

Article

Mathematical Reconstruction of Eroded Beach Ridges at the Ombrone River Delta

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Abstract: Several remotely sensed images, acquired by different sensors on satellite, airplane, and drone, were used to trace the beach ridges pattern present on the delta of the River Ombrone. A more detailed map of these morphologies, than those present in the literature, was obtained, especially at the delta apex, where beach ridges elevation is minor. Beach ridges crests, highlighted through image enhancement using ENVI 4.5 and a DTM based on LiDAR data, were then processed with ArcGIS 9.3 software. Starting from this map, a method to reconstruct beach ridges segments deleted by the transformations of the territory is proposed in this paper. The best crest-lines fitting functions were calculated through interpolation of their points with Curve Expert software, and further extrapolated to reconstruct the ridges morphology where human activity, riverbed migration, or coastal erosion eliminated them. This allowed to reconstruct the ridges pattern also offshore the present delta apex, where the shoreline retreated approximately 900 m in the last 150 years. Results can be further used to implement conceptual and numerical models of delta evolution.

Keywords: beach ridges; mathematical reconstruction; curve fitting; Ombrone River Delta

1. Introduction

Deltas are dynamic depositional landforms, sensitive to changes in both the terrestrial and marine environment [1,2], constantly reshaped by river input, tides, and waves [3,4]. Wave-dominated deltas are characterized by a cusate morphology, a steep offshore profile, and the presence of more or less curved beach ridges parallel to past shoreline positions [5]. This allowed to reconstruct Holocene delta formation phases for many rivers, and to date, the various morphologies when archaeological remnants were present or if radiometric dating were executed [6,7].

Fluctuations in fluvial sediment supply were also assessed for several deltas, being the most important factor controlling the spatial and temporal variation in beach ridges development [8,9]. Spits are frequently present near the river mouth, sometimes overpassed by the coastal progradation and detectable in the delta area, others eroded by waves. Beach ridges frequently evolve in coastal dunes which reflect a huge amount of sediments that are redistributed by waves and moved inland by winds forming elongated and parallel morphologies behind the coastline [10]. A fast accreting coast makes the formation of several low crests, whereas a slowly prograding or a stable one allows the growth of few high dunes [11,12]. Beach ridges morphology and related pattern could be used as markers of morphodynamic variations: they can give information on past wave regime, climate conditions, sediment supply, and sea level change [13–16].

In historical times, fast delta progradation is frequently induced by fluvial input increase, ascribed to the population development on the catchment area accompanied by intensive deforestation [17,18].

Just short (months) and medium time (years) changes in sediment input can induce delta apex reshaping, resulting in different delta lobes morphology and beach ridges patterns. Fast progradation periods, due to higher sediment input by the river, sees a sharp cusp and the rotation of the river mouth towards the dominant wave front direction, as described for the Ombrone and Arno River deltas [19]; on the contrary, a reduced fluvial input determines a flattening of the cusp up to a rectification of the coastline and downdrift shift of the river mouth [20,21].

Conceptual models of cusped delta evolution have been proposed by ref. [19,22], whereas other authors ref. [2,21,23,24] used numerical models to explain delta asymmetry and wave reshaping of the river mouth during erosion and accretion phases. For deltas characterized by alternating phases of growth and erosion, not all the beach ridges at the delta apex can be identified, since their most offshore part has been beheaded during the erosion phases [12]; in addition, some segments can be leveled by human activity, especially agriculture, or cut by the river course migration.

A full reconstruction of the delta evolution needs to know the delta shape at its extreme expansions, even if later cut by erosion; this is of outmost importance when conceptual or numerical models based on wings surface are to be developed.

The possibility to observe the secular trends of beach ridges on the Ombrone delta plain represents a valuable opportunity to obtain useful information on its complex geomorphological evolution, where one of the main drawbacks is represented by the loss of geographical information due to natural and anthropic transformations of the territory over time and the lack, or inaccuracy, of ancient cartography. The problem was solved through a mathematical reconstruction of the missing portions of the beach ridges inspired from the observation of their geometry and how their planar forms remind of specific mathematical functions.

On Earth, a number of geomorphic elements have a regular shape, including small-scale landforms such as cirques, drumlins, sand dunes, alluvial fans, dolines, polygonal soils and cracks, columnar jointing, and scoria cones, to large-scale landforms such as composite and shield volcanoes [25]. Geomorphometry is the science of quantitative land-surface analysis and a variety of landforms are fitted by mathematical functions, often by means of regression analysis [26].

Just to remain in coastal environment, zeta bays in equilibrium with approaching refracted waves are fitted by a logarithmic spiral as proposed by Silvester and Hsu [27], or the equilibrium nearshore profile is mathematically described by the Dean equation [28].

Following a similar approach, a method to reconstruct beach ridges, where they have been eroded or razed by human activity, is hereafter proposed using fitting equations.

Results can be further used for a detailed model on the delta evolution reconstruction, which is not the aim of this study.

2. Study Area

The Ombrone River delta is in Italy, located on the Southern Tuscany coast (Italy), between Castiglione della Pescaia and Monti dell'Uccellina, in the Maremma Regional Park (Figure 1). The dominant waves direction is from South-West [24], and for the present research, is assumed to be a constant wave climate over the historical times [29,30]. The regional longshore transport direction is from south to north [31,32]; subsidence in the alluvial plain was measured in 3 mm/year [33] and this is the only significant vertical movement in the considered time lapse. Sea level rise is about 1 m since the roman period [34].

The ancient gulf of Grosseto started to fill with the material transported by the Ombrone River during the Holocene transgression, but the most internal beach ridge is very likely associated to a sand bar closing a lagoon. When the lagoon was almost silted, the river could directly empty into the sea

and started the delta formation. This is dated to the early Roman period [35] and explained with the intense deforestation carried out within the watershed by the Etruscan, first, and by the Romans, later.

During the last twenty centuries, the delta apex grew for approximately 6.5 km at the apex, with a very fast expansion in the 14th–18th century [36], when an intense deforestation occurred. Some authors also see in this delta expansion, the effect of the Little Ice Age [35,37]. Two main erosional phases have been identified, the first after the fall of the Roman Empire, and the second with the Black Death epidemic; in both cases a strong population reduction induced the abandonment of many cultivated areas and the growth of the forest [36].

Furthermore, at the end of the 19th century, these tendencies drastically reversed with the erosion of the coastline at the river mouth, caused by agriculture abandonment, riverbed quarrying, dams and weirs construction; whereas wetland reclamations, through river course diversion, started some centuries before depriving the river load mostly in its finer fraction. Results of these works were poor since sediment compaction was restoring the original wetlands [38].

Since the end of the 19th century, the delta apex started to retreat, and it is now approximately 900 m back from its most prominent position (depicted in a 1881 topographic map). Before shore protection works were carried out in 2013–2014 on the southern lobe (submerged groins) and milder in 2016 on the northern one (short wood permeable groins), the erosion rate was approximately 10 m/year [17].

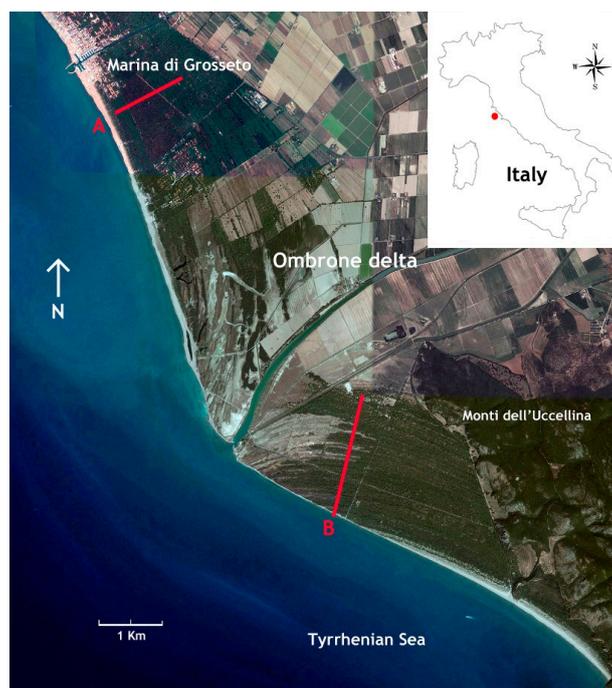


Figure 1. The Ombrone River delta and the position of the two topographic profiles drawn in Figure 3 (Google Earth image).

Delta morphology is slightly different in the two lobes [6,36,37]. The northern side hosts inter-dune swales and, near the river course, some permanent ponds, possibly old channels to connect salterns to the sea. Dunes progressively merge to the north in few parallel ridges; the inner one is attributed to the Etruscan period, the next five to the Roman time, followed by seven Medieval and the last four belonging to the Modern Age [39].

Agriculture activity and urban development at Marina di Grosseto deleted some segments of these dunes. The southern side is almost uninhabited, dunes are closer, and their continuity is more preserved, but at the apex, where they are far lower, seasonal ponds form and in the wetter period most of the apex is flooded. The Monti dell'Uccellina, with their seaward projection, limit sediment

dispersion and, even if in the past centuries the prevalent longshore transport was to the north, the delta could symmetrically grow. (Smaller volume but shorter base in the southern side). The River Ombrone delta, hosts many beheaded ridges; but the well-preserved morphology of those remained allows to test a methodology to mathematically reconstruct the lost segments.

3. Material and Methods

For this study, a detailed beach ridge map was obtained through the combination of several data sets, produced by active and passive remote sensors, and processed with various methodologies. A LiDAR (light detection and ranging) survey acquired in 2008 by the Ministry of the Environment, with 1×1 m ground resolution, was used to derive a 3D model of the beach ridges area. Where agriculture flattened the ridges, ad hoc topographic surveys were carried out, and a higher vertical resolution DTM (digital terrain model) was produced from low altitude drone imagery using the structure from motion (SfM) technique.

Satellite images used span from Landsat TM and Landsat ETM+ (from 1986 to 2002); Quickbird (2004); Landsat 8 (2015) and Sentinel 2a (2017); in addition, some Google Earth images were used. Pixel size goes from 2.44 m (Quickbird) to 30 m (Landsat TM).

Remotely sensed images helped in tracing ridge crests where ridges were flattened, and soil moistures helps to discriminate sand from silty/clayey soils present in the interdune swales. This was obtained with specific image processing, such as normalized difference of vegetation index (NDVI), tasseled cup transformation (brightness, greenness, and wetness) [40], principal components analysis (PCA), and RGB (red-green-blue) color composites of the results of the different elaborations. Recent topographic surveys, regional cartography, and old aerial photos acquired in 1944 by RAF (Royal Air Force) were also used. Images were then wrapped on the Lidar 3D model to assist their photo interpretation.

All these data were processed using ENVI 4.5 (Harris Geospatial Solutions Inc., Broomfield, CO, USA) and ArcGIS 9.3 (ESRI) softwares in order to produce a detailed beach dunes/beach ridges map of the delta area in the WGS84 UTM32 reference system (Figure 2) and leading information was derived from LiDAR data, whose resolution was maintained also after the following image overlapping.

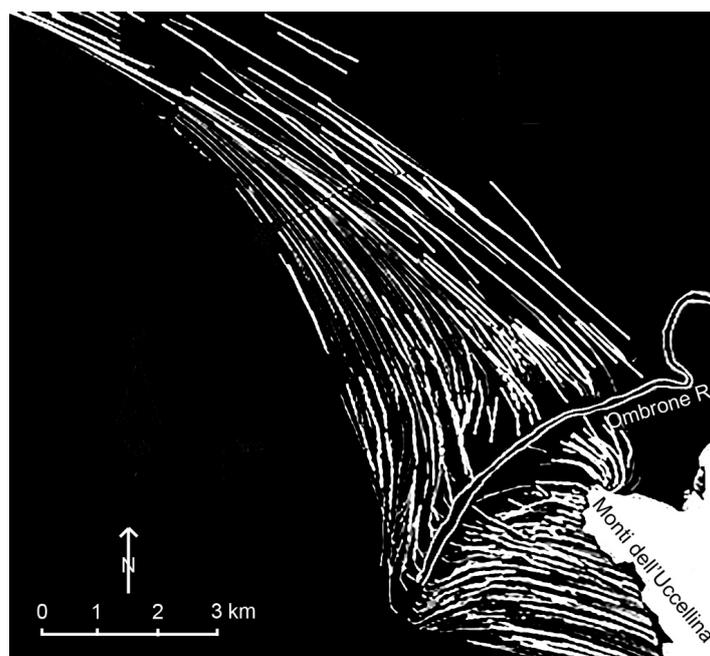


Figure 2. Ombrone River delta, beach ridges pattern mapped through the combination of different data sets and elaboration methodologies.

From LiDAR-DTM, several cross-shore profiles were extracted, and minor beach ridges sequence and evolution phases were recognized and relatively dated, starting from the main delta evolution periods described in the literature [36,37].

From the position, geometry, and height of some ridges it was possible to pair them across the gap formed by the river or by agricultural flattening. In Figure 3, profiles crossing the dunes/ridges system on the two delta wings are drawn and ridges associated and numbered (see Figure 1 for profiles location). In the northern profile, all the morphologies are compressed, both because the profile is located far from the delta apex, and because sediment is distributed along a wider area (the northern limit of the cell—Punta delle Rocchette—is 24 km from the river mouth, whereas the southern, one—Monti dell’Uccellina—is 7 km only).

Profiles show the differences in height and distance between ridges, and how some of the highest/largest ones on the delta wings and associated to apex erosion or stability periods, comprise more than one crest, due to an overlapping of more dunes.

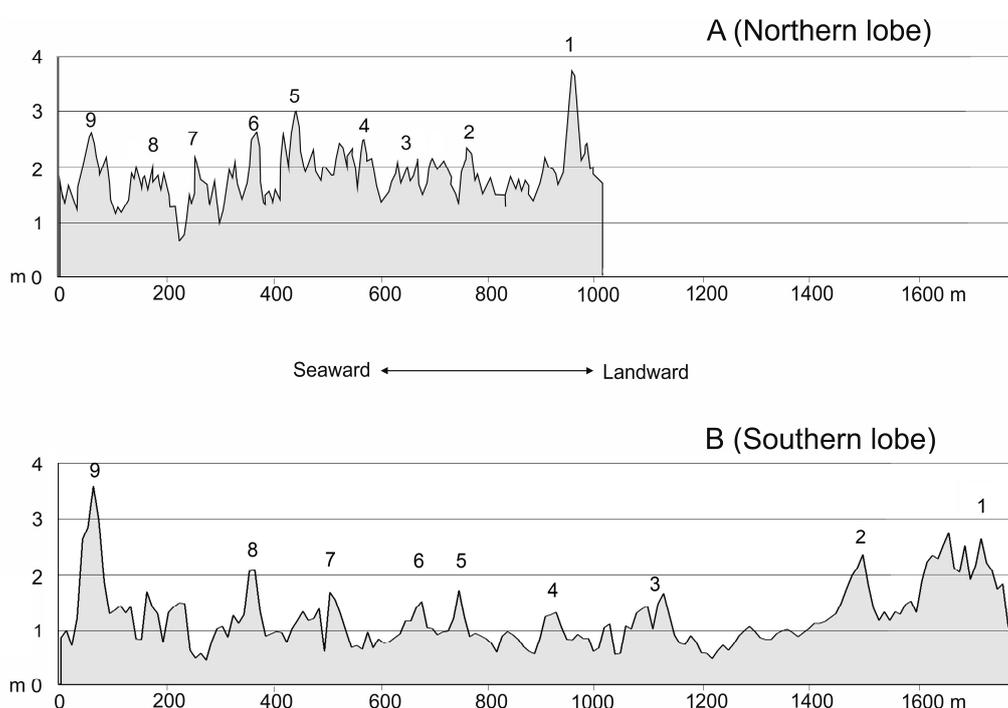


Figure 3. North (A) and south (B) profiles from the early 15th (1) century until the limit of the progradation in middle 19th century (9). Due to the difference in deposition rates, horizontal scale cannot be considered a time scale.

Sixteen beach ridges from the early 15th to the middle-19th century have been selected representing different periods of the delta evolution, both when accreting and when eroding. In the first case, beach ridges plant geometry is more curved at the apex with ridges sharply converging (Figure 4); on the contrary, soon after a period of delta erosion their planform is more rectilinear since beach retreats at the apex but progradation goes on at the wings (actually it is a form of beach rotation) [12].

Along each beach ridge, several x,y points were digitized where each ridge crest was more evident; one point every 50 m on average. Along this distance, ridges are almost rectilinear and more points do not increase the accuracy. They were further rotated and shifted in a Cartesian coordinate system with the y-axis coincident with the direction of the terminal river course.

In order to mathematically reconstruct the missing parts of the beach ridges, 33 families of linear and not linear regression models were tested, both for progradation and for erosion beach ridge shapes. The calculation was done using a specific curve fitting software (CurveExpert Pro 1.4, Hyams Development, Chattanooga, TN, USA). The software provides a ranking of the best fitting functions

and they are also displayed in the graphing window with statistical results, such as standard error and correlation coefficient. Values x, y for points of interpolated and extrapolated curves are also available and useful for the reconstruction of the missing parts of the delated beach ridges.

4. Results

Finding equations that well fit the ridges allows to reconstruct their original plan form in the stretches where they have been erased by human activities or by coastal erosion.

Among all the 33 regression models tested, two distinct families of functions, respectively Weibull (Equation (1)) and Morgan–Morgan–Finney (MMF) (Equation (2)), were found out with lowest values of standard error and highest correlation coefficient. The former function better approximates more rectilinear beach ridges of older coastlines or of erosional phases (more flat lines); whereas the latter function better fits curved beach ridges of fast accreting stages (Table 1).

To a lesser extent, Hoerl (Equation (3)) and 3th degree polynomial (Equation (4)) were the following two better equations in the fitting ranking.

$$\text{Weibull : } y = a - be^{-cx^d}. \quad (1)$$

$$\text{MMF : } y = \frac{ab + cx^d}{b + x^d}. \quad (2)$$

$$\text{Hoerl : } y = a b^x c^x. \quad (3)$$

$$\text{Polynomial : 3th - degree } y = a + bx + cx^2 + dx^3. \quad (4)$$

Obviously, the robustness of the method depends on the extension of interpolated beach ridges too, and is correlated to the segment form: linear or arcuate. For very short segments, results exponentially lose significance.

Table 1. Relation between beach ridge and best four fitting mathematical functions. ER = apex erosion, PR = apex progradation. In bold, the best standard error for each ridge.

Year (ca.)	Evolution Type	Standard Error [m] for Four of the Best Different Fitting Models			
		MMF	Weibull.	Hoerl	3rd Degree Polynomial
1500	ER	5.1	3.2	4.0	3.3
1550	PR	14.4	16.6	16.4	22.2
1600	ER	16.6	12.6	14.5	19.2
1615	PR	7.0	11.4	15.8	27.5
1625	ER	14.3	12.8	16.8	23.9
1650	ER	12.5	8.2	7.2	16.3
1660	PR	5.5	9.3	12.3	18.9
1675	ER	16.6	10.0	11.9	12.6
1700	ER	15.2	7.1	9.4	8.4
1725	ER	13.4	8.5	10.2	18.2
1750	PR	9.3	12.1	21.2	16.2
1775	ER	18.8	14.7	19.6	32.7
1800	ER	16.4	11.5	13.1	9.5
1820	ER	16.5	5.6	18.7	21.1
1830	PR	6.4	14.9	15.5	23.8
1850	ER	29.7	13.2	20.7	11.8

In the table are reported precise year, just to have a temporal reference to be attributed to every mapped beach ridge, but there may be indeed an uncertainty of several years. The correlation coefficients range are from 0.999 to 0.997.

In Figures 4 and 5, the real 1625 (apex erosion phase) and 1750 (apex accretion phase) beach ridges on the south lobe of the delta are drawn together with the best 4 fitting models produced through extrapolation, near the river, of the first 4 km of each ridge. The graphs show Weibull (Equation (1))

better approximates more rectilinear erosional beach ridges and MMF (Equation (2)) curved beach ridges of progradation phases.

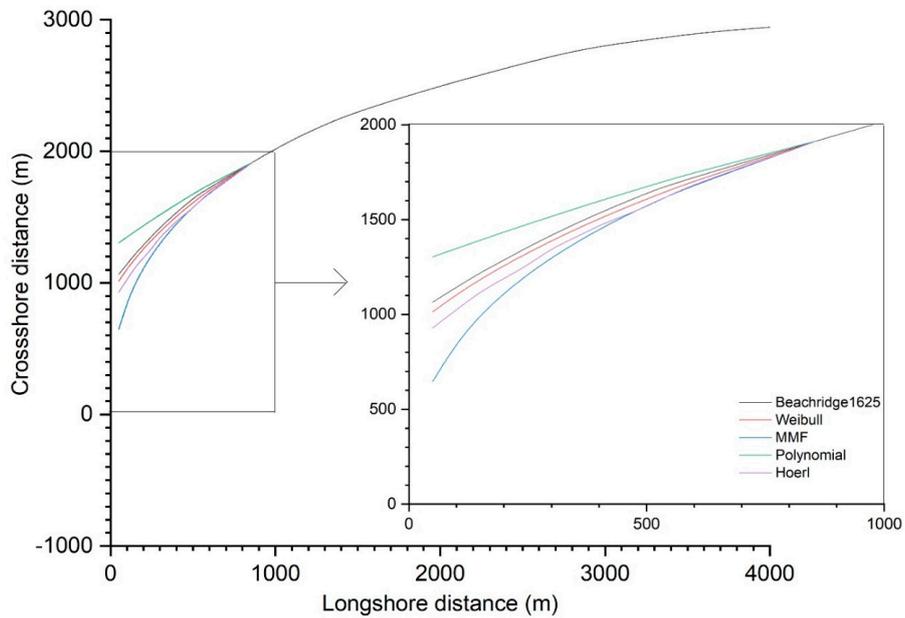


Figure 4. Real beach ridge 1625 ca., correlated to an erosional period, with the four best fitting mathematical functions.

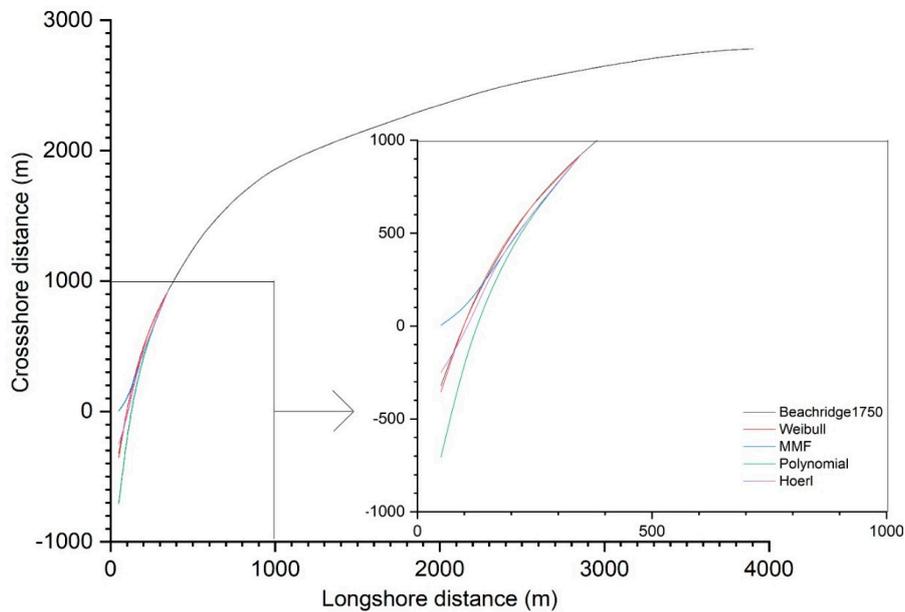


Figure 5. Real beach ridge 1750 ca., correlated to a progradation period, with the four best fitting mathematical functions.

Starting from all the beach ridges mapped in Figure 2, the main evolution phases of the Ombrone River delta, for the considered period, are reported in Figure 6. The considered period is from the early 15th to the middle 19th century, after which reliable topographic surveys are available.

Beach ridges deleted near the river because of watercourse shifting or truncated by a subsequent erosive event have been mathematically reconstructed according to the methodology proposed.

Beach ridges beheaded at the river mouth are represented in cyan and those related to the cusped progradation in red. In blue and purple, their reconstructed morphologies with mathematical functions.

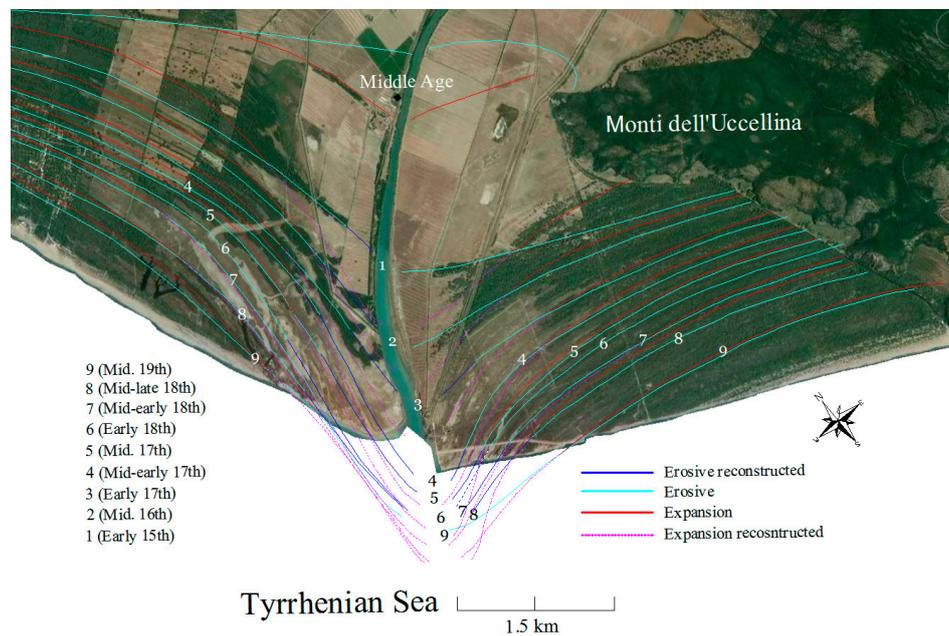


Figure 6. Beach ridges reconstruction for main historical phases from the 15th to the 19th century.

5. Discussion

Quantitative approach in Geomorphology became established in the mid-20th century [41], but equations fitting coastal landforms arrived a few decades later, like those aforementioned, by Dean [28] and by Silvester and Hsu [27]; both, although developed on actual morphologies, are used to forecast the shape a landform (nearshore profile and zeta-bays) will reach at equilibrium. What is done in this paper is the reconstruction of ancient landforms in those parts which have been later eroded.

In a period in which approximately 31% of the world beaches are eroding [42], and considering that erosion generally starts at the river mouth and gradually expand laterally [22], many present cusped river deltas lost their apex. Further, agricultural works and urbanization frequently flattened, or at least hid, original morphologies. This makes it impossible to fully reconstruct the natural delta morphology and study its historical evolution.

The proposed method needs high-resolution data, which was obtained from active and passive remote sensing systems. In this way, a detailed reconstruction of beach ridges morphologies was done, and several accretion and erosion phases mapped. Thirty-three different fitting curves were generated though interpolation of control points on the beach ridges/dune crests and their accuracy in describing those morphologies was assessed.

The further extrapolation of the last seaward points allowed to reconstruct the ridge segments which were eroded during the last 150 years, thus obtaining information on the past delta apex shape. On the other sides, interpolation made it possible to identify reaches flattened by agriculture or by other anthropogenic activities. For ridges formed during delta expansions phases (more curved at the tip), the MMF model proved to be more accurate than all the other tested; whereas ridges formed during delta tip erosion, more flattens, were better reconstructed by the Weibull equation.

6. Conclusions

The mathematical interpolation and extrapolation of the functions fitting the ridge crests at the Ombrone River delta allowed to reconstruct their entire morphologies, not only in the part eroded during the last 150 years, but also where similar processes worked in the Middle and Modern Age.

On these bases, it will be possible to develop more accurate models of delta evolution in order to better explain the different morphology characterizing the updrift and the downdrift delta sides, and to forecast future shoreline displacement in this coast rich in natural and economical elements.

The hoped application of this method to other deltas, using different equation coefficients, could help to solve similar problems and improve the method itself.

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