The use of changes in small coastal Atlantic brooks in southwestern Europe as indicators of anthropogenic and climatic impacts over the last 400 years

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Abstract

Unlike other aquatic continental ecosystems such as lakes, small coastal brooks have not been used as indicators of anthropogenic or climatic impacts. Our study addresses reconstructing the evolution of coastal brooks in the southwest of Spain from the early 17th century to the end of the 20th century using fieldwork, remote sensing, historical sources and microrelief. These brooks have had a continuous regression, losing 84.7% of their length since 1630 AD. From the 17th century to the beginning of the 20th century, climatic factors were responsible for the filling and siltation of the thalweg of brooks with sandy sediments of eolian origin. The alternation of dry and humid periods during the Little Ice Age in southern Spain favoured the mobilisation of sandy sediments in a process of secondary dunification, which was initiated during the 18th century and prominent at the end of the Little Ice Age. This process has coincided with a loss of water availability or an increase of aridity in some lakes and lagoons of southwestern Europe at the end of the 19th century. However, during the second half of the 20th century, the average annual rate of thalweg regression almost quadrupled to 432.2 $m \cdot year^{-1}$ mainly due to anthropogenic impacts associated with logging. These changes coincide with the mobilisation of sandy sediment and the erosion of coastal brooks in southwestern Portugal and other continental aquatic ecosystems in southwestern Spain. Therefore, we believe that changes in small coastal brooks can be used as indicators of anthropogenic and climatic impacts and, in the future, as sentinels to study the effects of climatic change just as lakes, reservoirs and rivers are considered.

Introduction

Because of their own vulnerability, aquatic ecosystems such as lakes, wetlands, and streams, are good indicators of environmental change at different scales (Williamson et al. 2008). In the case of rivers, flood cycle history has been used as an indicator of changes in historical climatic trends (Glaser et al. 2010). It is through this that paleohydrology and historical hydrology provide knowledge of hydrological events beyond the use of instrumental records (Brázdil and Kundzewicz 2006). Several studies successfully used this information source, as proxy data, for the reconstruction of the historical climatology of Europe (Glaser et al. 2010) and in the Iberian Peninsula (Barriendos and Rodrigo 2006). Other continental aquatic ecosystems have been used as indicators of changes in climatic trends and anthropogenic impacts. Lake sediments, for example, have been used for paleoclimatic reconstruction in various lakes of the Iberian Peninsula (Valero-Garcés and Moreno 2011; Morellón et al. 2012). These lakes were also used to determine the impact of changes in land use (Corella et al. 2011, 2013), the impact of human activities on trophic levels (Vetter and Sousa 2012) or the impact of forest fires (López-Blanco et al. 2011). Wetlands, such as coastal lagoons or peat-bogs, have been used as indicators of trends in climatic changes (Sousa and García-Murillo 2003) and anthropogenic impacts (Álvarez-Cobelas et al. 2001; Sousa et al. 2009a). For all these reasons, lakes (Adrian et al. 2009; Williamson et al. 2009a), wetlands, streams (Williamson et al. 2008) and reservoirs (Williamson et al. 2009b) are considered to be sentinels of climatic change.

The use of historical information (documentary and sedimentary records) of rivers for flood risk evaluation has expanded considerably in recent years (MacDonald 2012). In the case of SW Europe, floods produced intense impacts on society during the last few centuries (Barriendos and Rodrigo 2006; Glaser et al. 2010). Nevertheless, while research over the past few decades in palaeoflood hydrology has generated spectacular advances (Czymzik et al. 2010), coastal brooks continue to be neglected as a source of information for anthropogenic and climatic impacts. In our opinion, this is mainly due to three reasons:

1) Flow is generally less than that of rivers. In Mediterranean latitudes, their flow tends to be minor and often seasonal.

2) There are no long historical records related to brook flow and the impact of human activity.

3) Brooks have little representation in the territory. Historical documentation tends to be scarce in references to brooks. In historical cartography, they are represented with poor accuracy or even (due to the problem of scale) eliminated.

Taking into consideration these limitations of source data, we propose to study the possibility that small coastal brooks can be used as indicators of changes in climatic trends and/or changes in land use. Given the limitations previously stated, a different methodological perspective from that which has been used for lakes, rivers and other continental aquatic ecosystems is required. It is necessary to study antropogenic impacts and climatic trends that affect the length and distribution of coastal brooks over an extensive period of time.

For that, we have examined the brook thalweg evolution in SW Europe (Doñana Natural Park, SW Spain) from the 17th to 20th century and answered the following questions: (1) Have the lengths and/or distributions of thalwegs of coastal brooks in SW Europe changed during the last four centuries? (2) What have been the principal factors responsible for these changes? (3) Can the changes in the small coastal brooks be used as indicators of anthropogenic and/or climatic impacts in SW Europe?

To achieve these goals we have (1) developed a methodology to map and quantify the evolution of brook thalwegs from 1630 AD to 2000 AD using multidisciplinary methods based on aerial photography interpretation, historical data and microtopography; (2) analysed and quantified changes in secular climatic trends and changes in land use in the study area; and (3) analysed if the changes in climatic trends and land use can explain modifications of brook thalweg during the last 400 years.

Study area

We selected coastal brooks of the western region of the Natural Park of Doñana (Abalario) that are included in the biosphere reserve of Doñana. These brooks are located in the SW of Europe (south of the Iberian Peninsula), within a coastal eolian sheet occupying an area of approximately 49800 ha (Custodio et al. 2009), with a Mediterranean climate that is tempered by its proximity to the Atlantic Ocean (García-Barrón et al. 2011).

Within this coastal eolic mantle there are 11 small brooks and coastal gullies that drain directly into the Atlantic Ocean (Fig. 1) whose basins occupy a total area of 3723.1 ha. They are located between the coastal tourist resorts of Matalascañas and Mazagón (Figs. 1b, 1c) and correspond with manifestations of the aquifer system that discharges to the sea in the form of small springs and seepage areas (Custodio et al. 2009). The majority of the brooks do not have permanent flow, and during the periods when this occurs, the flow is very weak. Specifically, from east to west, are the following brooks (Fig. 1b): Arroyo del Oro (Golden Brook), Arroyo Harinoso (Floury Brook), Arroyo Harinosillo (Little Floury Brook), Arroyo Rompe-culos (Rompe-culos Brook), Arroyo Marxagón (Marxagon Brook), Arroyo la Huesa (Grave Brook), Arroyo Morla (Morla Brook), Gully 1, Gully 2, Arroyo del Salto del Lobo (Wolf Leaping Brook) and Barranco del Picacho (Picacho´s Gully).

The protected natural area where these brooks are located has traditionally been a hostile territory for humans due to extensive flooding, malarial areas (Sousa et al. 2009b) and the inadequacy of its sandy land for cultivation (García-Novo et al. 2007). Because anthropogenic impacts are relatively recent, we can reconstruct changes in land use with great detail and accuracy.

Methods

Changes in total length of brook thalwegs

To reconstruct the evolution of brooks over the past 400 years, different sources of information were used, depending on the availability of records for each period (Table 1). The total length occupied by brook thalwegs was mapped at a scale of 1:25,000 beginning with the current conditions and going backward in time to five different periods: 2000, 1987, 1956, the end of 19th century (*c.* 1869) and to the beginning of the 17th century (*c.* 1630). Thalweg length was measured using a planimeter (*PLANIX 5000*) in the five studied periods.

The series of aerial photographs consulted were taken from flights in 1956 (1:33,000), 1987 (1:20,000), and 2000 (1:30,000) together with Landsat TM (1986), SPOT (1989), and Landsat TM (1990) satellite images. The stereoscopic analysis of aerial photographs, with the help of satellite images, allows for the accurate reconstruction of brook thalweg conditions in a cartographic database scaled at 1:25,000 during this period.

Documentary data from archives and other sources were compiled and analysed. These were mostly dated between the 16th century and the first third of the 20th century. We also reviewed more than 80 historical maps dated between the 15th and 20th centuries that included the study area. Of these, 35 were compiled where brooks in the study area were completely or partially mapped. The historical sources used for each period are listed in Electronic Supplementary Material, ESM-1. The complete list of historical maps is shown in

ESM-2, and the list of historical technical documents related with changes in land use is shown in ESM-3.

Various authors have shown the methodological possibilities of using combined historical maps with other sources, such as aerial photography or satellite images, to reconstruct changes in different regions and ecosystems (Petit and Lambin 2002; Bromberg and Bertness 2005; Prieto and Rojas 2012; Sousa et al. 2013). Despite the possibilities that historical maps provide information for reconstructing wetlands, forests, or land use changes it is appropriate to compare these results with other complementary data sources (Gimmi et al. 2011).

The length of brook thalwegs in 2000, 1987 and 1956 were mapped based on fieldwork and stereoscopic photo interpretation of aerial photographs and satellite imagery. The length at the end of the 19th century and the beginning of the 17th century was estimated on the basis of historical interpretation using the map that previously reconstructed conditions in 1956 as a reference. However, these data do not allow for standardised mapping on their own because historical maps do not have standardised screening. Therefore, to avoid possible errors and inaccuracies in delineation, the information obtained from historical sources must also be compared with the microrelief analysis. The value of a detailed topography study to identify changes in vanished or transformed wetlands has been shown by Heimo et al. (2004) and Sousa et al. (2010).

To transfer data from historical sources to a standardised map at the scale of 1:10,000, the microtopography of the brook basins was reconstructed by manual interpolation of approximately 400 topographic elevations following the previously published method (Sousa et al. 2013). ESM-4 displays the methodological sequence used to obtain the microrelief.

We also measured the morphometric characteristics of each brooks. For each basin surface we calculated the Sinuosity Index (*SI*) and the Drainage density (*Dd*). The *SI* was calculated according to Leopold et al. (1964) as the ratio:

$$SI_j = L_j/\delta_j \tag{1}$$

where L_j is the total channel length or thalweg of the brook and δ_j is the distance in a straight line between the start and end of the corresponding brook. According to Hickin (1984), we classified the Degree of meandering (*Dm*) as minor ($SI < 1.2$), appreciable ($1.2 < SI < 1.5$) or severe ($SI \geq 1.5$). Drainage density (*Dd*) was calculated according to Bohn et al. (2011):

$$Dd_j = L_j/A_j \tag{2}$$

where L_j is the total channel length or thalweg (km) and A_j is the total basin area (km^2) of the corresponding brook.

Impacts of human activity and related climatic trends

There are many studies of the anthropogenic impacts on the Doñana protected area, as highlighted by Granados et al. (1988) and García-Novo et al. (2007). For the specific basins of the studied brooks, Espina and Estévez (1993), Sousa and García-Murillo (2003) and Custodio et al. (2009) analyse diferent aspects linked to recent anthropogenic impacts. Finally, Sousa et al. (2013) analysed changes in land use in the study area from the 14th century (first available data) to the beginning of the 21st century. With this, there is enough detailed information to determine changes in land use in this area.

The intensity, distribution and quantity of rainfall can affect the erosion processes. In turn, these variables are involved in sediment mobilisation and their subsequent deposit in low-lying topographical areas, such as small lagoons basins or brook thalwegs. To achieve this, the disparity and intensity of rainfall erosivity in the study area was calculated using two separate indexes (Modified Fournier and Specific Disparity indices).

Of all the observatories near to the study area, the rainfall series (1817-2000) of San Fernando (Cadiz) was chosen because of possible homogeneity problems prior to 1882 that required the series to be rectified. As a result, the period from 1863-1881 was rescaled in accordance with the observatories located closest to San Fernando that provide historical series of simultaneous observation (Gibraltar, Cadiz-Urrutia brothers and Lisbon).

Gregori et al. (2006) emphasise the ability of the Fournier index (Fournier 1960), especially in its modified form (Arnoldus 1980), to describe the characteristics of the precipitation regime and its relationship with unstable events such as quick flows, erosivity, and shallow landslides. In our study, the calculation of the annual rainfall erosivity was based on a Modified Fournier Index:

$$I_{MF} = (\Sigma p_i^2)/P \qquad (3)$$

where p_i is the monthly rainfall (i = 1, 2, …12) and P is the corresponding total annual rainfall. For the same total rainfall, the modified index is affected by the irregularity of intra-annual distribution of rainfall.

Additionally, the consecutive string of dry years and wet years (rainfall disparity) can increase the mobilisation of sediments when vegetative cover that previously intercepted rainfall decreases. To analyse the evolution of the gap from 1890-2000 we used the Specific Disparity Index (I_{di}) developed by García-Barrón et al. (2011). This index quantifies the consecutive alternation of wet and dry years. We used the following equation:

$$I_{di} = [((p_i - p_{i+1})^2 + (p_i - p_{i-1})^2) / 2]^{1/2} / \mu_i \qquad (4)$$

where p_i is total rainfall for the year i, p_{i+1} and p_{i-1} is the rainfall of the previous and following year, and finally μ_i is the average of the three previous values.

Results

First, we present the results from 2000 to 1956 followed by results from 1956 to the 17th century. The combination of these results will allow mapping and quantifying the development of brook thalwegs. Finally, we present the principal changes of intensity in precipitation aggresivity and disparity in the study area.

Results from 2000 until 1956

In Table 2, the three first columns show the brook length was substantially reduced by 21.6% (2.7 km) during the period from 1987 to 2000 and 51.7% (13.4 km) from 1956 to 1987. During the latest period (1987-2000) brook thalwegs were reduced unevenly, a change that occurred only in the most western brooks (Grave Brook, Morla Brook, Picacho's Gully, and especially Wolf Leaping Brook), all of which are close to the coastal tourist centre of Mazagón. However, in 1956 and 1987, the average reduction was greater and more widespread compared to the previous period, with the brooks furthest away from the coastal urban location of Mazagón being the most affected.

Aerial photographs from 1956 also show that the area occupied by the phreatophytic vegetation was much greater than the current distribution, and this occurred in all brooks studied. The presence of these communities, which took refuge at the deepest points of the thalweg (García-Murillo et al. 1995) including plant species and subspecies (like *Osmunda regalis* L., *Thelypteris palustris* Schott, *Lonicera peryclimenum* subsp. *hispanica* (Boiss. & Reut.) Nyman or *Frangula alnus* subsp. *baetica* (É. Rev. & Willk.) Rivas Goday ex Devesa) indicated that the climatic conditions were milder than at present (García-Murillo and Sousa 1999).

Results from 1956 to the 17th century

We divide this section into two periods from 1956 to the end of the 19th century and from the end of the 19th century to the beginning of the 16th century, because data sources differ for each period.

From 1956 to the end of the 19th century

From the end of the 19th century to 1956 the length of the brooks was much greater than during the second half of the 20th century (Table 2). From historical maps with the greatest detail some of the longest brooks appear to be connected with an extensive lagoon (Figs. 2a, 2b, 2c) called "Laguna de Invierno" (Winter Lagoon). This large seasonal lake and other extensions, although with peat-bogs characteristics, disappeared at the end of the 19th century (Sousa et al. 2010). The resulting historical maps incorporate brooks reconstructed from microrelief. The total difference between estimates extracted directly from the historical cartography of Coello (1869) and the estimates of brook reconstruction is also supported by the microrelief (30.5%, ESM-5). Regardless, the cartographic reconstruction based on microrelief demonstrates that the reduction in brook thalwegs is not limited to the period from 1956-2000; however, it is less pronounced from the end of the 19th century to 1956 (reduced by 30.2%; i.e., 11.2 km). Similarly, in the immediately preceding period (1956-1987) there was a generalised reduction in all brooks (except Picacho's Gully). This was slightly more pronounced, however, in the brooks that have a basin with a greater surface area (Golden Brook or Leaping Wolf Brook). In addition, unlike during the period from 1987-2000, there was no clear trend based upon proximity to settlements.

Documentary sources corroborate data obtained from historical maps from the end of the 19th century. Gonzalo y Tarín (1886) lists these brooks in his geological report and indicates that it is not correct to denominate Golden Brook (“Arroyo del Oro”) as the Golden River (“Río del Oro”), although he does note that the watercourse is permanent.

Geological and topographic mapping prepared by corresponding Spanish administrations during the first half of the 20th century also corroborated these results. Both the geological mapping of the area (Gavala 1936) and topographic mapping at a scale of 1:25,000 (National Topographic Map 1949) and 1:50,000 (National Topographic Map 1951) illustrate brooks of intermediate length between the historical mapping at the end of the 19th century and aerial photography from 1956. Indeed, in some frames of the 1956 flight some small sections of the original thalweg from the late 19th century can still be recognised, however, they are already clogged with sand and completely disconnected from the main brook by small tongues of sand.

From the end of the 19th century to the beginning of the 17th century

At the end of the 16th century human activity in this area was limited and linked to traditional and marginal communal uses. Historical maps provide less information than those of late 19th and early 20th century due to obvious technical limitations, such as scale, and are less detailed because of the unpopulated nature of the area.

Of all of the brooks studied, the only one that was depicted in the maps of the 16th century is the Golden Brook. Brook thalweg length was clearly greater than depicted from the second half of the 19th century (Figs. 2d, 2e, 2f).

Historical mapping does not provide information for observed differences, but other historical sources exist. Between the mouth of the Guadiana River on the border with Portugal and the Guadalquivir river, 10 watchtowers were built. The closest towers to the study area (Oro, Asperillo and Higuera watchtower) can be seen in Fig. 1. These towers were constructed between 1577 and 1638 (Mora 1981) to facilitate the navigation. ESM-6 summarises the most outstanding texts extracted from historical documents.

Texts from the 16th to 18th centuries refer repeatedly to the Golden River, as with the historical maps from the 18th and the first half of the 19th centuries. It is conceivable that this *a priori* change in the naming of a water course from Golden Brook to Golden River could indicate a channel of greater significance, both in terms of flow and permanence. This is confirmed by written documentation from the 16th century (ESM-6). Later in the 18th century, file 837 (1740) and file D-27 (1756) (see ESM-3 and ESM-6) made reference to the flow of Golden River and predicted that this drainage would eventually destroy the Oro watchtower, as happened later (Mora 1981).

Therefore, historical sources suggest that there was a gradual regression of brooks and their flow since the beginning of the 17th century. In our opinion, the higher flow might explain why Golden Brook (presented as the major watershed) was the only brook depicted in 18th and early 19th century cartography. Table 2 illustrates the corresponding results for the estimated length of each brook at the beginning of the 17th century, the surface of its basin, and from these data the Drainage density (*Dd*), the Sinuosity Index (*SI*). The Degree of meandering (*Dm*) according to Hickin (1984) is calculated (ESM-5).

Since the beginning of the 17th century to the end of the 19th century brook reduction was widespread (Table 2), although it displays different intensity in each case. Although brook reduction relative to the previous period is high, it should be noted that this represents a longer time period (239 years) than the other three previously studied periods.

Table 2 also lists that the highest *SI* values (Golden Brook and Leaping Wolf Brook), which correspond to the brooks that have a drainage basin occupying a larger surface area and with a greater length (taking into account all of their branches and forks). As stated by Leopold et al. (1964), an increase in total length increases drainage basin area. The surface of each brook basin demonstrates a strong linear correlation to their total length estimated for 1630 (Fig. 3a).

The evolution of brooks from the 17th to the 20th century

The results obtained in the previous sections allowed us to map the evolution of brooks since the beginning of the 17th century to the end of the 20th century (Fig. 3b).

There is evidence that the segment slope is more pronounced during the second half of the 20th century. Each of the four periods has a different timeframe. Therefore, to compare them it is more suitable to analyse these results as an annual average rate. This is compiled in Table 3 where the cumulative percentage of disappeared thalweg compared to total length in 1630 was calculated (assuming complete regression of 100%) and the mean annual rate of regression in each period ($m \cdot year^{-1}$).

Although it is a continuous process the intensity of this regression is not always the same. The results of Table 3 depict that the average annual rate of regression of brook thalwegs has changed its intensity over the last 400 years. During the second half of the 20th century (1956-1987) this rate increased significantly (432.2 $m \cdot year^{-1}$), coinciding with the intensification of land use changes. However, these same results show that during brief periods when human activity in this area was limited there was also a significant rate of regression (the 17th to 19th century was 113.0 $m \cdot year^{-1}$; the 19th to the first half of the 20th century was 128.7 $m \cdot year^{-1}$). During the last decade of the 20th century (1987-2000), land use was restricted and conservation-oriented because this area was declared Natural Park in 1989. Despite this, the average regression rate is 207.7 $m \cdot year^{-1}$ (almost twice that at the beginning of the 20th century). This leads us to ask, what are the causes of these changes? Are there other natural factors intervening that are independent from land use changes? To assess this possibility we studied erosive and sediment mobilisation capacity by means of the aggressiveness and rainfall disparity.

Results from changes in the rainfall distribution

Fig. 4a represents the evolution of accumulated deviations from rainfall aggressiveness (Modified Fournier Index; Arnoldus 1980) with regard to the average rainfall from 1817-2000. The continuing upward trend indicates periods of high rainfall erosivity, while the continuing descending sections indicate periods of low rainfall erosivity. In this same figure, we also indicate the period of increased forestry activity in the study area according to the data of Sousa et al. (2013) as well as the end of the Little Ice Age (LIA, hereafter) in Andalusia according to the dating of Castro-Díez et al. (2007). Two periods of higher rainfall erosivity can be recognised: 1893-1904 and 1958-1969. This second period exhibits the most pronounced and prolonged increase during the last two centuries, roughly coinciding with the afforestation of species with rapid growth in the study area (Fig. 4a).

One of the main characteristics of the precipitation regime in extensive areas of the Iberian Peninsula is the large interannual variability: years with below average rainfall contrast with other years - sometimes consecutively - with high rainfall values (García-Barrón et al. 2011). This change in the distribution of rainfall in consecutive years could encourage the intensification of the erosion processes and sediment mobilisation. Thus, we have depicted the calculation of the evolution of Specific Disparity Index in the study area from 1970-2000 (Fig. 4b). This figure shows a clear trend towards increasing the rainfall disparity during the last third of the 20th century. Although rainfall aggressiveness decreases after 1969, rainfall disparity increases.

Fig. 5 integrates in schematic form the results presented so far. Fig. 5a represents the evolution of Brooks during the last 400 years. Fig. 5b summarises the evolution of the thalweg of an average brook type since the beginning of the 17th century until siltation and ilustrates how communities of phreatophytes tend to withdraw from the edges of the main channel to take refuge in the deepest areas of the thalweg (García-Murillo et al. 1995). If the process of filling the thalweg continues, it will end up displacing phreatophyte communities with more xerophytic species (Sousa and García-Murillo 2003).

The gradual occupation of the deeper areas of the thalweg by vegetation could act as a screen, thereby slowing the movement of sand displaced by wind and favouring deposition by gravity in the most depressed areas of the thalweg (a positive feedback process). Finally, planting rapidly growing species in the entire study area leads to the progressive disappearance of the original thalweg.

Discussion

Causes of brook regression: Principal impacts derived from climate from the 17th century to the beginning of the 20th century

The climate has been an important driving variable affecting wetland ecosystems over geological time; however, their changes are relatively slower than anthropogenic changes (Álvarez-Cobelas et al. 2001). According to Pfister et al. (1999) in the case of the Iberian Peninsula, in contrast to other more northerly areas of Europe, climatic change is related more to changes in precipitation than to changes in temperature. At the beginning of the 17th century the total length of brook thalwegs was much greater than they are nowadays and generally had greater flow compared to later centuries. At the end of the 19th century, total brook length had reduced by 42.1% compared to what was observed at the beginning of the 17th century. This change was most pronounced in the brooks of the greatest length and largest basins, as well as a higher *SI*. This makes us consider that rather than anthropogenic factors prior to the 20th century, the changes are related mainly to the hydrological characteristics of every brook.

During this period, anthropogenic impacts were very limited. The populated area closest to the brooks, Mazagón, did not begin its development until 1963 (García-Novo et al. 2007). From the 17th to the 19th century, the population in the study area was very low and limited to a few fishermen, lighthouse keepers and carabineers around the coastal watchtowers.

From the climatic point of view, this period coincides partially with the LIA, which in southern Spain was, in general, a cooler and wetter period (Valero-Garcés and Moreno 2011) with an increase in floods (Valero-Garcés et al. 2008). In Andalusia, the LIA was generally characterised by an increase in precipitation (whose principal phase took place between 1590 and 1650) and led to an associated increase in flood frequency (Rodrigo et al. 2000) and increased availability of water in wetlands (Sousa and García-Murillo 2003). Within this general framework, the reconstruction of precipitation anomalies during the LIA shows that Andalusia alternated between dry periods (mid-16th and mid-18th centuries) and wet periods (end of the 16th century, early 17th century and the end of the 19th century; Rodrigo et al. 1999).

The coastal dunes of Doñana are characterised by their dynamic nature, especially at the human temporal and spatial scales (Ojeda et al. 2005). In fact, since the start of the 18th century, the neighbouring Doñana National Park has shown a revival of dune activity coinciding with the increase in dry periods (Granados et al. 1988). The outcome of this eolic activity was invasion of sand and the overfilling by sand dunes of some of the largest lagoons of the Doñana National Park (Sousa et al. 2009a). These changes in climatic trends triggered what Granados et al. (1988) and Merino et al. (1990) have called "secondary dunification".

In contrast, wet periods which were obtained from climatic reconstructions based on proxy data, in general coincide with increased water flow (around 1630) or greater length (second half of the 19th century) relative to the 20th century. These wet periods can be tentatively compared to the dates of the minimum sunspots during the LIA. Near the Maunder Minimum (1645-1715), cabotage navigation took drinking water from both the Golden and Grave Brooks. The Dalton Minimum (approximately 1790-1820) was a period of cooler and wetter climate in southern Spain (Rodrigo et al. 2012). During this period, brook flow was greater and more permanent, and the thalweg length was also far greater than what it was throughout the 20th century.

Additionally, in this case, greater sinuosity implies a thalweg that is divided into several branches. This increases the ability to capture and retain more sediment during periods with the most erosive rainfall. In the study area, the three most sinuous brooks ($IS > 2$) are precisely those that have been reduced the most since the early 17th century to 1956 (Golden Brook 59.4%, Wolf Leaping Brook 71.6%, and Picacho's Gully 86.6%).

Reforestations performed in the 18th century and subsequent degradation or disappearance of the autochthonous vegetation during this process, mainly destined for the ships of the Spanish Armada, constitute another factor that also may have favoured erosive processes during this particular period. However, the techniques employed during the 18th century as well as the location and extent of this process in the study area, cannot compare with the intense transformation process that took place during the second half of the 20th century. Moreover, Gonzalo y Tarín (1886) considered these afforestations should be expanded to stop the fast progress of the flying sands. In our opinion, it refers to the process of secondary dunification that in some areas would become prominent at the start of the 20th century.

At the beginning of the 20th century, the study area experienced an increase in the cumulative frequency of dry years and very dry years (Sousa et al. 2013). The beginning of this relatively drier phase, which occurred after the last humid peak of the LIA in southern Spain, also coincides with a loss of water availability or an increase in aridity in southern lakes and lagoons such as Lake Zoñar (Martín-Puertas et al. 2008), the Tejo Lagoon of the eastern central (Romero-Viana et al. 2009) and even in the northern Iberian Peninsula (Morellón et al. 2012; Corella et al. 2013).

Causes of brook regression and principal anthropogenic impacts during the 20th century

Most of the rivers, lakes, estuaries and wetlands of the Iberian Peninsula have been affected by the regulation of their flow and the overexploitation of aquifers, especially in the south and along the Mediterranean coast (Ibáñez and Caoia 2013). In the study area, although Atlantic coastal brooks have drastically reduced in length during the last 400 years, the most intense changes have occurred throughout the 20th century. The average annual regression rate intensified during the second half of the 20th century, reaching 432.2 $m \cdot year^{-1}$, which was almost quadruple in the rate observed from the 17th to the 19th centuries.

In Mediterranean areas such as the Iberian Peninsula, hydrology and sedimentary processes are strongly influenced by anthropogenic factors (Morellón et al. 2011). In fact, anthropogenic change in wetland ecosystems is largely a process of the 20th century (Álvarez-Cobelas et al. 2001). For the brooks studied, the acceleration in thalweg decline from 1956 (Fig. 3b) and coincides with logging in the study area. From 1936 until 1972, almost the whole surface of the western area of the Doñana Natural Park was exploited by monocultures of fast-growing species (Espina and Estévez 1993). The southernmost area of Doñana Natural Park, where the majority of the study brooks and basins are situated, was occupied by *Pinus pinea* L., and the most northerly area was occupied by *Eucalyptus globulus* Labill. and *Eucalyptus camaldulensis* Dehnh. (Sousa and García-Murillo 2003). The desiccation effect from the high evapotranspiration rates of monoculture eucalyptus plantations led to a reduction in the height of the water-table (Trick and Custodio 2004; Custodio et al. 2009).

Several studies have documented in detail the process of logging in this area, and this has had little alteration by anthropogenic activity until the second third of the 20th century (Kith 1936; De La Lama 1951; Espina and Estévez 1993; Sousa and García-Murillo 2003). The ultimate goal was to not only revalue an unproductive territory but also to halt the advance of dunes and to eliminate the wetlands that were breeding grounds for the mosquito *Anopheles atroparvus*, a transmitter of malaria (Kith 1936; Patrimonio Forestal del Estado 1941; Sousa et al. 2009b).

Another anthropogenic impact to consider is derived from the growth of population centres that are located close to brooks such as Palos de la Frontera, Moguer and especially Mazagón. The mouths of brooks closer to the coastal tourist centre of Mazagón have also been affected by the occupation of part of the original thalweg by urban infrastructure. Groundwater abstraction by the tourist resorts of Matalascañas and Mazagón have a clear negative effect on the level of the water table and wetland flooding (Manzano and Custodio 2005; Custodio et al. 2009). In fact, the lagoons of the Mazagón area have disappeared or have become epigenic (Custodio et al. 2009). This effect may have been accelerated with the development of campsites and irrigation areas during the final years of the 20th century and the first years of the 21st century. Likewise, an equivalent negative impact has appeared in the peridunar lagoons of the neighbouring Doñana National Park resulting from the abstraction of groundwater in the coastal tourist centre of Matalascañas (Muñoz-Reinoso 2001; Serrano et al. 2008; Sousa et al. 2009a). Human pressure on coastal areas has increased constantly, driving the reduction in coastal wetlands (Valdemoro et al. 2007) and small coastal brooks that are in a similar situation.

This major anthropogenic impact coincides with a period with the greatest intensity of rainfall aggressiveness in the last two centuries (Fig.4a) and an increase in rainfall disparity during the last third of the 20th century (García-Barrón et al. 2011) that overlaps with the period in which the soil was more unprotected due to logging activities increasing the erosion and sedimentation processes.

Brooks as indicators of anthropogenic and climatic impacts in SW Europe

The regression of the small Atlantic coastal brooks is a process that has possibly occurred in other coastal areas of southwestern Europe that have similar geomorphological characteristics. Devereux (1982) recognised brook regression in southern Portugal at the beginning of the 20th century. According to this author, changes in the distribution of rainfall in the months of January to April, rather than the global quantity, is the cause of the destabilisation of Algarvian gullies and their colonisation by vegetation (greater by changes in land use).

Costas et al. (2012) identified phases of high eolic activity in the SW of Portugal from 1570 AD and 1710 AD. These authors tentatively relate this first pulse of eolic activity with the onset of the LIA or the transition to the Maunder Minimum. On the other hand, the second pulse of eolic activity (1710 AD) coincides with the beginning of secondary dunification in southwestern Spain (according to Granados et al. 1988) and the end of the Maunder Minimum (according to Costas et al. 2012). To associate directly and unequivocally the accumulation of sand with drier periods or wetter periods is a complex problem because it may be affected by regional climatic variations (Costas et al. 2012) and by changes in land use (Merino et al.

1990). Grove (2001) studied the effects of the LIA in Mediterranean Europe and confirmed that the same climatic conditions that induced the advance of glaciers during the LIA were also responsible for an increase in flood frequency and sedimentation.

The relative importance of anthropogenic and climatic impacts and the interaction between them in the sedimentation process varies over time, so the relative strength of attributes for each of the factors is complex (Morellón et al. 2011). The intensity of the impacts arising from changes in land use makes the effects of changes in climatic trends more difficult and even masks them (Parmesan et al. 2011). Therefore, although climate is considered to be a driving variable that affects the ecosystems, the effects of anthropogenic impacts occur during shorter periods of time and can be more easily identified (Álvarez-Rogel et al. 2007).

The results of this study reveal that changes in land use have secularly affected the functioning of the small coastal brooks of SW Europe. Moreover, the evolution of the coastal brooks studied has been influenced by different changes in precipitation trends. For these reasons, brooks can also be considered sentinels of climatic change just as occurs with streams, rivers, ponds (Williamson et al. 2008), reservoirs (Williamson et al. 2009b) or lakes (Adrian et al. 2009). Because they are located in a protected natural area, they must be appropriately managed according to their uniqueness. The necessary measures must be enforced to protect what remains of the Atlantic flora and the natural drainage channels to halt the imminent risk of disappearing.

Conclusions

During the last 400 years the coastal brooks of southwestern Spain have drastically reduced in length by 54.3 km (84.7% smaller relative to the 17th century). Although this process has been continuous, its intensity was not always the same.

The beginning of this process seems to be linked to the alternation of wet and dry periods in the southern part of the Iberian Peninsula during the LIA, and especially after the 18th century (average annual regression rate of 113 m·year-1), in what some authors have called secondary dunification (Granados et al. 1988; Merino et al. 1990). This process temporally coincides with a pulse of eolic activity in SW Portugal approximately 1710 AD (Costas et al. 2012) and seems to be linked to climatic variability, particularly rainfall.

At the beginning of the 20th century in the southern Iberian Peninsula, a process of aridisation began that also drove the regression of brooks until reaching an average regression rate of 128.7 m·year^{-1}, coinciding with a decrease in wet and very wet years and an increase in dry and very dry years.

Finally, during the second half of the 20th century, brook regression intensified to an average rate of 432.2 m·year^{-1} due to logging of fast growing species and an increase of tourist centres along the coast. Although during this period the consequences of human activity are much more apparent, this impact was intensified by the increase in rainfall aggressiveness, which favoured the mobilisation of sandy sediments and the sedimentation of brook thalweg bottoms.

The applied methodology does not permit the brooks studied to serve as proxy data; however, they are good indicators to track the anthropogenic and climatic impacts (especially linked to precipitation), as well as their possible synergies in the southwest Europe. That is why, like other continental aquatic ecosystems, brooks can be considered sentinels of anthropogenic and climatic impacts that could take place in the future.

Acknowledgements

The authors are grateful to the Doñana Natural Park management for providing access to the study area, to Carola Pérez-Porras for helping with fieldwork and to the Andalusian Institute of Cartography. This study was funded by the Spanish Ministry of Economy and Competitiveness Project CGL2009-10683 and also by the Project 158-2010. Finally, we thank the anonymous reviewers their comments to improve our manuscript.

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Figures captions:

Fig. 1 Localization of the study area in the SW of the Iberian Peninsula (**a**), location of each of the studied brooks (**b**) and situation within the Biosphere Reserve of Doñana (**c**)

Fig. 2 State of the studied brooks in the historical cartography at the end of the 19th century (**a, b, c**), at the end of the 18th century and beginning of the 19th century (**d, e, f**)

Fig. 3 Dispersion diagram of the every brook basin surface and its estimated length at the beginning of the 17th century (**a**) and evolution of the length of the set of brooks thalweg and that of the two longest brooks from the beginning of the 17th century to the end of the 20th century (**b**)

Fig. 4 Accumulated deviations and mobile average each 11 years of the Modified Fournier index respect the average value in the period 1817-2000 (**a**) and Specific Disparity Index during the period 1970-2000 and linear fitting model to the series (continuous line), relative maximum values (dotted line) and explained variance (**b**)

Fig. 5 Evolution of the brooks (**a**) and diagram of the changes in the vegetation and thalweg of a brook type in the study area in the 17th century, 19th century, 1956, 1987 and 2000. The main changes in the use of land and climatic trends are included

Table 1 Data sources used for the reconstruction of the length occupied by the thalweg of brooks

Data sources	**Twentieth century AD (2000)**	**Twentieth century AD (1987)**	**Twentieth century AD (1956)**	**Nineteenth century AD (*c.* 1869)**	**Seventeenth century AD (*c.* 1630)**
Fieldwork	X	-	-	-	-
Aerial photography	X	X	X	-	-
Satellite imagery	-	X	-	-	-
Historical documents	-	-	X	X	X
Historical maps	-	-	-	X	-
Microtopographic analysis	-	-	-	X	X

Table 2 Thalweg length of the 11 brooks and gullies studied from 17th century to 2000 and morphometric or hydrologic characterization of the original state of the brooks at the beginning of the 17th century

Brook	**Length (km) in 2000**	**Length (km) in 1987**	**Length (km) in 1956**	**Microrelief 19th century (km)**	**Microrelief 17th century (km)**	**Basin surface (ha)**	**Drainage density (*Dd*)**	**Sinuosity Index (*SI*)**
Golden Brook	2.7	2.7	6.5	9.9	16.0	829.7	1.9	4.3
Floury Brook	0.8	0.8	3.1	4.5	5.5	284.6	1.9	1.6
Little Floury Brook	0.6	0.6	1.7	2.5	2.8	161.1	1.7	1.1
Rompe-culos Brook	0.7	0.7	2.8	3.2	5.4	277.1	1.9	2.0
Marxagon Brook	0.8	0.8	2.6	2.6	4.2	388.8	1.1	1.4
Grave Brook	1.3	1.7	2.0	3.3	3.3	289.5	1.1	1.1
Morla Brook	0.8	0.9	1.3	1.7	3.5	280.7	1.2	1.1
Gully 1	0.3	0.3	0.3	0.3	0.3	177.3	0.2	1.2
Gully 2	0	0	0.1	0.1	0.1	73.5	0.1	1.0
Leaping Wolf Brook	1.8	3.7	4.6	8.1	16.2	722.8	2.2	4.2
Picacho's Gully	0	0.3	0.9	0.9	6.7	238.0	2.8	2.4
Total	**9.8**	**12.5**	**25.9**	**37.1**	**64.0**	**3723.1**	**1.7**	**-**

Table 3 Summary of the evolution of brooks including the estimated change rate in each period (100% stands for the complete regression) and the mean annual rate of regression of all the brooks

Year	**Estimated length (km)**	**Length vanished with respect to length in 1630 (km)**	**Rate (%) vanished with respect to length in 1630**	**Accumulated rate (%) vanished with respect to length in 1630**	**Mean annual rate of regression in each period (m·year^{-1})**
~ 1630	64.1	-	-	-	-
~ 1869	37.1	27.0	42.1	49.7	113.0
1956	25.9	38.2	59.6	70.3	128.7
1987	12.5	51.6	80.5	95.0	432.2
2000	9.8	54.3	84.7	100.0	207.7

Figures:

Figure 1 (colour):

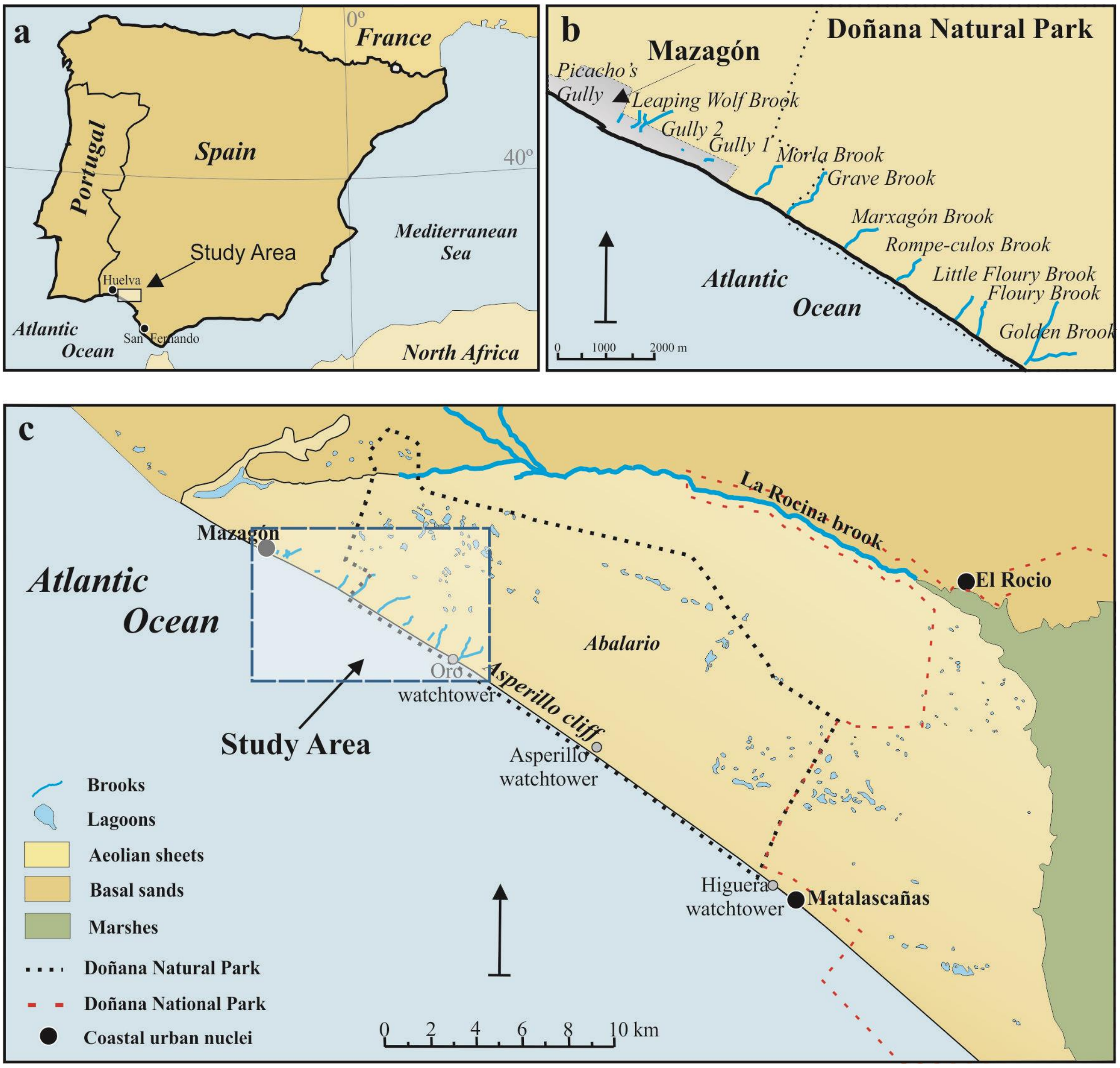
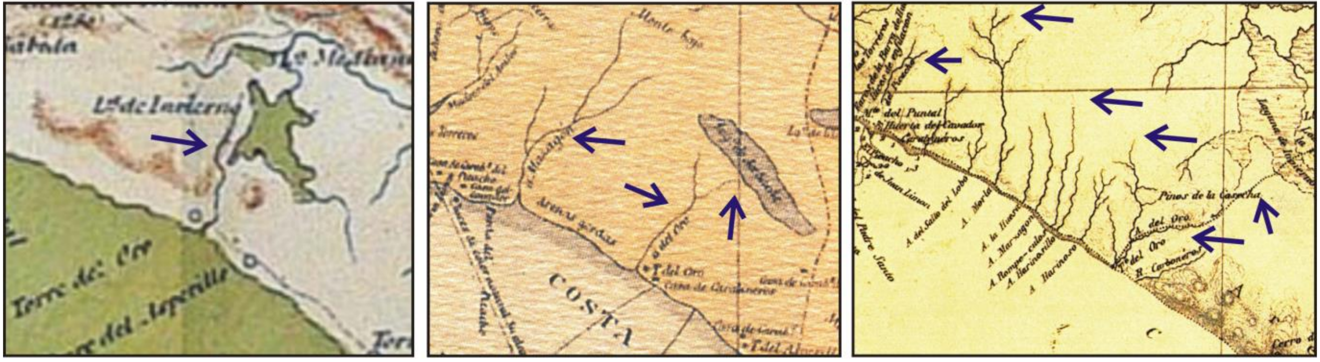


Figure 2 (colour)



(a) Valverde (1880) (b) Carrasco Padilla (1892) (c) Coello (1869)

(d) Quintana and Ceballos (1748-1752) (e) Poirson (1812) (f) Alabern and Mabon (1847)

Figure 3 (colour)

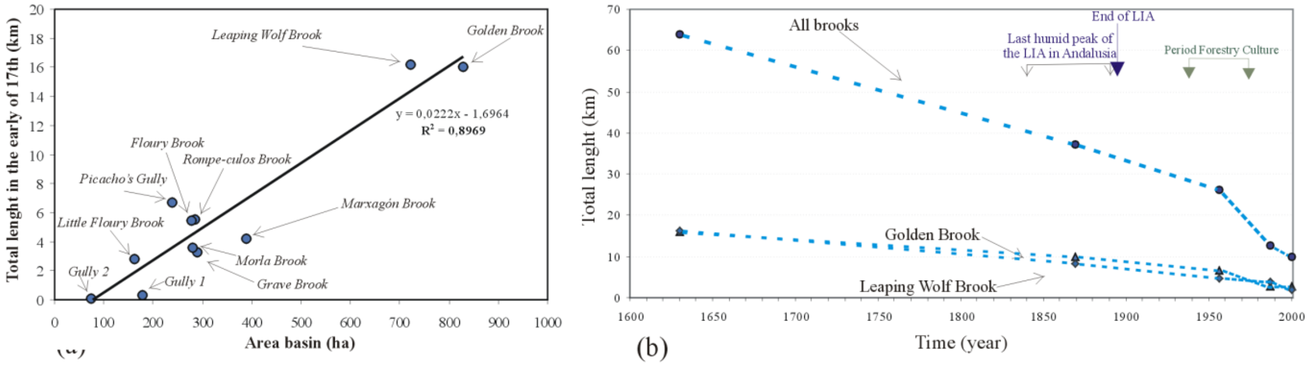


Figure 4 (colour)

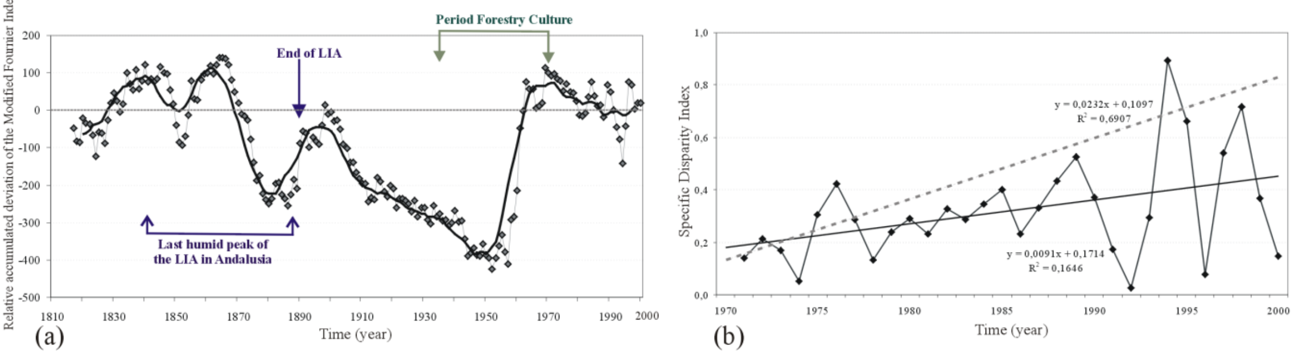
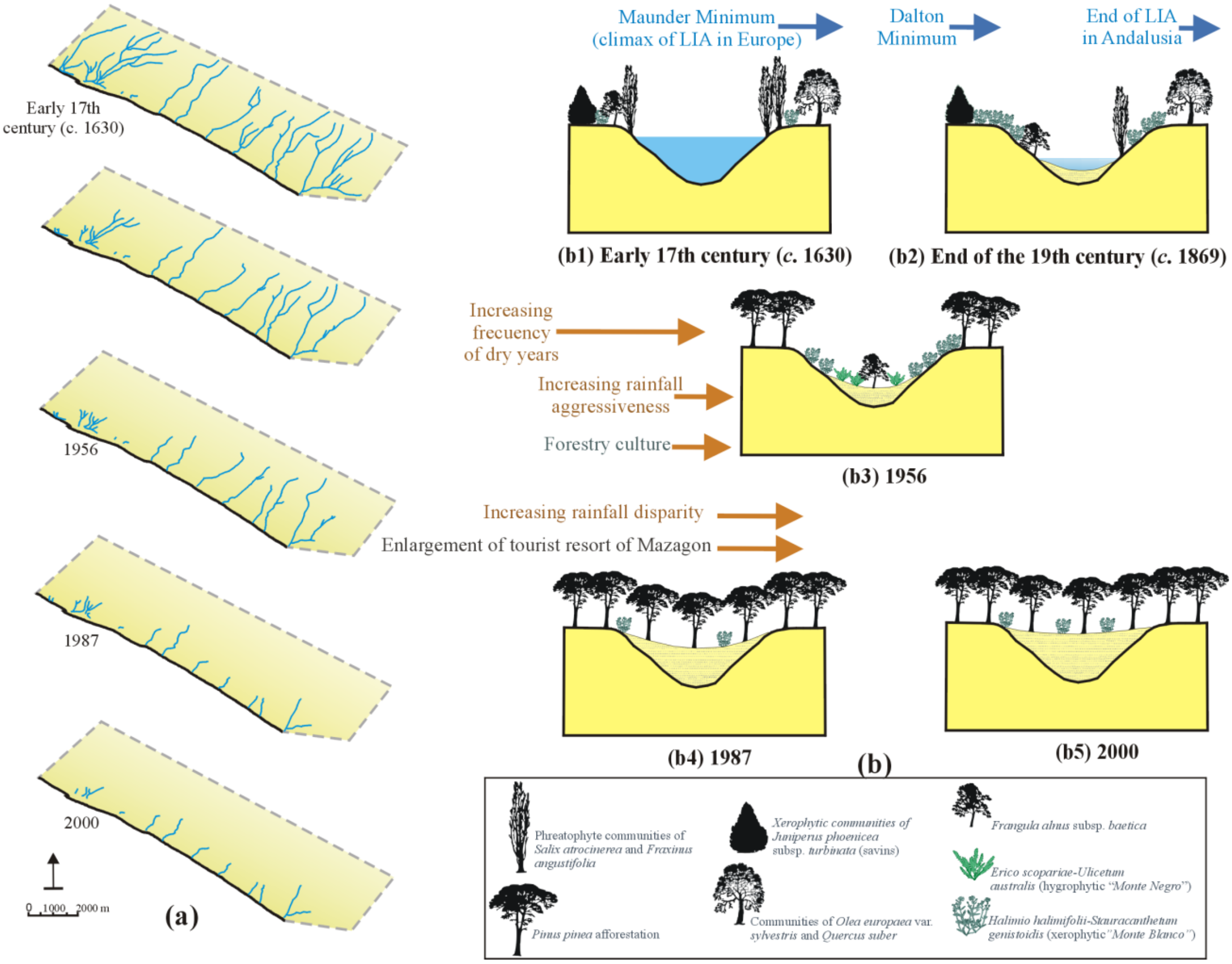


Figure 5 (colour)



Supplementary information

ESM-1. Summary of the historical sources with information about the studied brooks.

Period	Historical documents	Historical maps
≤ 17th century	Construction files of watchtowers along the coast (1577): D-1, D-2, D-3, D-6, D-12, D-13, D-14 y D-15	Alonso de Santa Cruz et al. (1555-1570)
18th century	FILE 837 from the Town Record Office of Almonte (1740), FILE D-27 construction of watchtowers along the coast (1756), Reports of Tomás López (ALONSO ÁLVAREZ DE CARDOSO, 1785)	Fernández de Sandoval (1743), Llobet (1748), Quintana and Ceballos (1748-1752), Espelius (1765), Gaver (1765), López, (1767), Alarcón (1768), Anonymous (1768), Salanoba (1770), Gussefeld (1781)
19th century	MADOZ (1848), GONZALO Y TARÍN (1886, 1887), HERASO (1890)	Saavedra (1810), Poirson (1812), Borghi (1817), Dufour (1837), Alabern and Mabon (1847), Dirección General de Correos (1860), Coello (1869), Gonzalo y Tarín (1870), Montojo and Salcedo (1875), Vogel (1879), Valverde (1880), Gonzalo y Tarín (1887), Carrasco Padilla (1892), Noriega and Cobo de Guzmán, (1897-1900), Anonymous (19th a C), Anonymous (19th b C)
20th century	SAN MIGUEL (1913), GAVALA (1936)	Ibáñez de Ibero (1902), San Miguel, (1913), Bonsor (1926), Gavala (1936), Mapa Topográfico Nacional (1949), Mapa Topográfico Nacional (1951), Mapa Topográfico Nacional (1972), Instituto Geológico y Minero de España (1976)

ESM-2. Historical maps (listed by date).

1555-1570. “Mapa de la parte occidental de Andalucía que se extiende entre las poblaciones de Aracena, Valenzuela, Vélez-Málaga y Cádiz”. Alonso de Santa Cruz, Pedro de Esquivel, Felipe de Guevara, Diego de Guevara, Juan de Herrera.. Map Library Instituto Cartografía de Andalucía, Seville.

1743. “Descripción de la costa del Coto de Dª Ana, y situación de la Almadava que en ella hay al sitio de la torre Carboneros, veintinueve de junio de 1743”. Francisco Fernández de Sandobal. In: Castrillo, M.C., 2000. Doñana Nombre a Nombre. Estudio de la toponimia del Parque Nacional de Doñana. Diputación Provincial de Huelva, Huelva.

1748. “Mapa del Reynado de Sevilla”. Francisco Llobet. In: Instituto de Cartografía de Andalucía. (1998). La Nueva Cartografía en España (del S. XVIII al XX). Consejería de Obras Públicas y Transportes, Junta de Andalucía, Sevilla.

1748-1752. “Mapa de la Provincia Marina de Ayamonte”. José Quintana y Ceballos. Plano Geográfico y Mapa General de los Pueblos, Montes, sus arboledas, extensiones, justicias, guardas que los custodian, vecindarios, matriculados y embarcaciones que comprende la Provincia de Ayamonte, una de las que componen el Departamento de la Capitanía General de Cádiz, según la revista de la Inspección ejecutada por el Ministro Principal de Marina de la misma provincia Don José Quintana y Ceballos. In: Gómez Cruz, M., 1991. Atlas Histórico-Forestal de Andalucía S. XVIII. Universidad de Granada, Granada.

1765. “Mapa o carta corográfica que comprende todas las provincias de marina que componen el Departamento de Cádiz, reducido de los que en escala mayor se han formado, con real orden”. José Espelius. In: Gómez Cruz, M., 1991. Atlas Histórico-Forestal de Andalucía S. XVIII. Universidad de Granada, Granada.

1765. “Plano de parte de la Costa y límite de esta provincia de Andalucía”. Antonio de Gaver. In: Olmedo, F., Cortés, J., 2011. Andalucía la imagen cartográfica hasta fines del S. XIX. Instituto de Cartografía de Andalucía, Sevilla.

1767. “Mapa del Reyno de Sevilla”. Tomás López. In: Gómez Cruz, M. (1991). Atlas Histórico-Forestal de Andalucía S. XVIII. Universidad de Granada, Granada.

1768. “Estado de las administraciones principales. y agregadas de la Real Renta de Tavaco del Reyno de Sevilla”. Félix de Alarcón. Map Library Instituto Cartografía de Andalucía, Seville.

1768. “Plano de demostrazión de los caños”. Anonymous. In: Castrillo, M.C., 2000. Doñana Nombre a Nombre. Estudio de la toponimia del Parque Nacional de Doñana. Diputación Provincial de Huelva. Huelva.

1770. “Carta Geográfica del Condado de Niebla”. Pedro Alonso Eguilart de Salanoba. Map Library Instituto Cartografía de Andalucía, Seville.

1781. "Carte de Seville". F. L. Gussefeld. Imp. Herederos de Homann. Map Library Instituto Geográfico Nacional.

1810. "Plano geográfico de Moguer, con los movimientos del General Lacy", por D. Angel Saavedra, Ayudante Primero de E. M. Plano Geográfico de Moguer y sus inmediaciones, referentes a los movimientos de la División General Laci en Agosto de 1810 quando batió a las tropas del general ArambergoAtula de León y Septiembre primero de 1810= Mampoey=(sic). Historic library of maps Servicio Geográfico del Ejército, Madrid.

1812. “L’Espagne et le Portugal”. J. B. Poirson. Edición Facsímil Instituto Geográfico Nacional, 1985. Madrid.

1817. “I regni di Siviglia, Cordova e Jaen compresi nell’ antica Andalusia, ed il Regno di Granata”. Bartolomeo Borghi. Firenze (ed.). Map Library Instituto Cartografía de Andalucía, Seville.

1837. “Mapa de Andalucía con las nuevas divisiones”. Auguste Henri Dufour. París (ed.). Scale ~ 1:550,000. Map Library Instituto Cartografía de Andalucía, Seville.

1847. “Provincias de Sevilla y Huelva parte de Andalucía”. R. Alabern and E. Mabon. Map Library Instituto Cartografía de Andalucía, Seville.

1860. “Carta de correos y postal de las provincias de Almería, Cádiz, Córdoba, Granada, Huelva, Jaén, Málaga y Sevilla”. Dirección General de Correos. Map Library Instituto Cartografía de Andalucía, Seville.

1869. "Huelva", Francisco Coello Coronel de Ingenieros Militares. Historic library of maps Servicio Geográfico del Ejército, Madrid.

1870. “Carta Geográfico-Minera de la provincia de Huelva”. Joaquín Gonzalo y Tarín. Historic library of maps Biblioteca Nacional de España, Madrid.

1879. “Spanien und Portugal in 4 blättern”. Von C. Vogel. Stieler´s hand. Atlas nº 41. Map Library Instituto Cartografía de Andalucía, Seville.

1875. "Costa Sudoeste de España". José Montojo y Salcedo. Sheet II (desde Huelva hasta la Torre de la Higuera). Según trabajos realizados desde 1865-1870 por la Comisión Hidrográfica a cargo de D. José Montojo y Salcedo. Dirección de Hidrografía, 1875. Historic library of maps Servicio Geográfico del Ejército, Madrid.

1880. "Provincia de Huelva", Emilio Valverde. Atlas Geográfico descriptivo de la Península Ibérica, Islas Baleares, Canarias y Posesiones Españolas en Ultramar. Historic library of maps Servicio Geográfico del Ejército, Madrid.

1887. "Mapa geológico y topográfico de la provincia de Huelva". Joaquín Gonzalo y Tarín. Historic library of maps Instituto Geológico y Minero, Madrid.

1892. "Nuevo mapa geográfico estadístico de la provincia de Huelva", José Carrasco y Padilla (Excma. Diputación Provincial de Huelva). Map Library Instituto Geográfico Nacional, Madrid.

1897-1900. "Provincia de Huelva, nivelación", F. Noriega and J. Cobo de Guzmán. Instituto Geográfico Estadístico. Historic library of maps Servicio Geográfico del Ejército, Madrid.

19tha C. "Provincia de Huelva", Anonymous. Historic library of maps Servicio Geográfico del Ejército, Madrid.

19thb C. "Provincia de Huelva", Anonymous. Historic library of maps Servicio Geográfico del Ejército, Madrid.

1902. "Mapa de España”, Carlos Ibáñez de Ibero. Publication 1884 and edited in 1902. Lit. Instituto Geográfico y Estadístico. Library Instituto Geológico y Minero, Madrid.

1913. "Las costas de la provincia de Huelva y sus variaciones en el periodo histórico". Maximino San Miguel de la Cámara. Boletín de la Real Sociedad de Historia Natural XIII, 434-468.

1926. “La llanura baja del Guadalquivir en los primeros tiempos de la época histórica, según Jorge Bonsor”. In: Hernández Pacheco, E., 1926. La Sierra Morena y la Llanura Bética (síntesis geológica). Instituto Geológico de España, Madrid.

1936. "Mapa Geológico de España E. 1:50,000 y memoria explicativa". Juan Gavala y Laborde. Sheet 1017 ("El Asperillo"). Instituto Geológico y Minero de España. Tip. y Lit. Coullant, 1936. Library del Instituto Geológico y Minero.

1949. "Cartografía Militar de España E. 1:25,000". Mapa Topográfico Nacional. Sheet 1017 ("El Picacho"), cuarto IV-III ("El Picacho") and Cuarto I ("El Abalario"). Servicio Geográfico del Ejército, 1952. Deparment of Plant Biology and Ecology, University of Sevilla, Seville.

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1976. “Mapa Geológico Nacional. Hoja 1017 El Abalario”. Instituto Geológico y Minero de España . Memoria y mapa. Instituto Geológico y Minero de España, Madrid.

ESM-3. Historical documents and unpublished technical reports with information about the studied brooks cited in ESM-1 (listed by date).

1577. FILE D-1 “Opinión adversa del Duque de Medina Sidonia a la construcción de las torres de almenara proyectadas en la costa de Arenas Gordas. 13 marzo/4 de mayo de 1577”. Compiled by Mora L (1981) Torres de almenara de la costa de Huelva. Diputación Provincial de Huelva, Huelva

1577. FILE D-2 “Idoneidad del maestro de cantería Luis de Montalbán para hacer las torres de Sanlucar, Arenas Gordas y Río del Oro. 10 de abril 1577”. Compiled by Mora L (1981) Torres de almenara de la costa de Huelva. Diputación Provincial de Huelva, Huelva

1577. FILE D-3 “Relación de las torres que parece ser necesario construir en la costa, desde Sanlúcar de Barrameda hasta el cabo de Santa María en Faro. Abril o Mayo de 1577”. Compiled by Mora L (1981) Torres de almenara de la costa de Huelva. Diputación Provincial de Huelva, Huelva

1577. FILE D-6 “Objeciones del Duque de Medina Sidonia a la construcción de las torres de Modolón, Higuera y Río del Oro. 4 de mayo de 1577”. Compiled by Mora L (1981) Torres de almenara de la costa de Huelva. Diputación Provincial de Huelva, Huelva

1577. FILE D-12 “Instrucciones de Luis Brabo de Lagunas al Corregidos y al Alcalde de la mar de esta villa para que los barqueros de la misma lleven la piedra de Chipiona a las torres de Arenas Gordas cuando comience su construcción. 25 de junio de 1577”. Compiled by Mora L (1981) Torres de almenara de la costa de Huelva. Diputación Provincial de Huelva, Huelva

1577. FILE D-13 “Luis Brabo de Lagunas trasmite la orden de S. M. para construir cuatro torres (Salabar, Carbonera, Higuera y Asperillo) en la costa de Arenas Gordas. Oposición del Cabildo y alternativa que expone. 5 de julio de 1577”. Compiled by

Compiled by Mora L (1981) Torres de almenara de la costa de Huelva. Diputación Provincial de Huelva, Huelva

1577. FILE D-14 “Luis Brabo de Lagunas trasmite la orden de S. M. para construir cuatro torres de almenara en la costa desde Río del Oro hasta la punta Arenilla. Excusas del cabildo por falta de propios y pobreza del vecindario. 11 de julio de 1577”. Compiled by Mora L (1981) Torres de almenara de la costa de Huelva. Diputación Provincial de Huelva, Huelva

1577. FILE D-15 “Brabo de Lagunas trasmite la orden de S. M. respecto a las cuatro torres mencionadas en D-14. El Cabildo pretexta su lejanía del mar, pero ofrece trescientos mil maravedís a pagar en tres anualidades consecutivas. 12 de julio de 1577”. Compiled by Mora L (1981) Torres de almenara de la costa de Huelva. Diputación Provincial de Huelva, Huelva

1740. FILE 837. “Copia de la Instrucción que Procede el Señor Don Francisco Rodrigo de las Quentas Sayas del concejo de su Majestad su oidor en la Real audiencia de Sevilla Juez de arbitrios, y de la Comisión de la Nueba Real Junta sobre tierras baldias y dehesas” (sic). Archivo Municipal de Almonte compiled by Castrillo MC (2000) Doñana Nombre a Nombre. Estudio de la toponimia del Parque Nacional de Doñana. Diputación Provincial de Huelva. Huelva

1756. FILE D-27. “Relación de las Plazas, Torres, Puestos Fortificados, Edificios Militares y Poblaciones de la Costa de Andalucía desde la Raya Occidental del Reyno de Granada hasta la de Portugal en Ayamonte según el Estado en que se hallan el año 1756”. Anonymous. Compiled by Mora L (1981) Torres de almenara de la costa de Huelva. Diputación Provincial de Huelva, Huelva

1785. ÁLVAREZ DE CARDOSO, A. “Respuesta del párroco de Almonte D. Alonso Álvarez de Cardoso a las Relaciones enviadas por Tomás López”. Compiled by Ruiz González

JE (1999) Huelva, según las relaciones enviadas por los párrocos al geógrafo real Tomás López en el siglo XVIII. Diputación Provincial de Huelva, Huelva

1848. MADOZ P "Diccionario Geográfico-estadístico-histórico de España y sus posesiones de Ultramar". Biblioteca Santa Ana (reprinted 1990), Almendralejo

1886. GONZALO Y TARÍN J "Descripción física, geológica y minera de la provincia de Huelva. Tomo I Primera Parte: Descripción física". Imprenta y fundición de Manuel Tello, Madrid

1887. GONZALO Y TARÍN J "Descripción física, geológica y minera de la provincia de Huelva. Tomo I Segunda Parte: Descripción geológica. Estratigrafía". Imprenta y fundición de Manuel Tello, Madrid

1890. HERASO J "Estudio sobre la fijación de las dunas situadas en el término municipal de Almonte, provincia de Huelva. Primera Parte". Revista de Montes 322:281-287

1913. SAN MIGUEL M "Las costas de la provincia de Huelva y sus variaciones en el período histórico". Boletín de la Real Sociedad Española de Historia Natural 13:434-468

1936. GAVALA J "Mapa geológico de España E. 50,000 y memoria explicativa. Hoja 1017 ("El Asperillo")". Instituto Geológico y Minero de España, Madrid

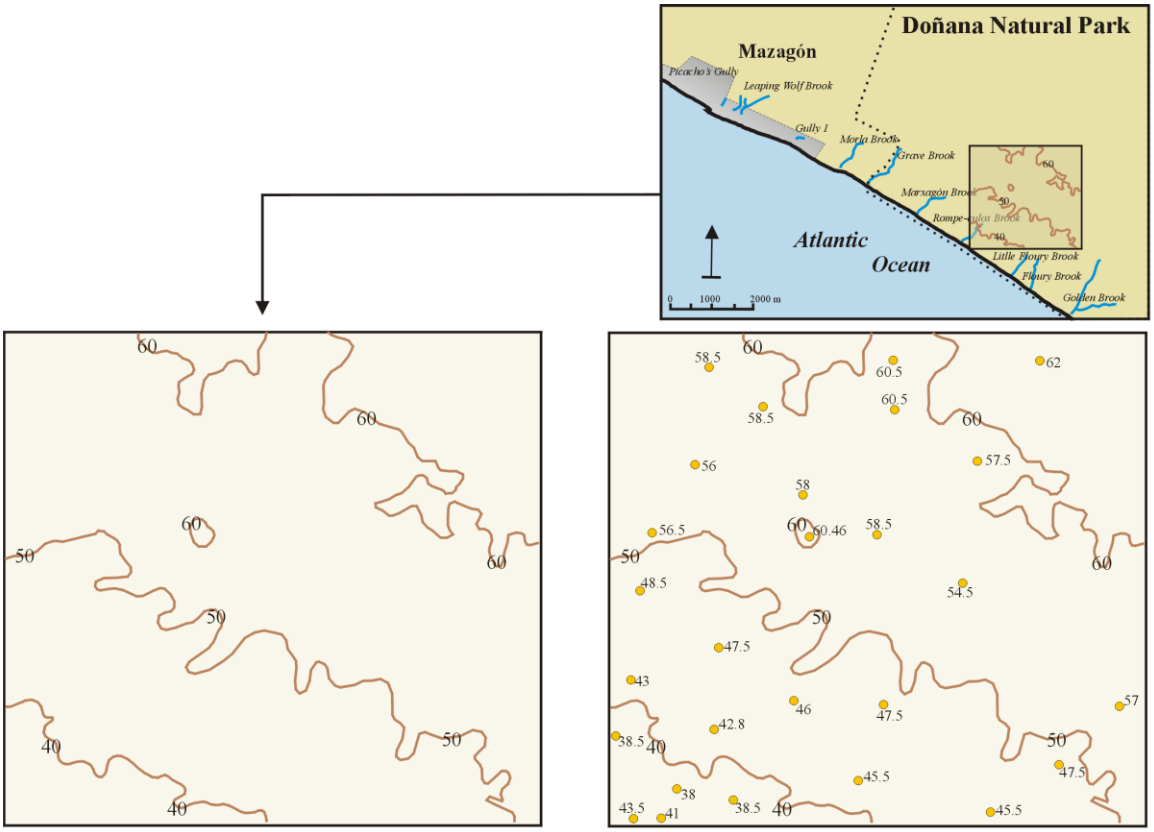
1936. KITH M "Propuesta de ampliación del proyecto de fijación y repoblación de las Dunas de Almonte". V División Hidrológico-Forestal del Guadalquivir. Unedited Technical Report, Huelva

1941. PATRIMONIO FORESTAL DEL ESTADO "Reconocimiento y propuestas de trabajos en la finca del Coto Ibarra". Unedited technical Report, Huelva

1951. DE LA LAMA G (1951) "Diez años de trabajos forestales". Revista Montes 39:195–201

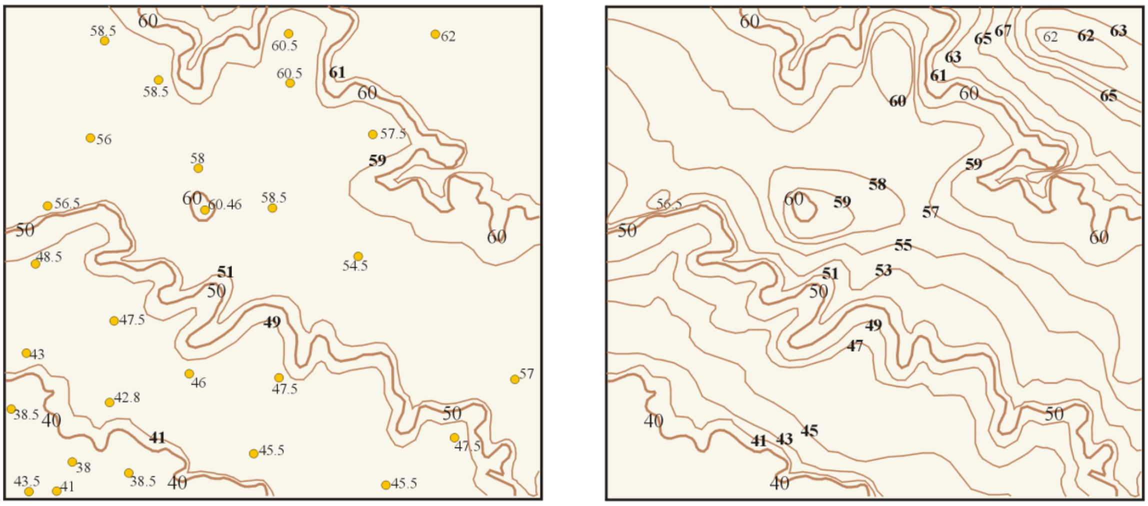
ESM-4. Methodological sequence used (a, b, c, d) to obtain the microtopography of the study area.

The map (1:10,000) displays the topographic isolines only every 10 m (a) and also includes a vast number of topographic elevations (b). These topographic elevations are used to gradually interpolate contours every two m (c); thus, generating a map with topographic isolines every two m (d).



(a) Topographic Isolines (scale 1:10,000)

(b) Topographic elevations (scale 1:10,000)



(c) Interpolation of topographic elevations

(d) Topographic isolines interpolated every 2 metres

ESM-5. Estimated error rate of the historical cartography and microrelief in 19th century and Degree of meandering.

Brook	Microrelief 19th century (km)	Coello (1869) (km)	Estimated error rate of the historical cartography and the microrelief in 19th century (%)	Degree of meandering (*Dm*)
Golden Brook	9.9	12.6	+27.3	Severe
Floury Brook	4.5	4.4	-2.2	Severe
Little Floury Brook	2.5	2.8	+12.0	Minor
Rompe-culos Brook	3.2	4.4	+37.5	Severe
Marxagon Brook	2.6	3.6	+38.5	Appreciable
Grave Brook	3.3	2.7	-18.2	Minor
Morla Brook	1.7	11.2	+558.8	Minor
Gully 1	0.3	-	-	Minor
Gully 2	0.1	-	-	Minor
Leaping Wolf Brook	8.1	2.6	-67.9	Severe
Picacho's Gully	0.9	4.1	+335.5	Severe
Total	**37.1**	**48.4**	**30.5**	**-**

ESM-6. Excerpt of historical quotations about the hydrologic features of the brooks during 16th and 18th centuries.

Fecha	**Fuente**	**Descripción**
1785	ALONSO ÁLVAREZ DE CARDOSO	*"[...] due to there is no river within its boundary but some tiny streams".*
1756	FILE D-27	*"Golden River wachtower: [...] it's surrounded and struck by the sea during the high tide and by the brook that during the low tide flows by its base, which produce ruin and supposedly the storms irremediably will end up destroying it..."*
1740	FILE 837	*"[...] and the Golden River watchtower that was ordered to be erected in the middle of the river between the land of Almonte and the village of Palos...".*
1577	FILE D-3	*"Golden River: From Higuera to Golden River there are three league and a great drinking water supply [...] and the enemy vessels usually go there to load water [...]". "Julianejo: From Golden River to Julianejo there are two leagues and abundant water, it is a fishermen place and the enemy vessels always go there and it is necessary an ordinary tower".*