Caterina Balletti*

Digital elaborations for cartographic reconstruction: The territorial transformations of Venice harbours in historical maps.

Keywords: Historic maps; georeferencing; geometric transformations; DTM; modelling.

Summary

The territory image given by historical cartography constitutes a very concrete base for a diachronical analyses of territory that involves in physical, historical, economical and social elements. The aim of historical analyses through cartography is to understand the present trim of territory, that is the result of antique choices, and to evaluate critically the evolving dynamics: past interventions condition present situation, such as today interventions would condition the future. The basic processing of georeferencing historical maps respect to today cartography makes the individuation and the application of innovative methods necessary to recover the metric and topological content of maps, for a both qualitative and quantitative reading.

The research presented in the paper is about a very important theme for the city of Venice and it describes planning and realizing works for safeguarding harbour activities in the past, to support the new interventions.

Maps (from the XVth century to our times) are meaningful documents to understand the development of a very delicate part of Venice, which received, during centuries, a constant and extended attention and competence by the Serenissima Magistracy. The work was about the definition and the application of rigorous methods of georeferencing and of 3d cartographic representations coming from computer graphic field which are not yet employed in ordinary practice. In our society, where visual communications has assumed a essential rule in information's spreading, cartogramphic documents, fitted to new technologies, can represent a easily perceptible and extremely incisive message in territory information's communication.

Cartography selected

For the study of the territorial transformations of the sea openings of Venice, a selection of maps that cover a period from 1500 to our days was used; these maps are important documents to understanding the evolution of this delicate part of the city of Venice, since the areas object of the study have always been the object of attention and interest by the city magistrature.

Historical cartography returns a precise image of the geographic reality of time, unique and priceless evidence of the phenomena that, as Marinelli writes (1881) "no oral or written description would be enough to describe them." Study of the historical cartography starting in 1500 allows us to describe the great planning and construction jobs of the sea openings guaranteed effective port use of the city of Venice.

* Università IUAV di Venezia – laboratorio di fotogrammetria – Circe, s. croce 1624, 30125 Venezia. [balletti@iuav.it]

Cartografia utilizzata per l'analisi dei profili di costa	Cartografia utilizzata per l'analisi dei fondali
• Cristoforo Sabbadino, Laguna di Venezia, XVI secolo. • Anonimo, Venezia e le sue isole, XVII secolo. • Anonimo, Laguna di Venezia, 1718. • G. Zuliani, G. Pitteri, Laguna di Venezia, 1784. • A. Grandis, A. Sandi, Laguna veneta, 1799. • A. F. von Zach, Carta militare topografico-geometrica del ducato di Venezia, 1798-1805. • A. Denaix, Laguna di Venezia, 1809-1811. • A. De Bernardi, Laguna veneta, 1843-1844. • G. B. Tonegutti, Laguna veneta, 1845. • Anonimo, Laguna veneta, 1866. • Magistrato alle Acque di Venezia, Carta topografica della laguna di Venezia, 1897-1901. • Ufficio tecnico LL.PP. del comune di Venezia, Laguna di Venezia, 1910. • A. Michieli, Laguna di Venezia, 1919. • Magistrato alle Acque di Venezia, O. Bernardi, Idrografia della laguna veneta, 1931. • Magistrato alle Acque di Venezia, Venezia, 1934. • O. Bernardi, Laguna di Venezia, 1937.	• A. Denaix, Laguna di Venezia, 1809-1811. • Magistrato alle Acque di Venezia, Carta topografica della laguna di Venezia, 1897-1901. • Magistrato alle Acque di Venezia, Venezia, 1934. • Carta Tecnica Regionale, 1984. • Magistrato alle Acque di Venezia, Aggiornamento delle batimetrie delle bocche di porto, 2003.

Table 1. The maps used

Methods of georeferencing

Georeferencing a *raster* image consists in assigning cartographic coordinates to each pixel of the image so that it can be superimposed on topographic maps.

Superimposition is obtained by digital images of geometric conversion and resampling: the geometric conversion is the process by which the grid of the original image is transformed into a new grid with the use of appropriate polynomials; resampling is the process that leads to assignation of the radiometric values of the pixels related to the new grid, according to the values of the original pixels.

The process of geometric transformation is done by identifying a series of control points that can be drawn from a map or a reference image containing the Cartesian reference system.

The geometric conversions applicable to a cartographic image can be classified into two categories: global and local transformations.

Global transformations are those whose parameters are valid for any point of the image after the modellation is chosen and calculated prior to transformation. The position of each point will be calculated by applying the parameters calculated based on the control points. These are the traditional plane transformations that biunivocally relate a system of points to another set of points, realizing the transition from the (o, x, y) system to the (O, X, Y) system.

These global transformations are used in the referencing procedure such as general transformation. At the same time, they are used to evaluate the presence and distribution of the deformations through an analysis of the residuals.
The general equation that regulates the passage between the two cartographic reference systems is represented by an "n" order polynomial such as:

$$X = \sum_{i=0}^{m} \sum_{j=0}^{n} a_{ij} x^i y^j \qquad Y = \sum_{i=0}^{m} \sum_{j=0}^{n} b_{ij} x^i y^j$$

which after being developed, assumes the form:

$$X = a_{00} + a_{01}y + a_{10}x + a_{11}yx + a_{02}y^2 + a_{20}x^2 + a_{12}xy^2 + a_{21}x^2y + a_{03}y^3 + a_{30}x^3 + ...$$
$$Y = b_{00} + b_{01}y + b_{10}x + b_{11}yx + b_{02}y^2 + b_{20}x^2 + b_{12}xy^2 + b_{21}x^2y + b_{03}y^3 + b_{30}x^3 + ...$$

The procedure that uses these polynomials is known as *rubber-sheeting*. If only the linear terms are considered, it leads to the linear transformations.
The equations are met exactly if the number of points known n is equal to ½ p, where p is the number of parameters taken into consideration. Clearly, if a large number of known points is available and an exact solution is required, a high degree of polynomials must be used.
In this case, non-linear transformations of an order equal to the second are used. In general, a higher than necessary number of points is used and the value of the parameters is estimated to the least squares; in this way, it is possible to evaluate the results of the transformation through the study of the distribution of the residuals, index of the "efficiency" of the transformation with respect to the two sets of points used.
The parameters of local transformations are calculated for each individual point of the image and have local validity. The objective is to deform only a part of the image without the rest undergoing substantial modifications. These use algorithms based on two different principles, which are:

- deconstruction of the dominion into finite elements,
- creation of force fields.

Algorithms based on the first principle have been used in cartography and are also implemented in some commercial software. On the other hand, the ones that only use the latter have been used only in computer graphics to obtain *warping* and *morphing* effects.
The local approach offers the advantage of enabling optimal adaptation of the image to modify with respect to the reference points. In general, there is an exact transformation for the known points and an approximate transformation for the others. Given that all the points are used, it is not possible to check the result of the operations using the usual statistical elements of error theory.

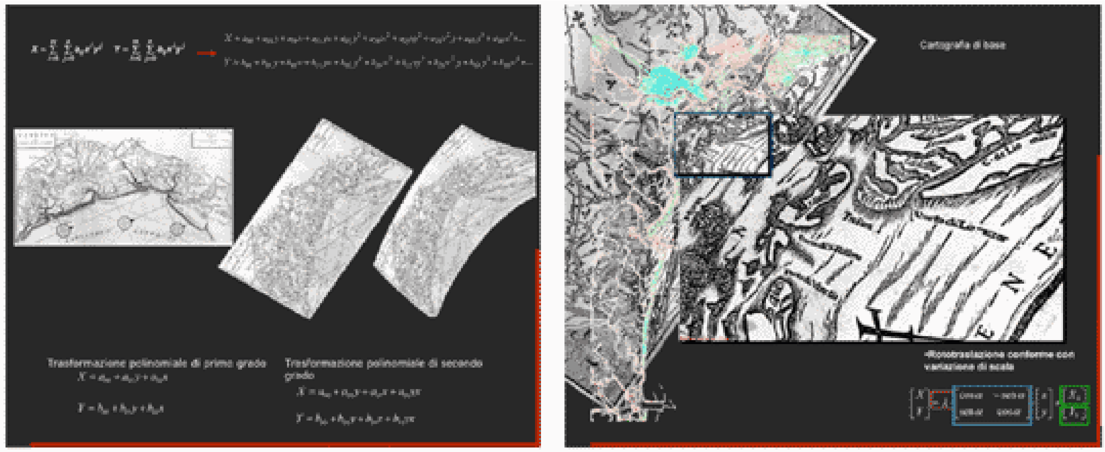


Figure 1. Effects of georeferencing: first and second degree polynomial transformations at left; transformation of helmert and warping at right

The geo-referencing procedure studied and applied by the authors foresees two subsequent steps: in the first, there is a global transformation that permits a general geo-referencing or elimination of the quantitatively greater differences between the two maps, which follows application of local transformations that make it possible to refine the results obtained in the previous step. An affine transformation was applied, while in the oldest maps and with diverse models of representation (perspective views or hybrid models) a roto-translation was applied with a variation of scale, intervening with local point-based warping transformations.

Extraction of geographic data

The georeferencing procedure makes it possible to obtain a historic series of maps in the same reference system, which in this case is official Italian cartography. The data that can be extracted from the maps are uniform and can be compared.

The study concentrated on two aspects of the morphological evolution of the sea openings: the progression of the coastline since 1500 to the present and evolution of the bathymetry of the sea floor pursuant to creation of the outer jetties (period 1809-2003)

The data was extracted respectively by digitalizing the coastlines and by numbering the bathymetric levels.

In the first case, by overlapping the profiles extracted from the maps considered, it was found that the coastline has remained essentially unchanged since construction of the outer jetties (Malamocco 1856, Lido 1897, Chioggia 1934). Afterwards, the coast underwent numerous changes, which in the span of a century have led to creation of new areas of land, clear especially in the area of Punta Sabbioni, Ca'Roman and Sottomarina.

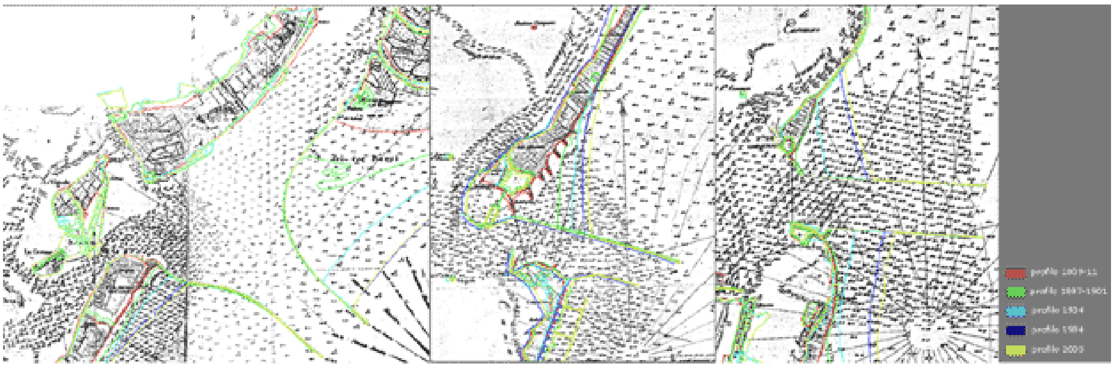
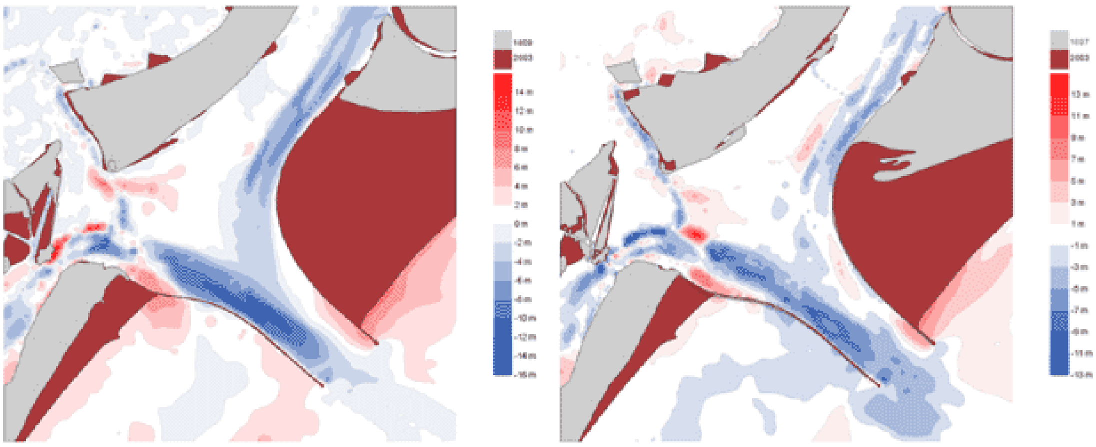
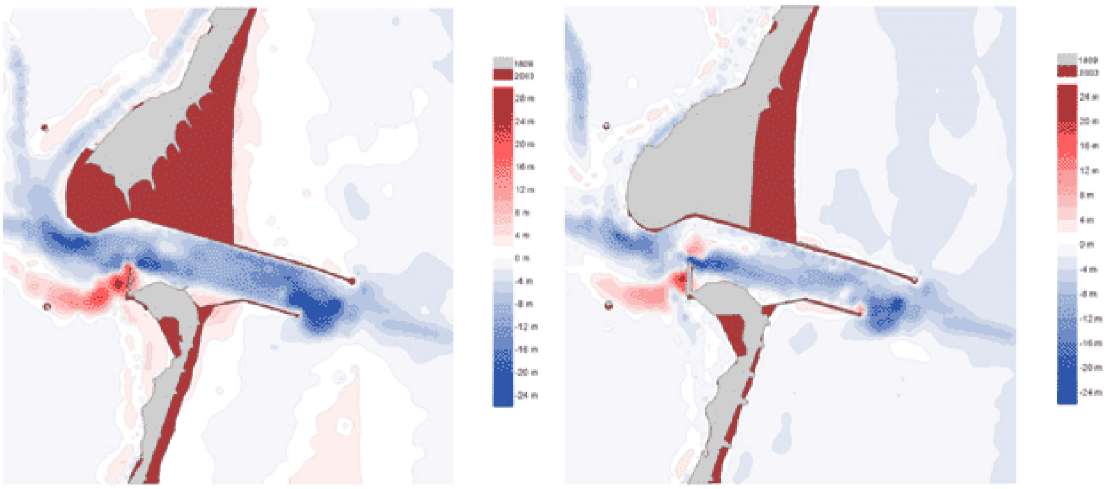


Figure 2. Comparison between the profiles of the sea openings from 1809 to 2003

A comparison of the digital models of the depths (DEM obtained based on the levels extracted) which describe the surface of the floors of the sea openings has made it possible to follow the changes in the floors, showing the excavation and interment areas.

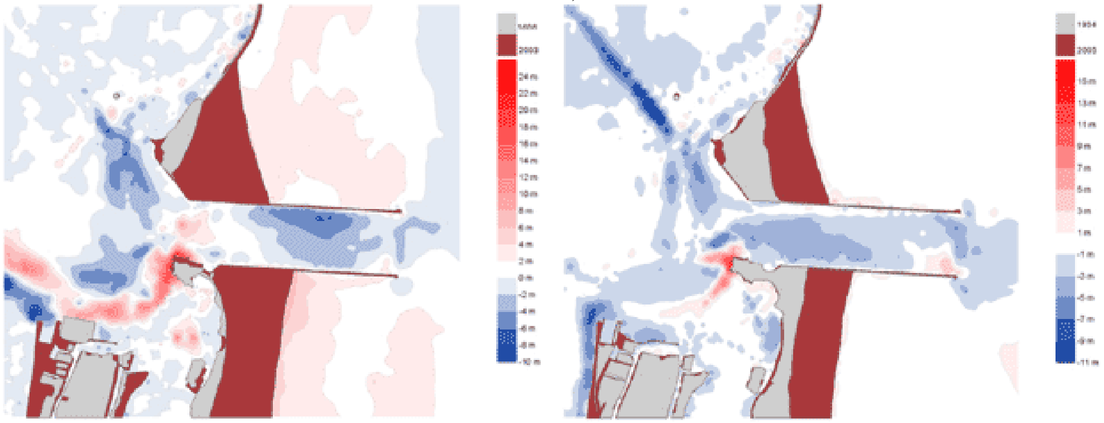


Figures 3-4. Comparison between the morphological data of the sea opening of Lido before and after construction of the jetties and the current information (at left, comparison 1809-2003; at right, comparison 1897-2003).



Figures 5-6. Comparison between the morphological data of the sea opening of Malamocco before and after construction of the jetties and the current information (at left, comparison 1809-2003; at right, comparison 1897-

2003).



Figures 7-8. Comparison between the morphological data of the sea opening of Chioggia before and after construction of the jetties and the current information (at left, comparison 1809-2003; at right, comparison 1934-2003).

Digital cartographic representation (*raster and vector)*

Development of the technological instruments in the past years has dramatically changed the way of representation and has significantly increased the descriptive capability, creating a sort of palette of computerized instruments for representing the territory, which offers infinite nuances.

The digital environment makes it possible to incorporate various supports, a meeting place of effective instruments of representation on the territory, in which to easily work by integrating descriptive databases to obtain theme representations and 3D reproductions, with images or filmed recordings directly linked to the geometry of the territory. The effectiveness of virtual reality systems is undeniable; it is possible to use 3D models, starting directly from cartographic data, for the verification through situations of all the design decision or planning works surmised.

The essential rules for representation on the territory and handling geometric data are the same.

Cartography makes it possible to translate realty by assigning codes and according to graphic devices, conventional and descriptive symbols, in a two-dimensional representation.

Those who handle territorial management know that it can be difficult to correctly describe a complex environment. Very often, this information is necessary to understand the territory or an event that involves it and identifies it precisely. The communicative aspect is still clear if you consider the information role and decision-making role of the data to be transmitted: the more information there is, the better these decisions can be made. Frequently, it is important to evaluate the need to represent changes in events over time, as in the studies of the sea openings of Venice.

The descriptive and cognitive aspects of the territory can be enriched and enhanced by systems that make it possible to integrate diverse elements, whether this is urban planning, morphological, or natural, or economic. This is a more complex representational opportunity but also more complete, because it links graphic elements in diverse scales with other information in order to increase the descriptive capability and improve management and communications.

The most recent experiences in this sector made by various research groups[1] have shown that when the traditional instruments are coupled with new media, the communicative instrument becomes more valid.

The usefulness of integrating geographic data and cartographic data, structured in a conventional way with multimedia instruments - and therefore, images, films and sounds – can be seen especially when it is necessary to present a planning project or intervention in a comprehensible and effective way that caters to an audience not only made up of specialists. Studies of the evolution of the sea openings of Venice has rendered an important and comprehensive example to evaluate which innovative or traditional methods cartographic representation (3D models, 2D and 3D animation, morphing) is most effective in transmitting information but also, and more importantly, to study which methods can be used and which can be integrated.

To this end, the data related to the morphological evolution of the beaches and sea floors extracted from historic georeferenced and present-day cartography was "re-represented" by using digital instruments to create representations that range from the most traditional of two-dimensional cartography to 3D cartography used in disciplinary sectors related to computer graphics.

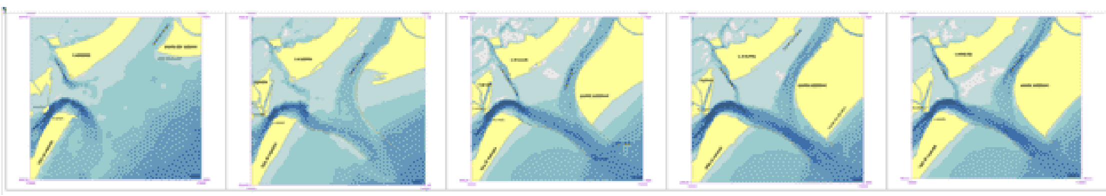
Static digital models

Elaboration of the morphological and bathymetric data extracted from historic cartography and compared with present-day data provided by the numeric CTR and the updates provided by the Water Authority in 2003 follows two essential models of representation: a static representation that refers to the consolidated cartographic models at level curves or surfaces (DTM, DEM, DSM) and a dynamic curve that starts with the widely used graphic in the field of architecture and is used in the sector of computer graphics, where the data, in the form of 3D, are visualized through animation.

There are different types of animation: morphing synthetic images that represent the various states of evolution of the phenomenon considered, actual virtual flights on 3D reconstructions obtained from the cartography that represent the evolution in the sea openings from a morphological and time perspective.

Numeric 2D cartography with representation of level curves

Territorial representation through level curves is the most used method to altimetrically describe the territory (bathymetric for sea floors) through maps (fig 9 -13).



Figures 9-13.

[1] See the activities performed at CIRCE of this university on the study of historic cartography and its georeferencing through new infographic instruments.

A level curve is an imaginary curve that connects all the points located at the same elevation with respect to a reference level.
In cartography, level curves are presented equally spaced at a constant measure, which is called "equidistant." Equidistance is the difference in level between one level curve and the next. Its value varies depending on the terrain and the scale of representation.
Usually, in order to make it easy to read a terrain, the curve designed with a more marked trait, called the "directrix", which in the case of official cartography, indicates the levels with respect to a fixed pitch.
The representations at level curves are generally obtained through manual interpolation or automatically starting with a TIN, DEM, or DTM.

Numeric 3D cartography: the digital model of the terrain (DTM)

In cartographic representations, the progression of the land cannot be represented as a surface that varies continuously in space but is visualized by level curves. This method is not appropriate to making modelling and numeric analyses.
This is why it has become necessary to develop new methods to describe the continuous variation of the depth of the sea floors.
The Digital Terrain Model is presented as a set of coordinates obtained by interpolation of several points by appropriate mathematic algorithms, starting from the measure, with respect to a certain reference system, of points of the physical terrestrial surface. These data measured must, clearly, be transformed in the selected reference system, so that other data can be admitted from different survey methods (photogrammetry, topography...) and measured with irregular distribution, must be transformed in the DTM method chosen.
Acquisition of the data has the purpose of creating prudent information underpinning generation of the DTM. The coordinates of bathymetric points (known in 3D) were determined in several ways:

a) from historic cartography: by digitalizing the triple coordinates representing the floor points starting with a scattered distribution present on the georeferenced charts with respect to numeric CTR;
b) from the bathymetric survey: only in the case of more recent cartography (CTRN 1984 and the Water Authority 2004);

Data processing constitutes the construction phase of a digital model, which makes it possible to describe the object along with the topographic and morphological elements typical of the surveyed surface.
Construction of digital models of the various ages was done with procedures of interpolation with bi-linear or bi-cubic spline functions on points located in the mesh of a regular grid. In essence, this meant determining the height in correspondence to each node of the regular grid with the most appropriate mathematical principle of interpolation starting with knowledge of the data acquired in the survey phase.
Among the numerous methods of interpolation, the statistical method, called *Kriging,* is used for processing the data of the sea floors taken from the cartography considered. This method is based on the regional variable concept and divides the altimetric variations into a correlated component with the adjacent ones and a component of casual error. Kriging uses an "iteractive" approach and produces a surface that passes through the points, esti-

mating the variance of each interpolated point, and remaining coherent with the starting data.

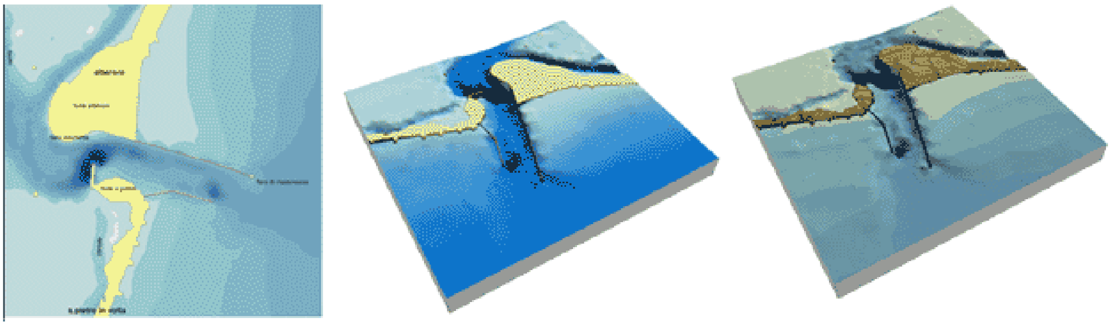


Figure 14. Representations of the DTM of the sea floor of Malamocco (1897): planimetric view at level curves; assonometric view of the continuous 3D surface. At the center, the model is mapped with an *image map* (a map where the radiometric value of the pixels varies according to the altimetric value); at right, the bathymetric value is represented by level curves while the description of the coast is given by the semantic contents of the historic geo-referenced map.

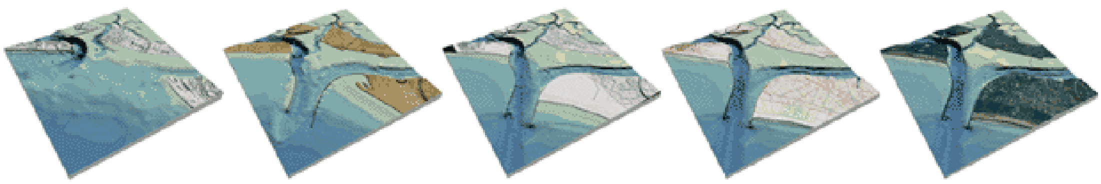


Figure 15. Representations of the DTM of the lido sea floor 1809-2003: assonometric views of the continuous 3D surface mapped the synthesis images of the different information levels (coastal evolution, sea floors and geo-referenced maps).

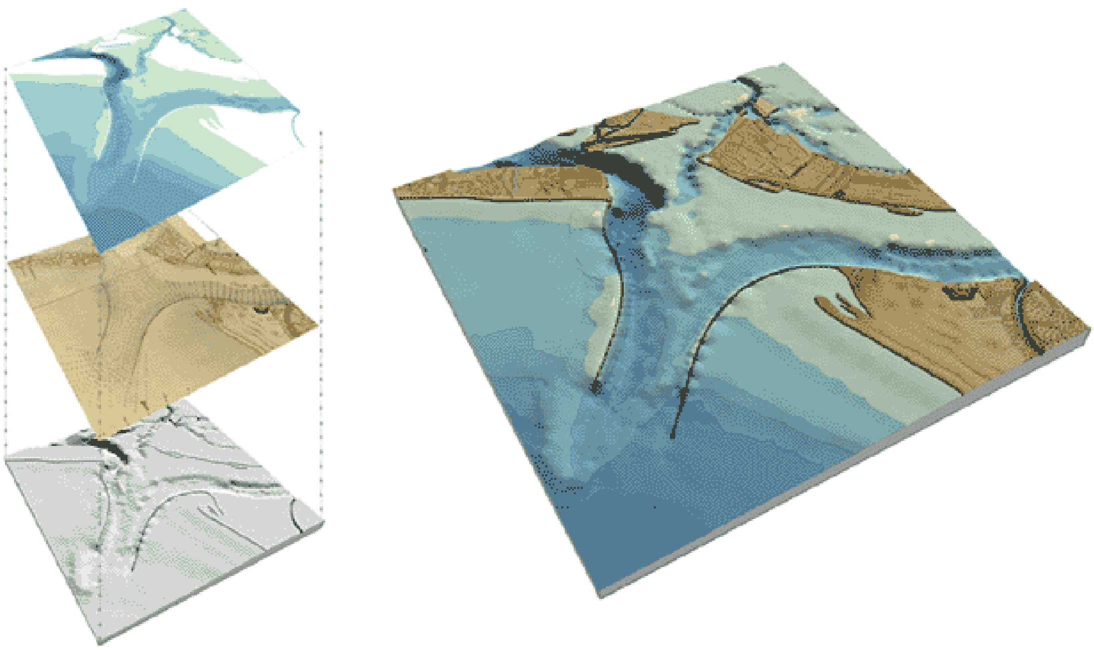


Figure 16-17. Superimposition of the information layers in visualizing the DTM of the Lido sea opening of1897: digital model of the surfaces, historic geo-referenced cartography and map of the level curves.

Dynamic digital models

Communication through animation is part of our culture and has deep roots; it is the next step in illustration, which we find traces of since ancient times in the caves. A scene, a tale, a chronicle are accompanied by images that illustrate salient moments and enhance them.

Animation from the perspective of the final user is none other than a sequence of images (composed of several *photograms* or *frames* to decrease their time distance) viewed at preset speeds, appropriately constructed to simulate movement, regardless of the construction technique.

The computer age has allowed us to create and process photograms in the digital environment with information technologies of variable nature (programmes of normal image processing, rendering in 3D environments, elaboration of data of variable nature) and therefore, montage of animation in accordance with the information that needs to be transmitted.

Morphing

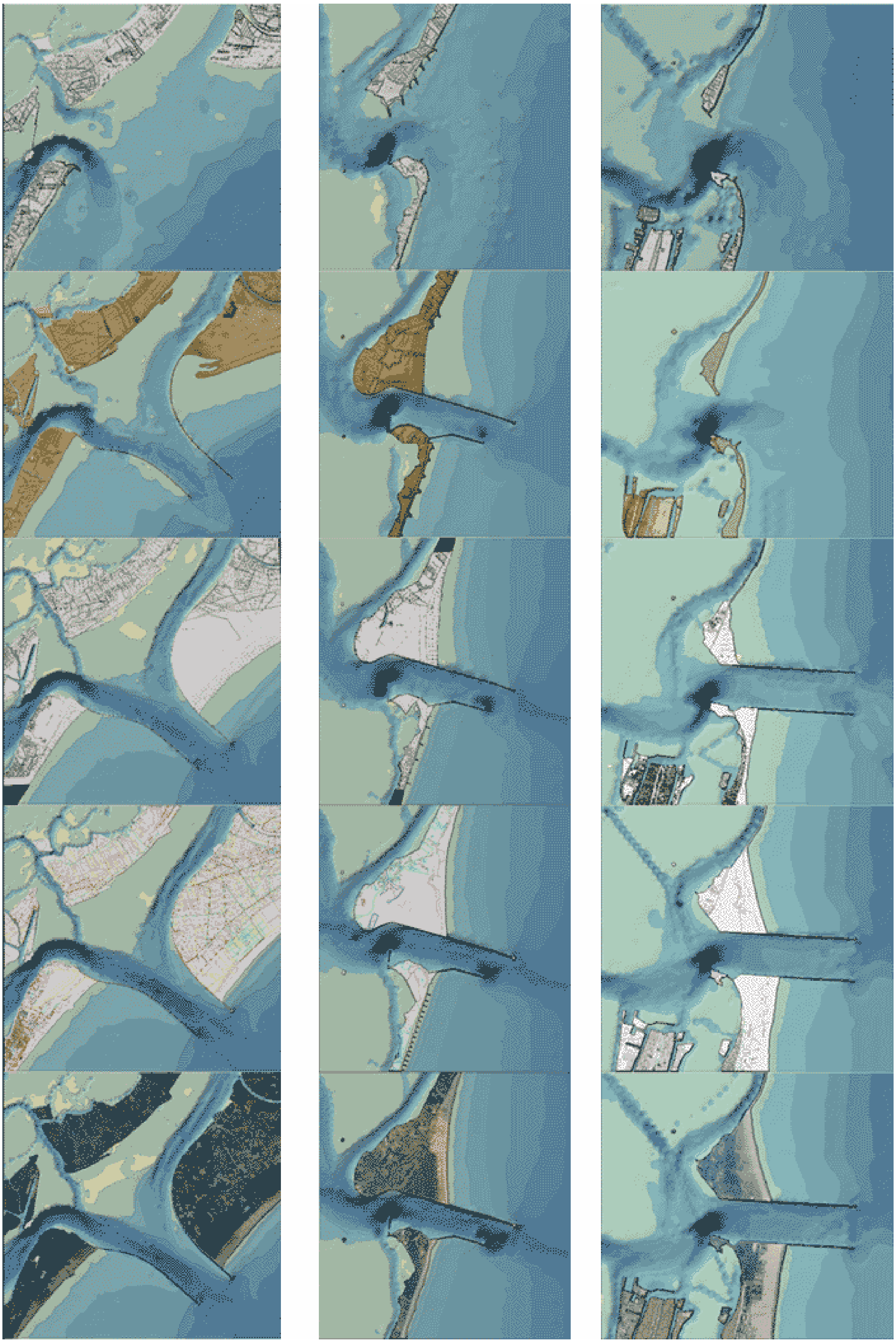
In computer-graphics, the term *morphing* defines a procedure that uses two images, a starting image and a final image, to create a sequence of intermediate images that are mounted sequentially to generate transformation animation between the objects represented.

This technique of manipulating the image precedes computer-graphics: indeed, since the earliest times of cinematography, morphing procedures have been realized by using optical illusions.

With the advent of computer graphics, in particular, with the spread of the use of computers in handling images, the methods of creating this type of special effects have developed enormously.

The first effect introduced was cross-over dissolution between the images, used previously in the cinema: given two images, a source and a destination, every pixel of every intermediate frame is given by the weighted average of the starting and ending images. If the animation to obtain envisages N frames, the 0 frame will coincide with the source image and the N frame with the final image.

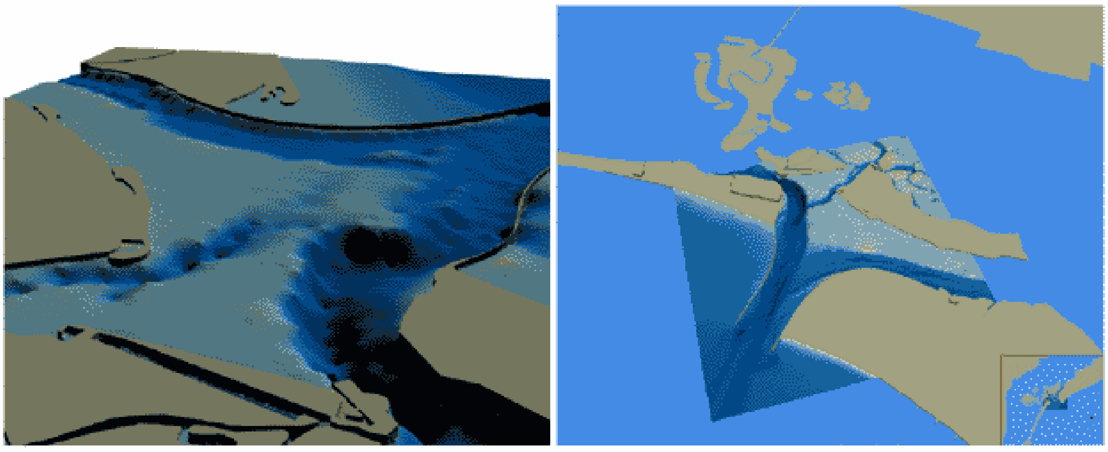
In recent years, the techniques described have been applied not only to images, but also to several classes of *graphic objects*. Among these, the most significant are the solids and sounds. The application of the same techniques used in two-dimensional images in the case of 3D and single dimension.



Figures 18-20. Planimetric views of the digital models in the time series considered: Lido, Malamocco and Chioggia. The sequences of images were used as basic photograms of morphing, animated with the purpose of highlighting the change of the three sea openings in the last two centuries.

3D animation

This type of animation, in architecture, is called *walkthrough*, because in computer graphics, it is possible to animate objects and motion pictures. Animation of motion pictures results in the "excursions" in computer-generated environments. Thus, a virtual journey is represented in a space that cannot yet exist (this is the case of architectural and urban planning projects) which actually exist, or which used to exist but have disappeared or are in ruins (the remains of ancient civilizations or archaeological sites in general). In these cases, computer graphics not only sets up a "world" but the possibility to travel it, which it assigns to a view: the point of view is what guides the journey through forms and objects, to become the central theme.



Figures 21-22. Animation frames realized with digital data extracted from cartography.

Photogrammetric animation was executed in the study of the sea openings, which corresponds to a virtual flight along the Venetian coast, not only in terms of space but also in terms of chronology, using textures of the models to render the images the result of the georeferenced historic charts and subsequent cartographic processing produced.
The flight was enhanced by transitional effects by succession of the cartographic description and 3D morphing effects to emphasize the change of the coastline and the sea floors following construction of jetties.

References

Grillo S. (1989). *Venezia. Le difese a mare. Profilo architettonico delle opere di difesa idraulica nei litorali di Venezia.* Venezia: Arsenale Editrice.

Favero, V., R. Parolini, M. Scattolin (1988). *Morfologia storica della laguna di Venezia*. Venezia: Arsenale Editrice.

Balletti, C., F. Guerra (2002). *Warping algorithms for Cadastre cartography georeferencing,* In VII International Congress of earth Sciencies 2002, Santiago, Cile.

Novello Massai, G. (2002). *Nuove forme e modelli per la conoscenza dwll'ambiente e del territorio*, in DDD_04 - Disegno e Design Digitale Nuove tecnologie, multimedia e standard grafici per la rappresentazione del territorio, edizioni Poli.design. Consultabile su http://www.mediadigitali.polimi.it/ddd/ddd_004/indice.htm

Carlon, C. *Cartografia digitale: elaborazione di carte storiche e di carte attuali*, tesi di laurea discussa presso l'università IUAV di Venezia, relatore Francesco Guerra, correlatore Caterina Balletti, anno accademico 2004-2005.