstream, the river's regime has become significantly seasonal. Thus, water levels in the lagoon are significantly reduced in the summertime and dry years, and the water practically disappears altogether during these critical periods. In parallel, the diversity of the fauna is constrained by the advance of the area sealed and pollution by urbanization and by the transformation of agriculture from its traditional forms to the growing use of plastics. As for the riverside vegetation, this has suffered a significant reduction, which has reduced the areas of refuge and reproduction for the birds. In addition to this, other disturbances related to the ongoing urbanization process that could affect wildlife would be the proximity of electrical lines, the landfill of waste, the increase in road traffic, and the spread of tourist activities such as paragliding and

Table 3
Principal component analysis, extraction and rotation sums.

Component	Initial eigenvalues			Extraction sums of squared loadings			Rotation sums of squared loadings			Communalities	Extraction
	Total	%V	C%	Total	%V	C%	Total	%V	C%		
1	7.53	44.31	44.31	7.53	44.31	44.31	6.14	36.14	36.14	Abandoned	0.975
2	4.11	24.17	68.49	4.11	24.17	68.49	2.82	16.59	52.73	Cultivated land	0.999
3	2.18	12.85	81.33	2.18	12.85	81.33	2.82	16.56	69.29	Alluvial plain	0.986
4	1.68	9.90	91.23	1.68	9.90	91.23	2.54	14.97	84.26	Beach/sand deposits	1.000
5	1.12	6.60	97.83	1.12	6.60	97.83	2.31	13.56	97.83	Roads and ways	0.999
6	0.37	2.17	100.0							Settlements	0.966
7	0.0	0.0	100.0							Delta	0.918
8	0.0	0.0	100.0							Tmax1	0.989
9	0.0	0.0	100.0							Tmin1	0.993
10	0.0	0.0	100.0							Tmed1	0.991
11	0.0	0.0	100.0							Pp1	1.000
12	0.0	0.0	100.0							Wind speed 1	0.953
13	0.0	0.0	100.0							Tmax2	1.000
14	0.0	0.0	100.0							Tmin2	0.976
15	0.0	0.0	100.0							Tmed2	0.922
16	0.0	0.0	100.0							Wind speed 2	0.964
17	0.0	0.0	100.0							Population	1.000

%V: Percentage of variance; C%: Cumulative percentage; Tmax1: Average maximum temperature climate station 1; Tmin1: Average minimum temperature climate station 1; Tmed1: Average temperature in climate station 1; Pp1: Precipitation (mm) climate station 1; Wind speed 1: Wind speed in climate station 1; Tmax2: Average maximum temperature climate station 1; Tmin2: Average minimum temperature climate station 2; Tmed2: Average temperature in climate station 2; Wind speed 2: Wind speed in climate station 2.

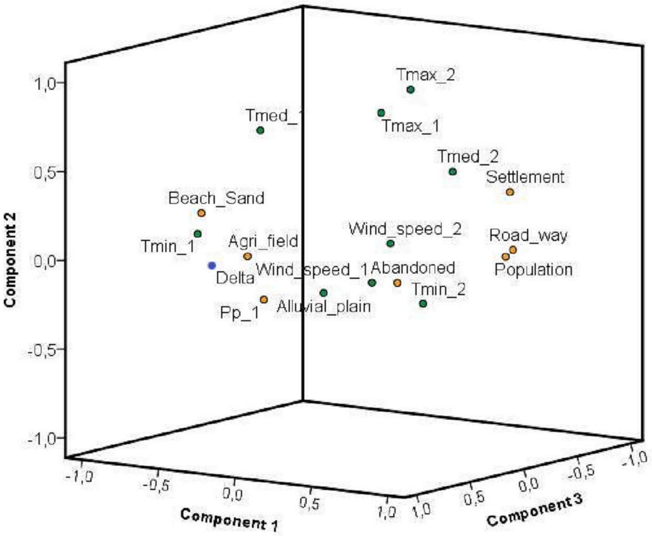

Fig. 7. Principal components. Climate variables (green), land-uses and population (brown) and delta (blue). Tmax1: Average maximum temperature climate station 1; Tmin1: Average minimum temperature climate station 1; Tmed1: Average temperature in climate station 1; Pp1: Precipitation (mm) climate station 1; Wind speed 1: Wind speed in climate station 1; Tmax2: Average maximum temperature climate station 1; Tmin2: Average minimum temperature climate station 2; Tmed2: Average temperature in climate station 2; Wind speed 2: Wind speed in climate station 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

horse riding.

We demonstrated that the delta studied in this research has historically undergone a process of constant change, reflecting how difficult it is to foresee future land-use patterns (as confirmed by the diversity and relative richness indexes). This demonstrates that only rapid and efficient land management plans considering different scenarios and drastic economic changes are capable of maintaining the delta. However, this is a weakness of current Spanish coastal law and local land planning (Negro et al., 2014), which have to face the challenge of managing the abovementioned population increase of 56 % from the present to 2050.

Table 4
Components obtained with the principal component analysis.

	Components				
	1	2	3	4	5
Abandoned	0.228	−0.163	−0.080	−0.943	0.036
Cultivated land	−0.586	−0.062	0.157	0.791	−0.039
Alluvial plain	−0.511	−0.347	−0.446	0.606	0.193
Beach/sand deposits	−0.790	0.181	0.296	0.505	−0.005
Roads and ways	0.929	0.081	−0.161	−0.320	−0.043
Settlements	0.857	0.389	−0.235	−0.160	−0.025
Delta	−0.890	−0.159	0.055	0.304	−0.075
Tmax1	0.102	0.777	−0.110	−0.098	−0.594
Tmin1	−0.416	0.184	0.868	0.100	−0.153
Tmed1	−0.208	0.746	0.578	0.027	−0.238
Pp1	0.082	−0.122	0.959	0.076	−0.230
Wind speed 1	−0.054	−0.214	−0.246	0.112	0.911
Tmax2	0.327	0.937	−0.064	0.099	0.030
Tmin2	0.821	−0.133	0.525	−0.008	−0.095
Tmed2	0.738	0.545	0.131	0.173	0.182
Wind speed 2	0.109	0.031	−0.186	−0.141	0.947
Population	0.949	0.060	−0.062	−0.299	0.035

Tmax1: Average maximum temperature climate station 1; Tmin1: Average minimum temperature climate station 1; Tmed1: Average temperature in climate station 1; Pp1: Precipitation (mm) climate station 1; Wind speed 1: Wind speed in climate station 1; Tmax2: Average maximum temperature climate station 1; Tmin2: Average minimum temperature climate station 2; Tmed2: Average temperature in climate station 2; Wind speed 2: Wind speed in climate station 2.

The Spanish Mediterranean coasts are dynamic territories and, since the 17th century, they have been areas of progressive gain and flash-flood type flooding, used mostly for winter pasture and permanent horticulture due to their fertile soils. However, during the 18th century, Southern Spain, especially Málaga province, began a transformation to (predominantly) sugarcane crops, which lasted until the 20th century. During that century, some engineering works began, such as the modification of the river towards a rectilinear channel, thus suppressing meandering to avoid flooding (Senciales González, 1996). Floods can also cause the deterioration of the soil ecosystem functionality, thus compromising human health and biodiversity in this area as other experts have remarked in other territories (Braud et al., 2016; Jonkman, 2005). River channelization would increase flow speed and reduce sediment deposition on the coast. In deltaic ecosystems characterized by

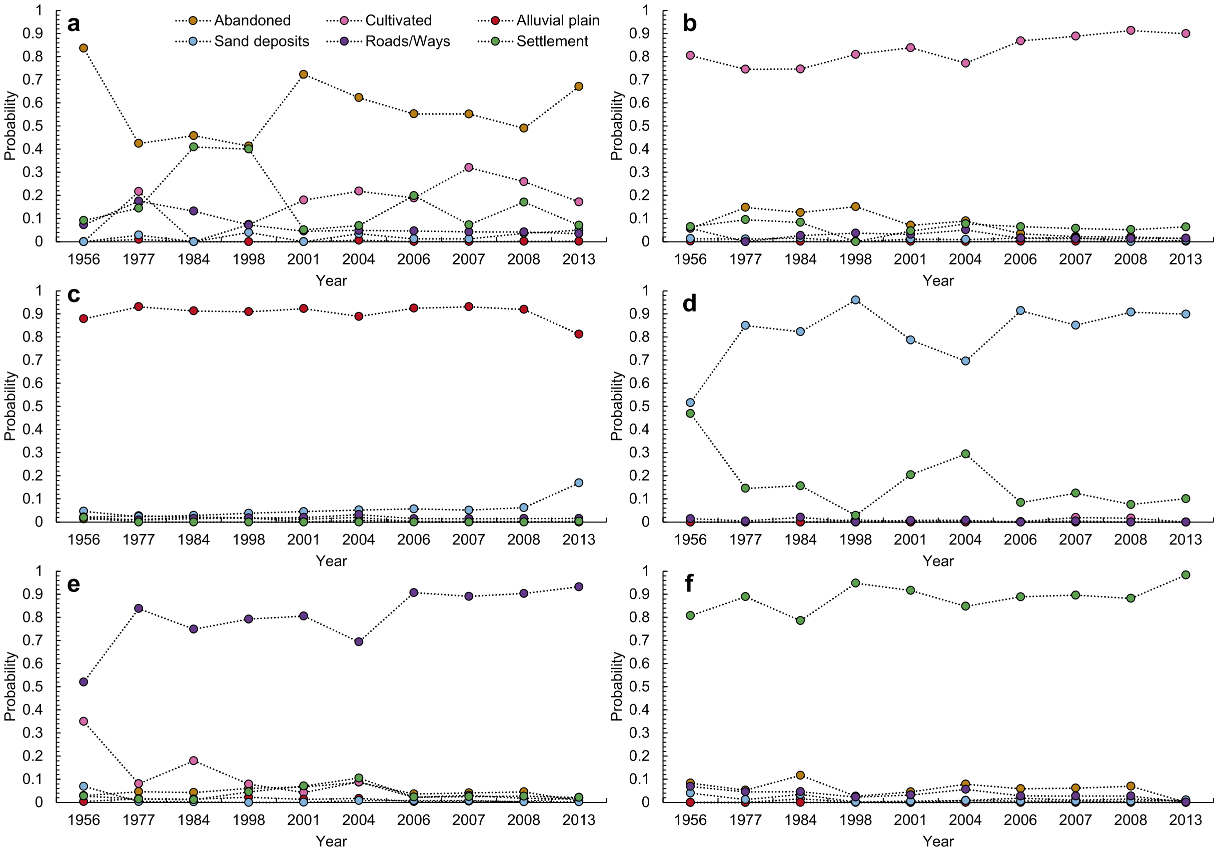

Fig. 8. Markov chain results. a. Abandoned; b. Cultivated lands; c. Alluvial plain; d: Beach and sand deposits; e: Roads and ways; f: Settlements.

a rectilinear coastline, and therefore, more exposed to western winds, one of the main causes of degradation is the overexploitation or mismanagement of the soil-water resources, which generate a loss of ecosystem productivity, deteriorate vegetation composition, and destroy rural livelihoods. In this area, there should be a consensus on the effects of future climate on the status of deltas. Such climate changes will likely be characterized by (i) higher temperatures, (ii) an increase in the degree of aridity, and (iii) shifts in the seasonal rainfall and wind regimes and a higher frequency of extreme events. These changes would affect the volume, frequency, intensity, and timing of precipitation events, which largely determine the structure and functioning of this Mediterranean fluvial ecosystem. To unravel this complexity, it is necessary to focus on the understanding of how biotic attributes interact with abiotic factors to ultimately drive fluvial ecosystem functioning, including that of its soils.

In the 1980s, the Viñuela dam came into operation, limiting the water supply to the delta (García-Aróstegui et al., 1998). The dam is probably why the beaches and sand deposit area decreased. Dams trap sediment that would normally travel down the river to the beach. Even so, at the end of 1996, the last event (so far) of delta flooding by the Vélez River took place. Already at this time, saline intrusions by the sea had been documented (Martínez et al., 2009), especially in the 1993–95 drought, which gave rise to intense water pumping until the aquifer was depleted. This process gave rise to a clear deterioration in the quality of the soil and the abandonment of much of the land closest to the sea (Lentini et al., 2009). Thus, a setback was documented by the authorities at the cost of these more salinized lands, which lost structure with abandonment and became susceptible to being easily destroyed by coastal erosion (Hzami et al., 2021; Nguyen et al., 2021).

At the same time, urban pressure, especially intensified in the first decade of the 21st century, began to give rise to occupations on the left bank of the delta, extending the centre of Torre del Mar towards positions that were increasingly closer to the riverbed. Such pressure itself conditions speculative movements that lead to new abandonment of land, sealing of nearby lands and pollution of water and soils including land with high productivity, in order to await transformation and sale at clearly higher urban prices. At present (2022), a mosaic space of plots still under cultivation is shown in front of other abandoned ones, and looming over the delta are urban projects centred on the conversion of the delta into a marina. Such projects are destroying the delta to turn it into a space invaded by the sea, surrounded by buildings, in the style of Ampuria Brava (Girona) or Port Grimaud (Costa Azul) (González-Guerrero and Pons, 2020; Jiménez and Valdemoro, 2019).

The wetland is affected by increasing environmental pressure without a determined policy for the conservation of this space, despite it being part of the inventory of wetlands in Andalusia, in its ideal condition as the habitat of species of microorganisms, flora and fauna. The current classification of this area in the framework of urban planning is as a “landscape protection land” (Junta de Andalucía). The most demanded action in recent years by various local conservation associations is the maintenance of a minimum flow in the Vélez river in order to stop the loss of habitats due to drying. This flow happens through a greater discharge from La Viñuela reservoir. Currently, the discharge of irrigation leftovers and rainfall from the urban centre into the river also contributes to maintaining a small continuous flow. Similarly, the treated wastewater from Vélez-Málaga municipality could help to slow down the drying process of the lagoon.

Our results demonstrated that the conservation of the cultivated land is key to avoiding a delta retreat and degradation by pollutants and soil sealing. However, only sustainable agriculture considering nature-based solutions (cover crops, mulches, etc.) and conservationist soil and water management strategies would avoid degradation and contamination (Kalantari et al., 2018). Therefore, future investigations should be focused on determining the status of the agricultural management systems within and surrounding the delta, and how to improve them, for example, reducing chemicals.

5. Conclusions

In this research, we combined different mapping techniques (aerial photography interpretation, field observations and manual digitalization), multivariate statistical analyses, and models to assess the past, current, and future status of the delta of the Vélez River to avoid degradation processes associated to soil sealing, erosion and contamination. The main limitation of this research was the previous absence of land use cover maps, economic activities (agriculture, industry, urban area per sectors, etc.) and real limits of the delta. Therefore, we spent a lot of time digitalizing and homogenizing the information. After finishing these exhaustive analyses, our results demonstrated that the drastic urbanization including new settlements, roads, and ways have negatively impacted the delta area, even in the alluvial plain, beaches, and natural sand deposits. The conservation of cultivated lands, although with a decreasing area over the studied period, obtained the highest correlation with delta conservation. Therefore, facing a strong and consolidated urban sprawl process and possible climate change patterns (especially temperatures), the most effective solution to avoid land degradation and stop the delta retreat, sealing and contamination is likely to be sustainable soil and water management plans in the cultivated areas, and the avoidance of new infrastructures and buildings in the alluvial plain and sand deposits. In the future, the combination of aerial photography with remote sensing data would allow us to update this research and conduct accurate results based on vegetation or reflectance ones.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gexplo.2023.107265.

CRediT authorship contribution statement

We wish to draw the attention of the Editor to the following facts which may be considered as potential conflicts of interest and to significant financial contributions to this work. [OR].

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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