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GIS APPLICATIONS FOR THE ARCHAEOLOGICAL ANALYSIS OF A MEDIEVAL TOWN: PISA, ITALY

1. A matter of principle

«Contrary to popular mythology, contemporary professional archaeologists may spend more time using GIS than a trowel» (Wheatley, Gillings 2002, 10), becoming the first interpreters of digital processing of archaeological data, since only those who are aware of the general principles connected to archaeological data recording can arrange the complex relationships required by their rationalization. Archaeology becomes the central point of view, so the development, not only semantic, from Geographical Information System to Archaeological Information System is fundamental. The acronym GIS is not only rather slippery and difficult to define in a precise or meaningful way (Wheatley, Gillings 2002, 9), but it's especially inappropriate in defining the specific nature of archaeological practice. In the analysis of an urban framework is essential to complement the information system, that stores, manages, processes and analyzes historical and archaeological data linking them to a geographical coordinates system, to a larger network, that includes specialists, organizations and institutional arrangements to collect, record, analyze and disseminate data (Favretto 2000, 165), defined with the broader term AIS Solution[1].

2. Pisa's Archaeological Information System

Over the past 10 years archaeological research in Italy has started to create urban archaeological GIS focused mainly[2] in Tuscany: Firenze (Scampoli 2007), Grosseto (Citter *et al.* 2007), Pisa (Anichini 2004-2005), Siena (Fronza, Nardini 2009), and in Emilia-Romagna[3]: Bologna (Pescarin *et*

[1] Pisa AIS Solution is composed of an institutional network of University of Pisa's Archaeological Department (Dipartimento di Scienze Archeologiche), Archaeological Superintendence of Tuscany (Soprintendenza peri i Beni Archeologici della Toscana) and Municipality of Pisa.

[2] The *Forma Urbis* project is one of the few exception (www.aec2000.it/lanciani/html/informazioni.html).

[3] From 1995 Emilia Romagna regional administration is developing the C.A.R.T (Carta Archeologica del Rischio Territoriale Archaeological Risk Territorial Map) System (Guermandi 2001). As far as 2008 C.A.R.T. system was updated for Bologna (town), Faenza (town) e Forlì (town, municipal country, provincial country). http://www.ibc.regione.emilia-romagna.it/wcm/ibc/menu/istituto/04attivita/13progetti/prog/cart.htm.

al. 2002), Faenza (Guermandi 2000, Guarnieri 2001), Forlì (Prati 2001), Modena (Cardarelli *et al.* 2001), Parma (Bigliardi 2007), Ravenna[4].

Pisa AIS was developed to manage heterogeneous data, which drawn the urban archaeological complexity, and to develop effective predictive tools, working on an intermediate scale which allows to analyse how the geographic space have influenced the economical, political and logistic choices. The choice of on an intermediate scale has led to the need to work with both topographical (geomorphologic, hydrographical, toponymic data, etc.) and urban data (archaeological stratifications, buildings, road network, hypotheses of historians and archaeologists, etc.), combining inter-site analysis and archaeological excavation GIS' resources. To combine multi-temporal and multi-scale data, it was necessary to provide for digital data conversion and georeferencering of archaeological excavation data acquired at different times and different scales and the integration and overlap of data obtained with different techniques and diverse topographical reliability and precision. To enable proper processing queries, it was necessary a comprehensive geographical and archaeological data entry, according to a consistent use of geometric primitives for reproducing vector objects. As a general principle it was decided to use points for georeferencing data with inexact location, surfaces (polygons) for georeferencing data with exact location, lines for georeferencing linear data with exact location.

Archaeological excavation data entry was based to the principles of archaeological stratigraphy (Nardini 2000), archaeological plans coming from a complete archaeological dataset or from a partial archaeological dataset have been addressed through an identical graphical representation, but using different files. Deposit is drawn as polygon, cut and symbol as line[5]. The inclusion of interpreted data developed by previous researchers[6] has been solved by drawing the same feature on two different files: the first one contains the real object, the second one the interpreted object. Typological analogous data, but gathered from sources with different reliability, have been distinguished through codes of trustworthiness. The frequent change of use of the same object has been undertaken linking the feature with an apposite RDBMS table, while the change of shape of an object which maintained the same use has been undertaken drawing two features with different attributes (Nardini 2004, 367). To summarize the AIS includes:

– geographical data;
– urban data;

[4] http://www3.unibo.it/archeologia/arcmed/progRa.htm.

[5] It has been opted to not use symbols for partially documented archaeological excavation data, to underline data incompleteness. Partially documented archaeological excavation data have a well-constructed attribute table, because they aren't linked to RDBMS.

[6] Interpreted data are essential information (Nardini 2004, 366).

– historical cartography data;
– all archaeological data from occasional findings to stratigraphical excavations.

For locating all the available data, different cartographies have been used: regional cartography (scale 1:5000 and 1:10.000) to describe the extra-urban territory; vector maps furnished by the Municipal Administration to reproduce the urban space. The AIS has been elaborated through the proprietary software ArcGIS 9.0 licensed by ESRI. This is a pragmatic, not ideological, choice related to the use of this software by the different partners of the AIS solution and to the perfect compatibility with MSAccess used for the RDBMS, based on the use of Visual Basic. Not a secondary factor, the digital format ESRI.shp is a standard format for vector data, that allows the exchange and the processing of data even with open source software.

3. Spatial analysis

This article describes the procedures related to the creation of the DTM of medieval town and the analysis of the marshy areas.

3.1 *Digital Terrain Model of medieval town*

The creation of medieval Pisa DTM meets the need to understand the urban settlement's choices especially in relation to the distinguishing environmental context to which the town was connected, characterized by a complex hydrographic system with wide marshy areas. The preliminary phase consisted in the analysis of the different models of interpolation, aimed at the choice of the method that best allows to calculate unknown values based on known values in their proximity. The elevation data were derived from different archaeological excavations – for which it was possible to trace the absolute dimensions with a degree of reliability exact or calculated and were georefered as points. Only 9 accurate elevation data are available for the Early Middle Ages (8^{th}-10^{th} century), whilst 91 accurate elevation data are available for the Late Middle Ages (11^{th}-12^{th} century) (Fig. 1).

It was, therefore, rejected the idea of creating a DTM for Early Middle Ages town. It was necessary to take into account the presence of the Arno River, which crosses from East to West the city. Archaeological evidence indicates that the route of the Arno river is essentially stable since the Late Middle Ages, so the bed of the river was considered very similar to the current average that is equal to -3 m above sea level[7]. Overall, the elevation points' location appears irregular, concentrated in the central portion of the city and lacking in eastern e

[7] http://geodataserver.adbarno.it/sezioni/viewer.htm.

southern areas. This kind of points' location fits well with kriging geostatistical interpolation. I have preferred to verify the validity of two different interpolation methods: IDW[8] and Kriging[9], excluding immediately TIN[10], because of its intrinsic preference for a more regular points' location, and Trend surface analysis[11]. The comparison between the two different interpolation methods was made on the basis of the calculation of root mean square deviation, that is the measure of the differences between the values predicted by a model and the values actually observed from the object being modeled[12].

[8] The Inverse Distance Weighting (IDW) interpolation produces a raster model. IDW interpolation becomes more accurate as the number of known values increases and as the distribution of values is more regular. The unknown values depends to a greater extent by the closest points, since the influence of a known value on an unknown value is weighted in inverse proportion to their distance (Forte 2002, 152; Wheatley, Gillings 2002, 193). This is an unconstrained method in which the result does not pass through the data points, but uses the points to approximate the value within both sampled and unsampled locations.

[9] The Kriging interpolation is a geostatistical, unconstrained method which produces a raster file. It is used in cases where both the distribution and density of the points are irregular. The method is based on the autocorrelation, i.e. the characteristic of the environment's properties of being in relationship with each other at some scale, which means that the sampled values in nearby locations tend to have similar behaviors, while values of the same variable measured in samples collected in places far from each other tend to have different behaviors, or at least tend to differ from the average values. Thus, the correlation between the values of the variable tends to decrease with increasing distance. The Kriging and IDW are conceptually similar and in fact the value of the unknown point is given by the weight of the known values around it and of the distance between them. The main difference is that the weight given to the points depends on the spatial structure and on the degree of distribution's spatial autocorrelation. To calculate the weights to be given to values around the unknown point, Kriging interpolation uses a semivariogram, that relates the distance between two points to the influence that these points have upon one another. The semivariogram contains three basic parameters:

– Range: the maximum distance within which there is an autocorrelation;
– Sill: the maximum value reached by semivariance;
– Nugget: unexplained part of the semivariance. It is due to measurement errors, instrumental errors and to the spatial variability present at a distance less than the minimum sampling distance (Terrosi 2007, 295).

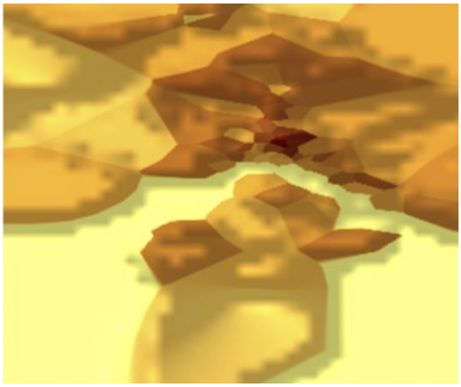
The semivariogram exhibits the value of spatial dependence, i.e. the autocorrelation. To obtain a continuous function the semivariogram should be combined with a mathematical model necessary to describe the general trend of spatial variation. The most used are circular, spherical and exponential model. The first two show a decrease in autocorrelation, until it becomes equal to 0 at a certain distance (range). The exponential models are applicable in the presence of an exponential decreasing of autocorrelation with an increasing distance.

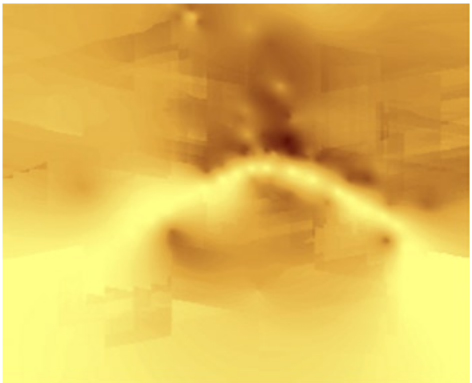
[10] The Triangulated Irregular Network (TIN) is a constrained method that produces a vector model that creates a network of triangles; each triangle that forms the network is created from a series of three points (mass points). The values of the model correspond to the known values, while the unknown ones are placed on the flat sides of the triangles, so the results is a faceted surface model. This vector model allows the calculation of derivative maps such as slope and aspect (Wheatley, Gillings 2002, 112).

[11] The Trend surface analysis is not appropriate for approximating complex surfaces such as topography (Wheatley, Gillings 2002, contra Terrosi 2007).

[12] The root mean square deviation (RMSD) or root mean square error (RMSE) is calculated by omitting a value between those used for calculating and using the remainder for the estimation of value in that location. The two values, those measured and those estimated, are then compared to measure the error. This comparison is repeated for all the values at which a measurement was made. The root mean square deviation of all differences becomes the measure of the validity of the estimate. The closer the value approaches 0, more the interpolation approaches the real values.

Fig. 1 – The location of the 91 elevation data available for the Late Middle Ages.

2 

 3

Figs. 2-3 – 2. The DTM obtained using *IDW* interpolation; 3. The DTM obtained using *Kriging* interpolation.

Using IDW interpolation (Fig. 2) with the following parameters:

Method Parameter(s): Power: 80,73
Searching Neighborhood:
Neighbors to Include: 5 (include at least 5)
Searching Ellipse:
Angle: 0
Major Semiaxis: 150
Minor Semiaxis: 310
Sector Mode: 2

we get a root mean square equal to 0,76.

Using Kriging interpolation (Fig. 3) with the following parameters:

Selected Method: Ordinary Kriging
Output: Prediction Map
Number of datasets currently in use: 1
Number of Points: 122
Semivariogram/Covariance:
Model: 30*Circular[13] (2382,3,1984,9,304,9)
Error modeling:
Microstructure: 1,9186 (100%)
Measurement error: 0 (0%)
Searching Neighborhood:
Neighbors to Include: 5 or at least 5 for each angular sector
Searching Ellipse:
Angle: 305
Major Semiaxis: 2382,3
Minor Semiaxis: 1984,9
Angular Sectors: 8

we get a root mean square equal to 0,63.

3.2 *The wetlands: marshes and swamps*

During the Middle Ages, the plain of Pisa was characterized by the presence of wetlands and marshes (Baldassarri, Gattiglia 2009) to get an idea, the more likely one of the extension of these areas, can assess their impact on the development of Pisa. GIS analysis, developed to locate possible marshy areas, has required complex operations[14] generated through a large

[13] It was decided to use the circular model because it gave the lower root mean square deviation.

[14] The process created is inspired by Macchi Jánica 2001 and Citter, Arnoldus-Huyzendveld 2007a, b.

amount of data from various sources analyzed through map algebra[15]. First of all geographic data: terrain elevation, assuming that the areas located at lower altitudes, in our case close to or even below sea level, are more prone to flooding; slope, considering the flattest land the more likely to flood; sunken areas or internal drainage areas. Then geopedological data through the use of the soil map (Arnoldus-Huyzendveld 2007; Volpe, Arnoldus-Huyzendveld 2005) and of CAR.G. (Regional Geological Cartography), considering the land of lakes, marshes and reclaimed areas the most suitable wetland areas. Finally toponymic data[16] with the identification of place names related to the presence of wetland areas and place names found in medieval documents in order to insert a chronological characterization.

The spatial analysis of data, duly reclassified and processed by using the raster calculator function, has created a map of areas potentially flooded in the medieval period. A fundamental part of this phase of work consisted in reclassification, i.e. the assignment of parameter values to the series of data obtained, from which depended the final result. The first stage focused on the geographic data. I have created a DTM of the examined territory related to

[15] Map algebra (Tomlin 1990) allows operations with raster data and represents one of the most important GIS analysis. In addition to standard arithmetic addition, subtraction, division and multiplication, this particular type of algebra also accepts the relational operators, i.e.<, >, =, etc. The logical operators AND, OR, XOR, NOT are also used and statistical, trigonometric, logarithmic and exponential operators. A prerequisite for the application of map algebra is that the input maps should have all the same resolution and be aligned to the pixel. Besides being able to act on individual cells, map algebra can also work with groups of cells to solve complex problems. Four types of functions are applicable to a raster:

– Local calculates the output raster based on the value contained in the cell of input raster processed by the function applied without taking into account the adjacent cells. The local functions are trigonometric, exponential, logarithmic.

– Focal calculates the output raster on the basis of the values of a number of adjacent cells, which is called focus. The selection of surrounding cells is established through a form defined by user and centered on the cell considered. Focal functions are those that calculate the standard deviation, the sum, the change of values in the immediate or extended vicinity of a given cell.

– Zonal calculates the output raster based on a comparison between two rasters. They do not operate on a single cell, but on groups of cells defined in a specific area; in the first input map are defined the values on which the operator acts, in the second input map are defined the input areas, creating a mask on which operations will be carried out. The result of these operations will be reported in the output raster.

– Global estimates the output raster cell values based on the algorithms applied to cells of the input raster. The global operators calculate the output raster by taking into account the values of all cells in the input raster. An example for this type of operator is the Cost Surface Analysis.

Map algebra operations should pay particular attention to input raster that contains the NoData value. This is not considered, in fact, equal to 0, but corresponds to an absence of data, so any operation involving a NoData cell in the input raster will produce a NoData cell in the output raster, so it is preferable to assign the value 0 to NoData, working through reclassification tools.

[16] The toponymic data have been handled by the method of Thiessen polygons. In fact one can easily assume to be true, that each name has the same importance, or weight, and thus its range is defined by the distance to other names of equal importance. The application of this principle has been used to define the areals of current (Thiessen_toponimi.shp) and of medieval toponyms (Thiessen_topo_med.shp). In the case of medieval toponyms we have to consider a greater uncertainty due to the difficulty of locating them and to the disappearance of some names.

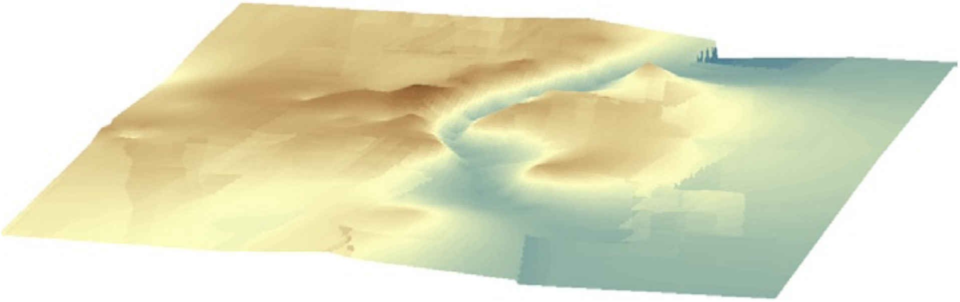


Fig. 4 – The three-dimensional reconstruction of the ground of late medieval Pisa.

the Middle Ages. Not being able to implement a medieval DTM due to the lack of sufficient elevation data related to the Middle Ages for such a wide area, it was decided to elaborate a DTM on current elevation data with the exception of post-medieval coastal advances[17]. From the resulting TIN file a raster DTM file was created with a resolution of 25 m per cell[18].The latter has been reclassified on the basis of the elevation values from 1 to 6, giving the highest value to areas with lower elevation, those more likely to be flooded. The raster DTM was also subjected to the function slope, expressed as the percentage of slope, and then reclassified (Fig. 5, Pl. V, a) compressing the values on a scale from 1 to 5 in order to assign higher values to areas with a lower percentage of inclination, i.e. areas with presumed greater propensity to flood. Latest data relating to geography are those of sunken areas: the raster DTM file was submitted to the sink function, reclassified with values from 1 to 5, in which higher values indicate areas more prone to be sunk.

The second stage focused on the pedological and geological data. The pedological data derived from the pedological vector map[19]: through a selection by attributes I identified lacustrine, fluvial-lacustrine and peat soils. The selection file was converted to raster and reclassified by assigning the values 10, 8, 4 and 0 to NoData. The geological data were obtained from geological vector map (CAR.G), through a selection by attributes marsh deposits and areas related to land reclamation have been identified and then reclassified by assign-

[17] I chose to use the 16th century coastline to take into account the progress of the shoreline during the medieval period, and to exclude all elevation points to the West of this line. This method is only partially regressive and therefore is not reconstructive. See Celuzza *et al*. 2007, 221 ss.

[18] The option of using 25 meters cells is linked to the desired degree of accuracy over an area of 350 km², that is related to the purpose of evaluating the likely, not the real extension of wetlands on Pisa area.

[19] Soil map of Tuscany (scale 1:250.000) is downloadable from http://sit.lamma.rete.toscana.it/websuoli/.

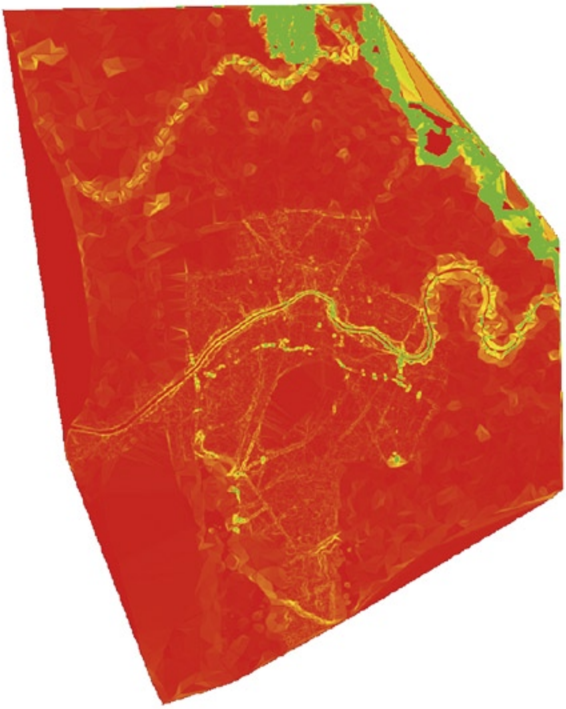


Fig. 5 – The reclassification of slope function applied to the DTM.

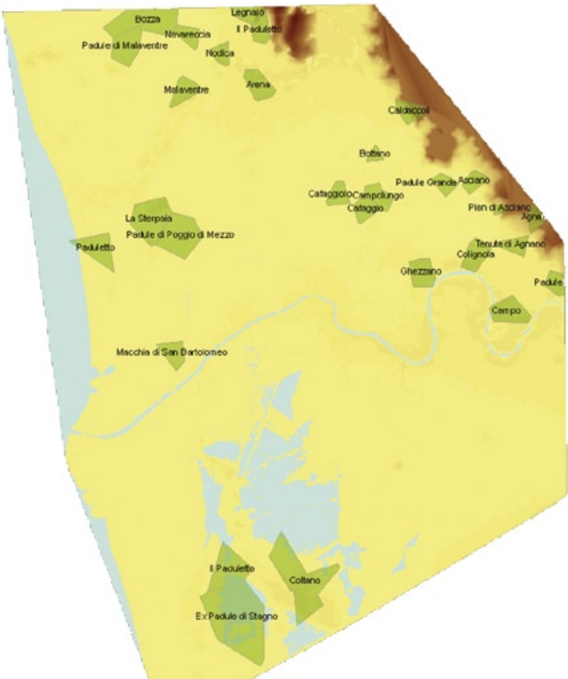


Fig. 6 – The *selection by attibutes* from toponymic vector map of features connected to marshy areas or mentioned as marshy areas in medieval documents.

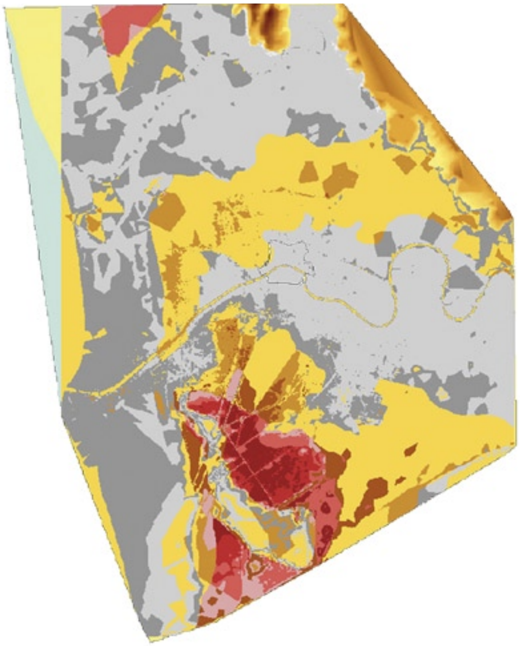


Fig. 7 – The map of potentially marshy. Reddish areas represent high potential for flooding; yellowish areas represent medium potential for flooding and greyish areas represent low potential for flooding.

ing the following parameters: 5 to marshy areas, 3 to land reclamation, 0 for all other land. The third stage consisted in the creation of the polygon file related to the toponyms, that has been created through a selection by attributes from toponymic vector map of features connected to marshy areas or mentioned as marshy areas in medieval documents. Selection has allowed the creation of the polygon file (Fig. 6, Pl. V, b), which was first converted to raster and then reclassified by assigning the value 3 to all toponyms selected and 0 to NoData. The final phase of the work consisted in map algebra analysis. Through the raster calculator the assigned values were summed and then reclassified from 1 to 10, as increasing values of the flooding potential. Overall, the geographic data weight 47%, geopedological data 44% and toponymic data 9%; the low incidence of toponymic data is due to their lower accuracy.

The resulting map of potentially marshy areas was split into three different color scales (Fig. 7, Pl. VI, a) representing the areas of high, medium and low potential for flooding. By overlaying the urbanized areas, for which the geological data is absent, it is clear how the data in some areas may be slightly underestimated by the absence of records. In fact, if we do not take into account the geological data as a whole, precisely because of the impact of urban areas, and we calculate the new raster file, we see a substantial coincidence of data in areas of high potential, but an increase in areas with medium potential in spite of those with a low potential. The last phase of the work consisted in comparing the results of spatial analysis and archaeological data for confirming the presence of marshy areas in areas identified as flooding. 31 different archaeological excavations have identified deposits related to medieval marshy areas: 29 are located within the area of medium potential while 2 are outside the areas potentially flooded. One result appears to be completely in contrast, i.e. the one represented by the presence of a early medieval necropolis in the area of medium potential, probably originally placed on a slight relief, flattened as a result of the intense post-medieval agricultural use. The results show the substantial validity of the model obtained, so the high and medium potential areas of flooding can be considered as areas actually flooded in the Middle Ages (Fig. 8, Pl. VI, b).

4. Raw data now!

The particular attention to the aspect of management of the archaeological raw data, which represent essential information for the next phase of analysis, led to the creation of a data store, that constantly implemented and made accessible, may serve to further future analysis (Gattiglia 2009). Making data available means to allow comparing data between each other. In general terms, it was decided to give up a concept of absolute objectivity, attempting to objectify the subjectivity, i.e. to explain the methodological background used in the encoding of digital data. This process does not change the formalization of the data taken by the individual researcher, but ensures the encoding of information on more abstract formal models, since it records through metadata the reasons and circumstances of the creation of a digital source, the details of its origin, its content, its structure and the terms and conditions applicable to its use, allowing both an extensive and continuous use of the data. In this way all data related to every single archaeological excavation (archeographic data, structure and format of digital data) were stored in text format, according to the chart below, to record the history of the data formation and to streamline search, location and selection operations and to make information accessible to everyone, even at a distance of time and space (Gattiglia 2009):

History of the investigation

– purpose
– issues
– methodology
– type of archeographic record
– geographical coordinate
– chronology
– scientific Director/excavation team
– more…

Sources used to create data

– questioned archives
– cartography used for georeferencing data
– previous archaeological investigations
– method and data structure
– creation of the dataset
– georeferencing data
– cartography used for georeferencing data
– list of files and their contents
– list of ID assigned
– list of codes and their meaning
– Thesauri
– systems used in data acquisition
– conversions to other formats.

Staff

– reports
– bibliography
– place of storage of archeographic record
– place of storage of findings
– more…

Data dissemination involved the selection of formats that allow for a wide possibility of interchange[20]. Databases created in MSAccess 2003, will be disseminated in.xml (Signore, Missikoff, Moscati 2005, 299), that is designed as a meta-language suitable to represent web content and information from databases and allowing the description in a hierarchical form of text content. XML is well suited to store in a transparent and flexible way archaeological data (D'Andrea 2006, 51) and its transparency[21] is an advantage compared to proprietary database formats and to the problems related to the continuous evolution of software. CAD files were created in Autodesk proprietary formats. Actually there are no standard formats for exchanging

[20] The digital data were produced for the most part with proprietary software. Although this choice may be questionable, it is also true that the open source represents the possibility of adopting alternatives, rather than a complete "conversion" (Pescarin 2006, 138), and the proprietary software represents the majority of the software we have to deal with in the creation of digital archives. The basic concept of the open data, in fact, pragmatically, is not, or not only, how the data has been created, but rather that they are shared and made available to the archaeological community. Therefore the choice of dissemination formats has been made with the idea of reaching the widest possible audience. It was not planned for any future implementation of the data, any difference between the native and the dissemination format, as expected to more complex projects such as the ADS archive.

[21] «Documents should be human-legible and reasonably clear» (http://www.w3.org/).

Fig. 8 – The result of this process is the hypothetical model of the landscape in the Early Middle Ages landscape (left) and in the Late Middle Ages (right), with the extent of the marshy areas, the road network and the rivers.

data between different CAD software. It was decided therefore to use the most common formats[22] which are AutoCAD AutoDesk.dwg and.dxf[23].Therefore we chose to distribute CAD files with these two formats although they should constantly be migrated to the latest version[24]. The GIS files were created with ESRI ArcGIS and will be disseminated in .shp. Images will be disseminate in JPEG format[25], which is open source and is also the standard for compressing photographic images. The text files will be disseminated in .pdf and in

[22] Since there are multiple files in a particular format more converters outcome for that format.

[23] http://ads.ahds.ac.uk/project/goodguides/cad/sect45.html.

[24] OpenDWG Alliance http://www.opendesign.com/ strives to make.dwg format an open standard.

[25] http://www.jpeg.org/.

Open Document Format.odf, standard format for saving and exchanging office documents, thanks to approval by ISO in 2006. Spreadsheets will be disseminated in .xls format, that is read by OpenOffice.org, Calc, Gnumeric, KSpread and Neo Office. For metadata the Dublin Core (DC)[26] has been adopted, born in the library field and managed by the Dublin Core Metadata Initiative (DCMI).

Type	Native format	Dissemination
Databases	MDB	XML
CAD	DXF, DWG	DXF, DWG
GIS	SHP	SHP
Images	JPEG, TIFF	JPEG
Spreadsheets	XLS	XLS
Texts	ODF	ODF, PDF
Metadata	ODF	ODF, XML

Table 1 – Native formats and dissemination formats.

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[26] http://dublincore.org/.

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ABSTRACT

The main use of GIS in archaeology is connected to regional research or management of excavation data sets. The use of GIS for urban archaeological research is far less extensive. The urban GIS about the medieval town of Pisa contains all archaeological data from occasional findings to modern stratigraphic excavations, geographical data, historical cartography data and urban data, each described by the geometrical shape (point, line, polygon) that best represents each feature. The distinguishing environmental context to which the town is connected is characterized by a complex hydrographic system; GIS analysis enabled us to study the relationships between the urban transformations and the surrounding environment. The article explains how geostatistical analysis allowed us to create a model of the ancient landscape and how the use of map algebra was useful in understanding the medieval environment. The difficulty in finding raw archaeological data, that is, all the excavation and fieldwork recording (planning of context, context recording sheet, photographs, findings quantification sheet), suggested the necessity to create an open digital archive and to provide possible standardization of digital formats, metadata records and archaeological data recording, so as to allow a comparison between the data.