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GEOSTATISTICAL AND DETERMINISTIC PREDICTIVE METHODS FOR A 3D RECONSTRUCTION OF THE ANCIENT MORPHOLOGY AND THE ANTHROPIC REMAINS OF THE EARLY MEDIEVAL PORT OF COMACCHIO (FERRARA – ITALY)

1. Introduction

In recent years predictive models have received increasing attention and by now they are well known among the scientific community. Yet, so far, they have been exploited mainly for the prediction of site location (see Verhagen, Witley 2011 for a general outlook on this topic) or, in some other scanty cases, to investigate the topographical distribution of a given pottery class (Herzog 2007), as well as to explore the growth of a settlement (Citter 2012). However, the use of predictive models for palaeogeographical reconstructions in archaeology happens to be still very rare and quite recent (Ferrarese *et al.* 2006; Fouache *et al.* 2010; Gattiglia 2012) while it is much more common in geological researches.

In this paper we report the first successful reconstruction of the ancient morphology of the early medieval port of Comacchio (Gelichi 2007a, 2007b, 2008, 2010a, 2010b; Gelichi, Calaon 2007; Gelichi *et al.* 2006, 2008a, 2008b, 2012) through deterministic and geostatistical interpolation methods. The former group of algorithms attributes values from the samples through specified mathematical formulae that define the regularity of the output surface without offering measures about the uncertainty of the predictions. The latter are based on statistical models such as autocorrelation, thus providing different surfaces and associated measures about the predictions and their uncertainty.

To choose the best Digital Terrain Model we compared more than thirty surfaces generated by both groups of interpolation methods, following a procedure mainly based on the comparison between the root mean square error values as suggested by the sparse literature (Hageman, Bennet 2000; Gattiglia 2012)[1]. In addition to this, we present the 3D reconstructions of some of the wooden structures found during the excavations. The juxtaposition of the Digital Terrain Models and these reconstructions gave us the possibility to identify different building phases and a clear spatial organization of the ancient structures.

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[1] For the general theory and some practical examples see http://resources.arcgis.com/en/help/main/10.2/ (accessed October 2016) and Haining 2003: because of the lack of manuals regarding these topics, we chose to rely mainly on the ESRI online guide, which could give precise instructions and tools to face such a technical issue.

2. Presentation of the site and raw materials

The archaeological history of the early medieval port of Comacchio started unintentionally in the 1920s thanks to the discovery of huge fronts of palisades during the excavation of the so called Collettore Ponti, an artificial drain W of the Villaggio San Francesco district, N of the town (Fig. 1). These structures were then interpreted as "palafitte" and mainly ignored by the scientific community, apart from some hints in the literature of the 1980s (e.g. Patitucci Uggeri 1986, 270). At the time of the discovery, in 1924, the orientation of the palisades was not clear, but in 1930 Francesco Proni, the supervisor of Regia Soprintendenza, suggested that those structures could be eastbound and that they could even reach the Villaggio San Francesco district (Uggeri 2006, 83, fig. 42). In fact, in 1996, during the monitoring of the construction of sewers, the archaeologists of the Tecne S.r.l. company found more than 900 perfectly preserved wooden posts, sometimes associated with floors made with planks, wicker and branches (Mazzavillani 1996).

The archaeological project carried out between 2008 and 2009 by Università Ca' Foscari di Venezia and led by Prof. Sauro Gelichi in the Villaggio San Francesco district was prompted by this extraordinary potential[2]. The excavations allowed to ascertain that the first occupations of the area, characterized by the presence of structures made of perishable materials, namely wooden planks and posts, dated to the VII century AD. Soon after, several factors, both natural and human, suggested that those archaeological evidences were to be ascribed to a port. On the one hand, the pottery record found on the contemporary ancient floors was almost entirely made of transport vessels coming from different Mediterranean areas (Negrelli 2007). On the other, the geological subsurface was not perfectly flat but characterized by gentle slopes. At first glance, the site seemed to have developed within a lagoon area dotted by small dry lands. Hence, the majority of the posts found in the 20th century could be interpreted as the remains of docks and jetties (Calaon 2007).

Recently, this interpretation has been validated by a general study of the early medieval landscape of Comacchio (Rucco 2015), and by several stratigraphic corings performed in 2014 by the writer along with Dr. Paolo Mozzi and Dr. Tiziano Abbà from Università di Padova, Dipartimento di Geoscienze. The site of Villaggio San Francesco developed on top of ancient coastal dunes, and was surrounded by a lagoon. The area was also crossed by several tidal channels and by natural and artificial waterways coming from the inland (Fig. 2). This extremely fortunate location allowed the early medieval settlement of Comacchio to become an *emporium* and to play a leading role

[2] A book is being prepared for the presentation of the results.

Fig. 1 – The site of Villaggio San Francesco, NE of Comacchio: the numbers correspond to the sections mentioned in the paper.

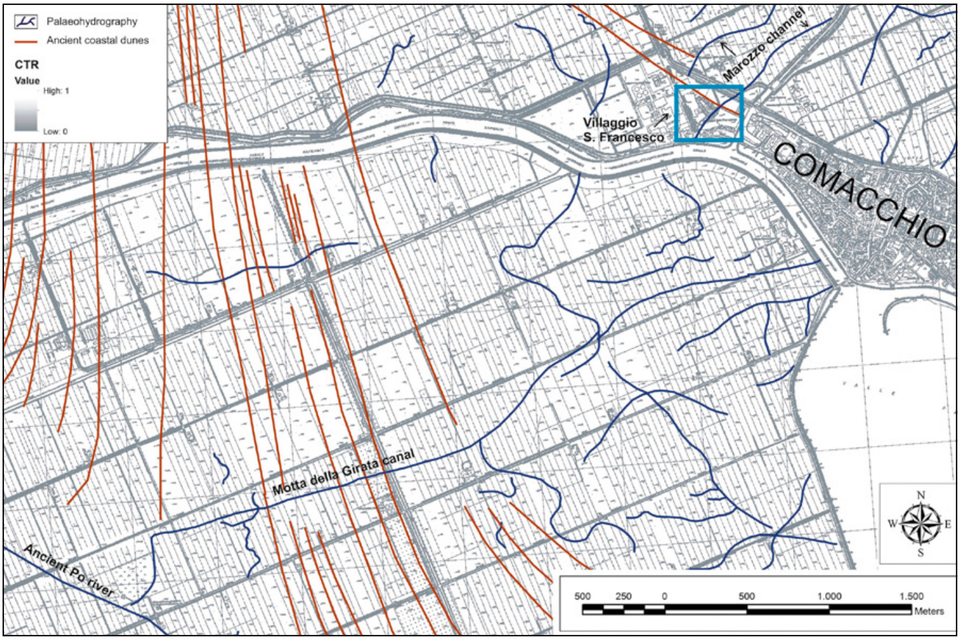

Fig. 2 – The Villaggio San Francesco district and its hinterland.

in the trading system of the Po plain (Gelichi 2007a, 2007b, 2008, 2010a, 2010b; Gelichi, Calaon 2007; Gelichi *et al.* 2006, 2008a, 2008b, 2012).

The major bulk of the raw data we used for the present study consisted, then, of almost 760 m of archaeological and geological sections sketched on the basis of the already mentioned trenches and corings[3]. In addition to these, we also used all the plans drawn during the excavations conducted in the area in 1996, where we found useful information for the correct reconstruction of the anthropic evidence of the port, such as the length and the diameter of the posts, and the extension of the docks.

A.A.R.

3. Method and calculation

3.1 *The initialization of the dataset*

In order to create a DTM (Digital Terrain Model)[4] through the interpolation of elevation values, we needed to analyze all the sections to identify the medieval levels. The operation happened to be particularly difficult since the area was partially submerged at that time: the port was built in a lagoon-like, sometimes marshy, landscape and the coastline used to be closer to the site; for this reason, the first step of the study was dedicated to the identification of the early medieval land surface level. We turned then to stratigraphy and found clear discontinuities and anthropic traces in close proximity or just above 2.7/3.0 m below the present surface. We also noticed that in every section all the early medieval layers were much thinner and flatter than the ones just below them, and that in general they were part of a multilayered 0.5/0.7 m thick anthropic basin, thus suggesting that they probably constituted a system of walking/working surfaces (Fig. 3).

Given these premises, we turned to informatics and created a shapefile of 335 points, each of them provided with an attribute corresponding to the elevation of these levels every 1 or 2 m circa of the above mentioned sections. The georeferencing of all the shapefiles and the DTMs created for the present study was made on the basis of the 1:5,000 *Carta Tecnica Regionale*.

A.A.R.

3.2 *The construction of the DTMs*

First of all, the elevation data were analyzed from a quantitative point of view through the ESDA (Exploratory Spatial Data Analysis) tools included in

[3] Since this bulk of materials is still being studied, we decided not to publish a detailed documentation. We postpone, then, the publication of this data to a future article.

[4] All the steps concerning the creation of the DTMs were made through ESRI ArcMap 10.2.

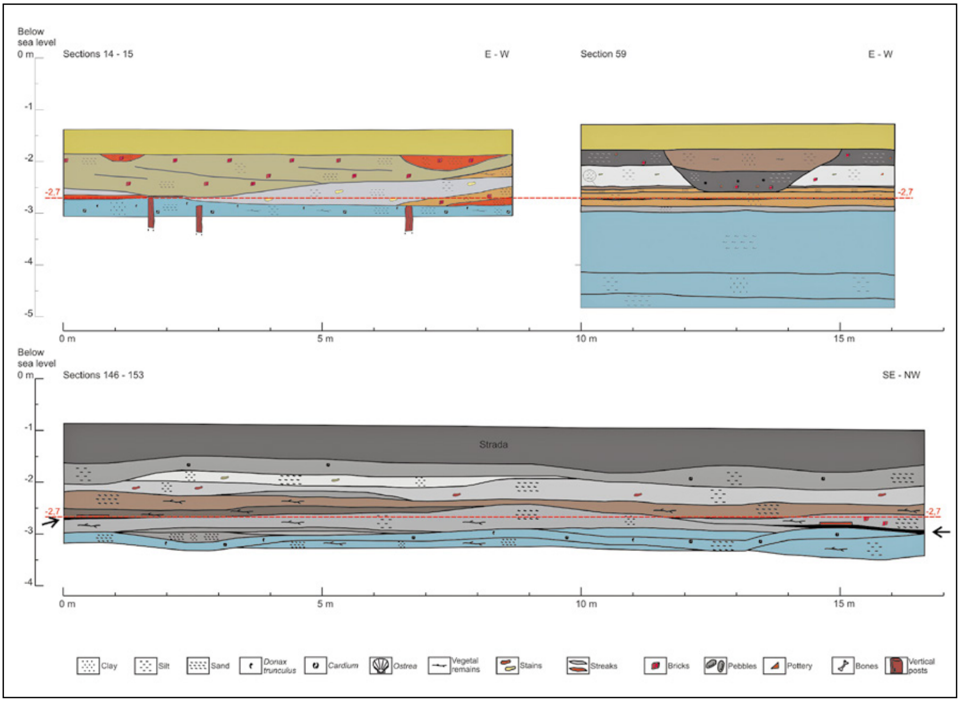

Fig. 3 – Some archaeological sections: the black layer marked by the arrows in the third section consists of wicker.

the Geostatistical Analys textension. We elaborated our interpolations starting from 335 elevation samples in a 53,900 m² wide area, so that the average density was calculated around 0.006 points/m². As we could see from the Histogram and the Normal QQ Plot, the spatial distribution of the samples seemed to be very close to a Gaussian curve. Moreover, the observation of the graphs from the Semivariogram and the Trend Analysis allowed us to notice the presence of a fairly probable spatial autocorrelation in addition to some NNE-SSW trends, which might be linked to the characteristics of the geological subsurface (Fig. 4).

We moved then to a test phase aimed at selecting the best interpolation method. In order to build the most reliable model we compared the RMSE (Root Mean Square Error) values of all the available predicted surfaces. The Optimize tool enabled us to automatically minimize the RMSE value working on different interpolation parameters, thus producing models that were optimized on the base of the same criterion and, for this reason, easily comparable both from a qualitative and a quantitative point of view thanks to

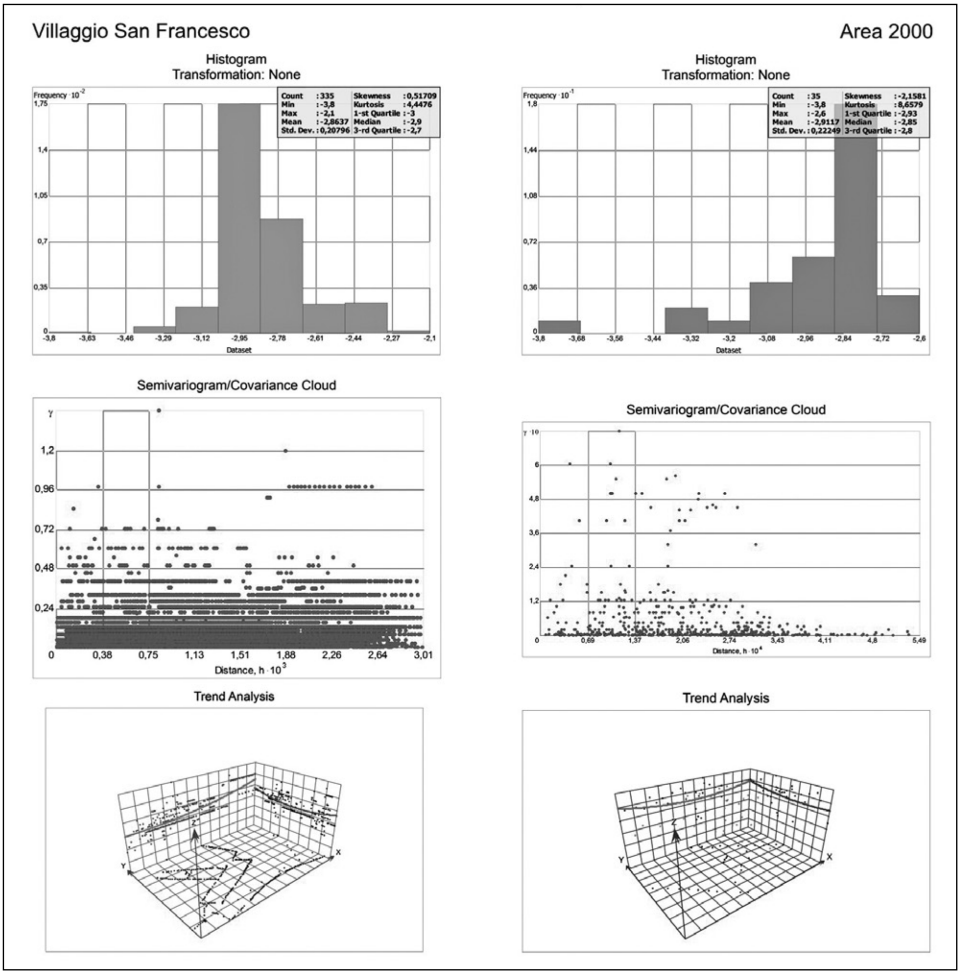

Fig. 4 – Results of the Elevation Data Analysis.

the Compare tool. Firstly, we tested the main deterministic methods (Inverse Distance Weighting, Radial Basis Functions and Local Polynomial Interpolation) and collected the lowest RMSE value (0.1067) through a RBF (Tab. 1).

Secondly, we moved to the main geostatistical methods (Ordinary, Simple, Universal and Empirical Bayesian Kriging): since we had already noticed the presence of probable directional trends, we compared the isotropic and the anisotropic model for each of the available surfaces, and consequently obtained the lowest RMSE value (0.1059) through an anisotropic Simple Kriging (Tab.

	VSF - Anisotropic Simple Kriging	VSF - Radial Basis Function	VSF - "Anisotropic" Radial Basis Function	AREA 2000 - Anisotropic Ordinary Kriging	AREA 2000 - Radial Basis Function
Searching neighborhood					
Standard	x	x	x	x	x
Neighbors to include	5	15	8	5	15
Include at least	2	10	8	2	10
Sector type	Eight	Full	Four and 45 degree	Four and 45 degree	Full
Major semiaxis	0,000235180805	0,000908265976	0,000235180805	0,000194817916	0,000166812378
Minor semiaxis	0,000352771207	0,000908265976	0,000352771207	6,539716342436387e-005	0,000166812378
Angle	14,58984375	0	14,58984375	128,84765625	0
Variogram					
Semivariogram	x			x	
Number of lags	12			12	
Lag size	2,939760057185141 2e-005			1,6234826331381722e-005	
Nugget	6,640110033255542 e-006			0,002883890331	
Measurement error %	100			100	
Model type					
Exponential	x				
Stable				x	
Parameter		81702,0435672246	81702,0435672246	1,961328125	62847,72715717550
Range	0,000235180805			0,000194817916	
Anisotropy	Yes			Yes	
Minor range	0,000352771207			6,539716342436387e-005	
Direction	14,58984375			128,84765625	
Partial sill	0,043110405112			0,077845466314	
Kernel function					
		Spline with tension	Spline with tension		Spline with tension
RMSE	**0,105893712116208**	**0,106734054504029**	**0,104714733552124**	**0,139309643572317**	**0,15479819306803927**

Tab. 1 – Reports of the chosen methods.

1, Fig. 5). Thirdly, we replaced the searching neighborhood parameters of the RBF with those provided by the anisotropic Simple Kriging. This allowed us to integrate the most accurate deterministic method with the geostatistical concept of anisotropy and to further reduce the RBF RMSE value from 0.1067 to 0.1047 (Tab. 1, Fig. 6). Most relevant, this procedure is absolutely original and has no parallels in literature so it should be taken with sensible and careful prudence.

In order to test the potential of this method, we took into consideration the northern half of the port and attempted to create a specific digital terrain model for a 1840 m² wide area around the excavation area '2000', the one with the best preserved and most peculiar wooden structures. We selected, then, 35 points from the original shapefile, obtaining an average density of 0.019 points/m². In this second case, however, the quantitative analysis brought a less clear result: as we could see from the Histogram, the most problematic values were those related to the spatial distribution of the samples, not very close to a Gaussian curve. The Trend Analysis graph seemed to indicate some NW-SE directional trends while the Semivariogram appeared to show the presence of spatial autocorrelation (Fig. 4).

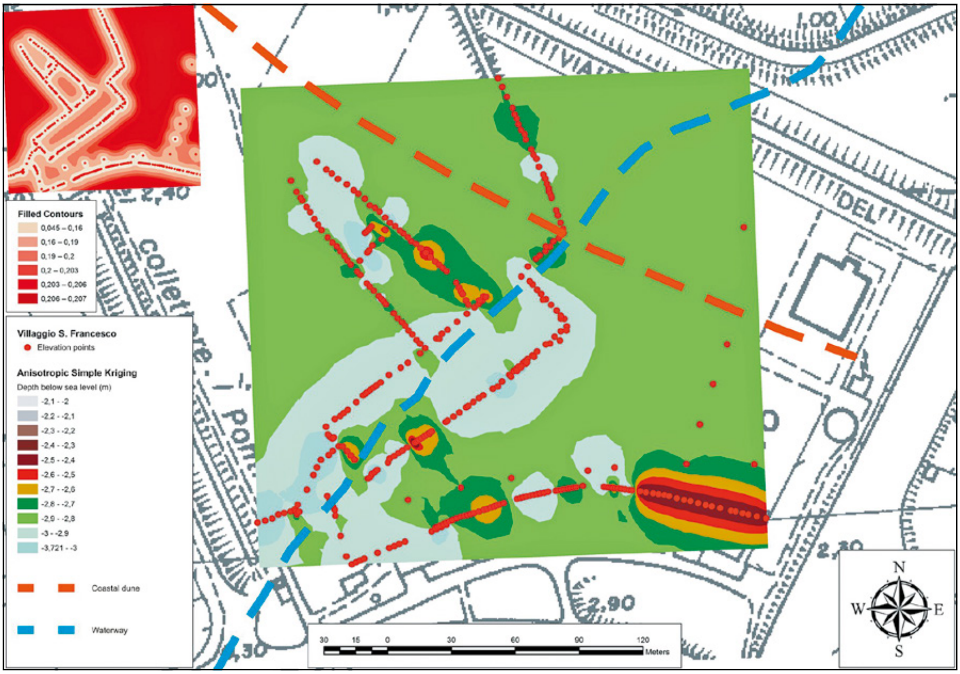

Fig. 5 – Anisotropic Simple Kriging: predicted surface and Prediction Standard Error Map in the top left corner.

Following the same procedure as discussed above, we tested the deterministic and the geostatistical methods, and collected the best RMSE results through a Radial Basis Function (RMSE = 0.1548) and an anisotropic Ordinary Kriging (RMSE = 0.1393) (Tab. 1).

M.V.

3.3 *The 3D reconstructions of the wooden structures*

In order to provide a likely image, a sort of snapshot of some areas of the ancient port, the first part of the work involved the creation of a landscape. To do this we imported the DTM into an AutoCAD 2014 project and built a second DTM drawing 1 cm distanced contour lines. Secondly, we elaborated a polygonal mesh to give the model the actual appearance of a natural surface and completed the "portrait" by adding a water layer at the early medieval level.

We moved then to the reconstruction of the anthropic remains. As a first step we created two shapefiles to collect all the information regarding posts and docks. The "posts" shapefile was made up of more than 900 points, each

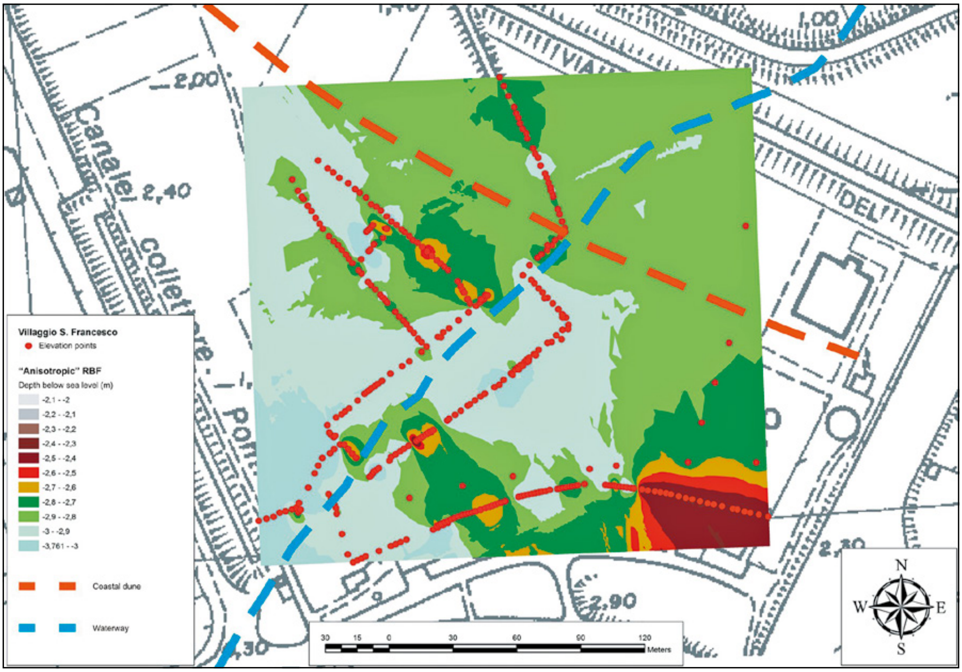

Fig. 6 – "Anisotropic" Radial Basis Function: predicted surface.

of them corresponding to one wooden element; these points were characterized by three attributes: diameter, elevation of the head and elevation of the tip. The "docks" shapefile was instead elaborated as a polygonal vector to represent the areal extension of the platforms, and was characterized by two attributes: the elevation of the surface and the thickness of the planks. The two shapefiles were then imported into the same AutoCAD 2014 project and all the elements were located in their exact topographical position. To give them a more realistic and accurate aspect, the .dwg file generated by AutoCAD 2014 was finally imported into a SketchUp Pro 2015 project where all the structures were given a static texture (Figs. 7-10).

D.V.

4. Results and discussion

4.1 *The early medieval morphology*

Before we started this research, recent studies had already shown that the port of Comacchio was built in close proximity to the coastline in a lagoon area where the water filled the basins between the late Roman dunes (Rucco 2015). We expected, then, the stretch up to the ridges of the dunes. Both the surfaces generated by Kriging and the "anisotropic" Radial Basis Function have confirmed this hypothesis. When the early medieval sea level is fixed at 2.9 m below the present-day surface, the reconstructed water basins follow two expected directional trends: the former, which is consistent with the alignment of the lowlands between the dunes, is NNW-SSE oriented; the latter, which corresponds to the fluvial axis formed by the Motta della Girata and the Marozzo canals[5], is WSW-ENE oriented (Figs. 5-6). Moreover, all the areas that were interpreted as dry lands by the archaeologists of Università Ca' Foscari di Venezia according to stratigraphic data (such as burials) happen to be located exactly in the dry lands of the predicted surfaces: this is a fundamental achievement since we deliberately avoided to include any elevation value coming from these archaeological excavations in the starting shapefiles (see footnote 3). As a whole, these considerations strengthen the reliability of our general models.

The DTMs we produced alongside the analysis of the archaeological documentation led us to conclude that the site was naturally suitable for the construction of a port, and did not need any significant reclamation except for the first thin anthropic deposits we found just above the ancient sea level. On the other hand, all the upper layers are to be seen as the expected result of the normal archaeological growth of the basin.

A.A.R.

4.2 *The early medieval structures*

Nine years ago, in the only study dedicated to the archaeological data collected during the 1996 excavations, Diego Calaon maintained that the wooden posts and planks found in the trenches were to be seen as docks protruding towards the water basins of the port. This interpretation was mainly based on the comparison with similar structures found in North European sites like Dorestad or Birka (Calaon 2007) but it lacked general topographic support and specific morphologic investigation.

As regards the structures situated within the wet areas of the predicted surfaces, our research has confirmed Calaon's hypothesis. Most of the wooden structures we are talking about represented the simplest way to enlarge the walking surface of the dry lands towards the lagoon. This is quite evident in

[5] The Motta della Girata Canal is a late Roman/early Medieval artificial diffluent of the *Padus Vetus* (ancient Po river). It starts some 4.5 km W of Comacchio and reaches the town after dividing at least into two branches. The northern one heads to Villaggio San Francesco and crosses the site. In modern times, the latter portion of this fluvial axis received the name of Marozzo Canal (Rucco 2015).

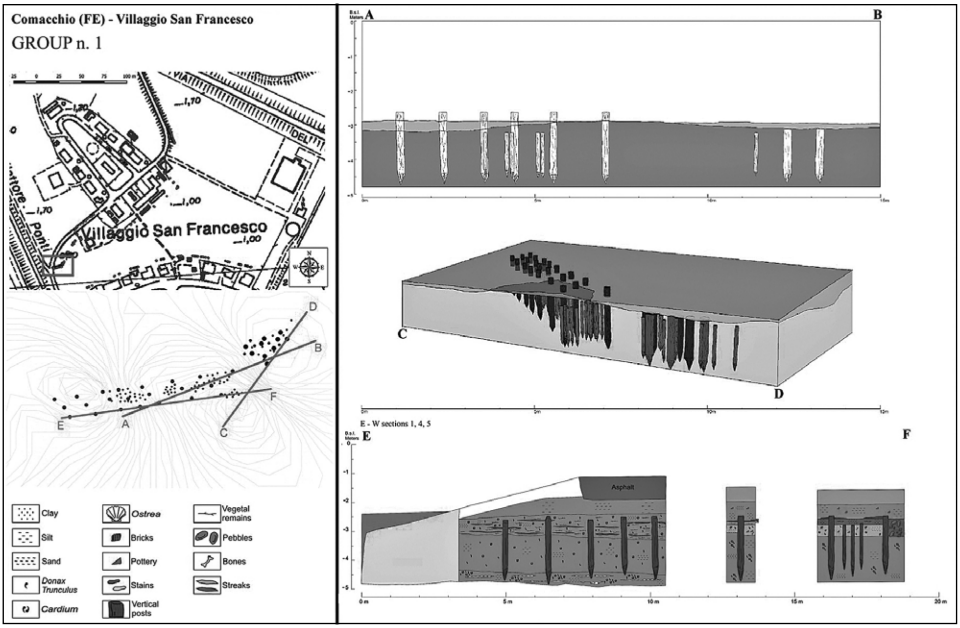

Fig. 7 – The first group of wooden structures.

the case of groups n. 1-2 (Figs. 7-8): these structures consisted of 20-30 cm thick vertical posts upon which rested the horizontal planks of the walkways. Moreover, the wooden surface used to be 20-30 cm higher than the water level (-2.7 m below the present sea level, Fig. 3) in order to face action of the tidal flows. Besides, group n. 1 is a clear example of different building phases: the thin and dispersed poles that we can see among the bigger ones seem to have been part of a previous structure. Furthermore, the average elevation of the head of these posts could indicate a lower sea level.

However, the juxtaposition of the models and the reconstruction of the wooden remains allowed us to recognize another type of structures. They were concentrated in the southern part of the site, where the predicted surfaces have the highest elevation values. From the technical point of view, these structures were not so different from the ones we described before; yet, they were built on the dry land and the horizontal planks rested on the same level of the ground; moreover, in one case, a big rough-hewn stone was found next to the planks on top of the rows of posts. Taken together, all these elements led us to interpret these structures as the foundations of massive buildings (Figs. 9-10). The most significant parallel for such an interpretation comes from the Villaggio San Francesco site itself: during the already mentioned excavations

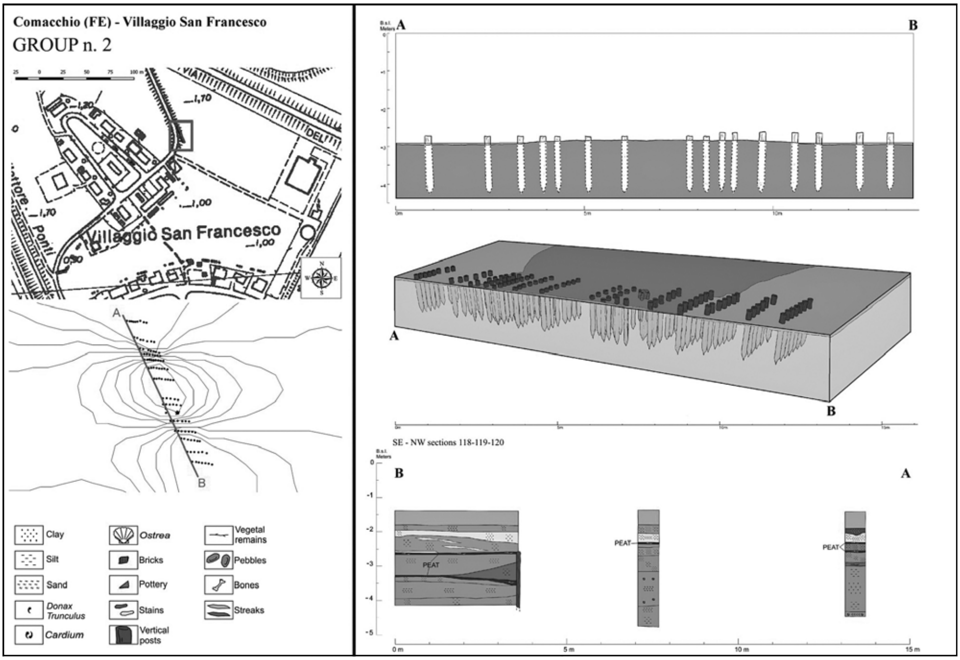

Fig. 8 – The second group of wooden structures.

carried out between 2007 and 2010 (see footnote 3), the archaeologists found a wall made of broken bricks founded just on top of a series of small posts in the area of groups n. 3 and 4.

Finally, among the foundation structures we also put a group of parallel rows of thin posts found nearby the already mentioned excavation area '2000'. There, the remains of horizontal planks are very rare but still on the same level of the ground. However, the frequent presence of wicker all over the area, and particularly between the head of the posts and the planks, stands up peculiarly (Fig. 3, section 146-153), even though this characteristic could be linked to a previous reclamation activity: the heads of the posts could be at the same level of the ground because this one had been previously raised. However, the archaeological evidence coming from the sections we analyzed is not sufficient to confirm this hypothesis.

By the way, the tradition of consolidating the ground with wicker and branches is part of the Adriatic history. An extraordinary parallel comes from recent excavations carried out in the island of Murano (VE). Between the VI and the IX century AD, the site of "ex Conterie" was characterized by several reclamation activities realized through the accumulation of silty and clay

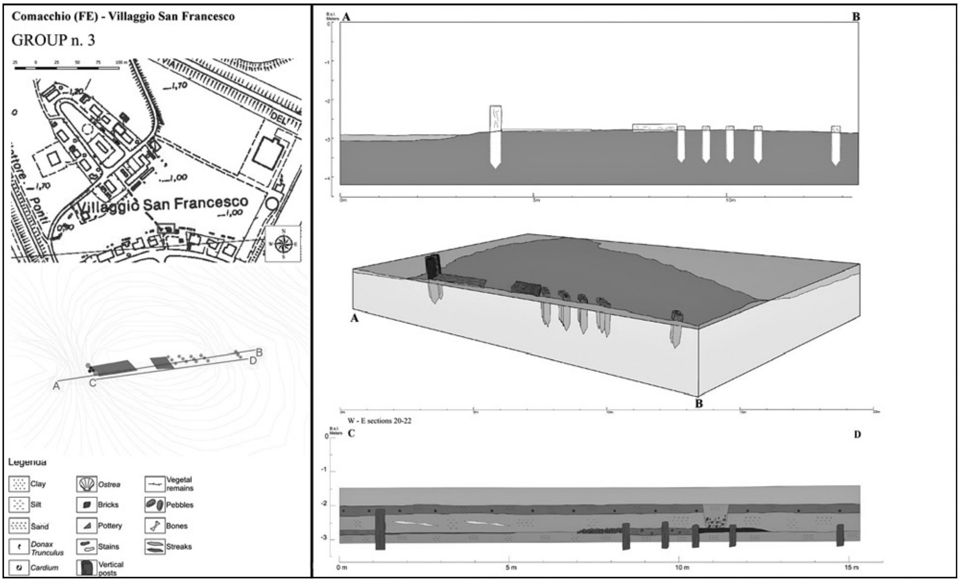

Fig. 9 – The third group of wooden structures.

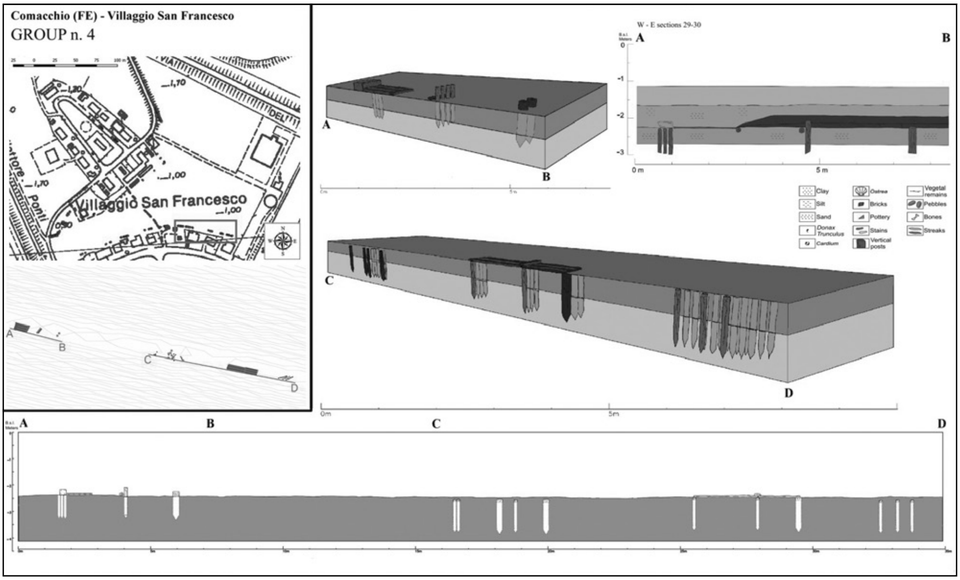

Fig. 10 – The fourth group of wooden structures.

deposits within wooden structures called "volparoni". In some cases, these deposits had been covered by a chaotic shedding of wicker and branches (Cozza, Valle 2014, fig. 22).

A.A.R.

4.3 *Some theoretic notes about the predicted surfaces*

During the calculation and the comparison phase of the predicted surfaces a couple of stimulating issues came to light.

First of all, let us consider the concept of anisotropy which is a clear indication of the existence of directional tendencies. It sounds peculiar that among the geostatistical methods the lowest RMSE values were collected through the anisotropic version of the algorithms, which is absolutely consistent with the buried stratigraphic architecture discussed in the previous paragraph. This is the reason why we decided not to alter the original dataset with detrending operations.

Secondly, some notes concerning the comparison among the four best surfaces deserve to be reported. As regards the general DTMs, both the "anisotropic" Radial Basis Function and the anisotropic Simple Kriging produced a very low RMSE value, which gives reliability to both the predicted surfaces. On the other hand, in the case of the specific DTMs, the significant difference between the RMSE value collected through an anisotropic Ordinary Kriging and the one produced by a Radial Basis Function might force the choice towards the former solution; however, the low number of elevation points taken into consideration for the specific DTMs represents a considerable element of weakness: for this reason, the two specific surfaces must be discarded in favour of the general ones.

Finally, we would like to point out that the surfaces we chose for the above discussed reasons are not a representation of the true aspect of the area but only a realistic sketch based on the interpolation of specific data, which is nonetheless undermined by an error factor that must be measured. For this reason, we chose to evaluate the different results from the same point of view (i.e. the RMSE value), and then to rely on the Prediction Standard Error Map (Fig. 5), which gave us the possibility to assign an error score to every point of the surface generated by a Kriging (the tool is available only for geostatistical algorithms).

M.V.

5. Conclusions

The ancient morphology of the early medieval port of Comacchio was reconstructed through two predictive algorithms, an "anisotropic" Radial Basis Function (deterministic) and an anisotropic Simple Kriging (geostatistical).

Although the two predicted surfaces show slightly different morphologies, both are in significant accord with the buried stratigraphic architecture and with the archaeological data. In this perspective, according to the morphology and the elevation of the ground on which they are built, the wooden structures can be interpreted as docks or foundations. It is particularly relevant that the latter seem to be more frequent in the southern part of the area, the highest one, which is very close to the Santa Maria in Aula Regia monastery, while the former happens to be much more present in the central and the northern part, the lowest and the wettest areas of the site.

As already shown, one of the most significant achievements of the long testing procedure was the acknowledgment of the importance of anisotropy, which can be related to the effects of the buried stratigraphy on the early medieval morphology. Another crucial aspect was the entity of the starting dataset: as we saw while comparing the general and the specific DTMs, the higher the number of elevation samples, the lower the RMSE value, and the better the final result. Moreover, the testing phase allowed us to identify the most important parameters to be set during the interpolation procedure, and to hybridize the deterministic and the geostatistical methods in order to obtain the most reliable prediction surface.

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ABSTRACT

The paper presents a reconstruction of the ancient morphology of the early medieval port of Comacchio through Kriging and Radial Basis Functions algorithms, and 3D models of the archaeological remains. The predicted surfaces are in significant accord with past hypotheses, also providing a good amount of certainty from a scientific point of view, since they appear extremely consistent with the geological data collected through stratigraphic corings. As a whole, the predicted surfaces and the 3D reconstructions of the wooden remains of the port offer fresh perspectives on the interpretation of the site by showing the existence of different building phases and spatial organizations, thus providing new guidelines for future excavations.