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figg. 9

Three-Dimensional GIS Geostatistical Analysis for the Stratigraphic Reconstruction of the Foglia River Aquifer (Pesaro, Italy)

Analisi geostatistica GIS tridimensionale per la ricostruzione stratigrafica dell'acquifero della bassa valle del Fiume Foglia (Pesaro)

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ABSTRACT - This work presents a new methodological approach to the elaboration of geological data using three-dimension (3D) geostatistical techniques. A 3D model of the Foglia River alluvial deposits (Northern Marche, Italy) is built up to investigate the geometry of sedimentary bodies. A large amount of well logs have been validated, organized in a geological database and subsequently interpolated using geostatistical 3D algorithms.

The geological data (boreholes, penetration tests) have been integrated with geophysical ones (seismic profiles, resistivity sounding). The data collected along the lower valley of the Foglia River are more than 700 subsoil investigations (550 borelogs, 150 penetrometric tests and some geophysical tests), stored in a GeoDatabase. All cartographic and alphanumeric data have been elaborated in Geographic Information System (GIS) environment.

This integrated approach offers many advantages for the comprehension and in-depth visualization of deposits geometry and for evaluation of their eteropic assesment. Furthermore, it allows for the acquisition of qualitative and quantitative information on hydrogeological settings, useful for water resources exploitation and protection. Moreover quering data and opportunely elaborating the resultant datasets it is possible to build new thematic maps, useful to elaborate aquifers vulnerability maps. The achievements are: (1) the construction of the geologic 3D model of the low alluvial plain of the Foglia River, (2) the comparison between the geological cross-sections elaborated from the 3D model and the traditional hand made sections and (3) an advancement of the stratigraphical-hydrogeological knowledge of the study area.

KEY WORDS: GIS, Geognostic Data, 3D Geological Model, Geostatistics, Foglia River

RIASSUNTO - L'acquisizione dei dati geologici risulta talvolta non facile e può anche avere costi elevati. Lo sviluppo di metodologie e di tecniche di elaborazione dati in grado di implementare i dati di input per ottenere nuova informazione costituiscono nuovi obiettivi di ricerca. Questa esigenza è molto evidente negli ambienti di pianura. Infatti, in questo particolare contesto geologico, solo i dati meccanici e geofisici, solo le prove dirette ed indirette possono offrire dati in grado di consentire una buona ricostruzione geologica.

Le tecniche di elaborazione tridimensionali (3D) e le nuove metodologie di implementazione dati (tra cui anche quelle di carattere geostatistico) risultano altamente strategiche e possono offrire nuove informazioni utili a ricostruire il contesto geologico, stratigrafico e l'assetto sedimentologico dei depositi alluvionali. Questo lavoro presenta un nuovo approccio metodologico per l'elaborazione dei dati geologici di sottosuolo utilizzando tecniche geostatistiche 3D. In modello geologico 3D dei depositi alluvionali della bassa valle del Fiume Foglia (Comune di Pesaro, Marche settentrionale) è stato costruito allo scopo di investigare la geometria dei corpi sedimentari.

Sono state uniformate numerose stratigrafie, organizzate in un database geologico appositamente progettato e successivamente interpolate utilizzando algoritmi geostatistici 3D. I dati geologici raccolti lungo la bassa valle del Fiume Foglia sono più di 700 investigazioni di sottosuolo (circa 550 sondaggi, 150 prove penetrometriche e alcuni profili sismici e di resistività), opportunamente archiviate in un GeoDatabase. L'insieme dei dati cartografici e alfanumerici è stato elaborato utilizzando un Sistema Informativo Geografico (GIS).

Il modello 3D realizzato ha consentito di visualizzare e comprendere la geometria dei depositi in profondità e di

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valutare i loro rapporti spaziali. È stato possibile ottenere informazioni qualitative e quantitative sull'assetto idrogeologico dell'area utili per lo sfruttamento e la protezione delle risorse idriche. Interrogando ed elaborando opportunamente i dataset, inoltre, sono state elaborati nuovi livelli tematici utilizzabili per la redazione di una mappa di vulnerabilità dell'acquifero.

I principali risultati conseguiti sono: (1) la presenza di due livelli di depositi fini ben sviluppati ma non continui lateralmente, tanto da non poter disarticolare l'acquifero principale in più acquiferi isolati, (2) la presenza di un acquifero sospeso, di scarso interesse applicativo, posato su una superficiale ma estesa lente di depositi limoso argillosi che funge localmente anche da protezione dell'acquifero principale dall'inquinamento e (3) la formulazione di un'ipotesi relativamente alla ricostruzione paleogeografia durante le fasi di deposizione dei terrazzi di ordine T3 e T4.

PAROLE CHIAVE: GIS, Dati geognostici, Modello geologico 3D, Geostatistica, Fiume Foglia.

1. - INTRODUCTION

The development of methodologies and techniques for data processing and the implementation of input data for the generation of new information are the new research goals. This requirement is very evident in particular geological context such as alluvial plains, where only direct and indirect investigations can offer data for a good geologic reconstruction. The elaboration techniques and the new data implementation methodologies result highly strategic and can offer new useful information to reconstruct alluvial deposits, stratigraphical context and sedimentological setting. This information is also useful for hydrogeological studies, for the evaluation of aquifer vulnerability, and for the protection and correct management of water resources.

Methodological problems exist in the management of a georeferenced geolithological database. In fact, stratigraphical data obtained by geognostic survey carried out by different geologists at different times and using different subsoil investigation methods are affected by each geologist's personal sensibility and by a varying degree of precision and detail which derives from the surveying technique. Data validation is the central step in data management in order to compare and correlate a dataset to get new information.

Relational Data Base Management System (RDBMS) and Geographic Information System (GIS) can offer solutions for geological data management. Furthermore, the introduction of three dimensional (3D) models considerably increases the possibility of analysis and the number of new information that can be caught from the distribution and the spatial relationship of geological bodies. In fact 3D models let the users to understand and visualize geological structures in depth and to obtain quantitative information on structural and geomorphologic aspects of the study areas. It is possible to apply 3D modeling and analysis techniques for different geological settings at different scales ratio, integrating geological (well logs, geological maps, cross sections) and geophysical data (seismic profiles), choosing between a geometrical approach (DE KEMP, 2000; DE DONATIS *et alii*, 2002; GALERA *et alii*, 2003; TANNER *et alii*, 2003) or a geostatistical approach (POETER & MCKENNA, 1995; NATHANAIL & ROSENBAUM, 1998; WINGLE *et alii*, 1999; MARINONI, 2003; REGLI *et alii*, 2004). A 3D geological model permits the extraction of a user-defined arbitrary cross section, provides a visual forum for discussion and communication and offers many analysis tools.

This paper is a presentation of an integrated workflow that provides for the homogenization and the comparability of geological data stored in a geological database, the data georeferencing and creation of thematic maps supported by GIS, and the construction of a geological 3D model using a geostatistical approach. The implementation of geological data provides spatial observations for new analysis and new information about deposits, useful for geological, hydrogeological and environmental applications.

2. - STUDY AREA

The lower alluvial plain of the Foglia River is the part of the Municipality of Pesaro (fig. 1) where most of the population and of the economic activities gather. The terraced deposits of the alluvial plain of the lower Foglia River are up to 3 km width and their ground water resources are particularly vulnerable. The current river bed runs on the right side of the valley at about 10 kms from the mouth, then it bends on the left up to its mouth.

Alluvial deposits are distinct in three orders of terraces beyond the present alluvial deposits. The topographically thigher terrace (T2) is present in some reduced and isolated edges in the left side only. The T3 terrace is primarily preserved on the right side and it is laterally joined to a wide detrital fan. The T4 terrace was the floodplain before the construction of the embankment that begins around 6 kilometers from the river mouth. The T4 high extension, in the terminal part of the river course, probably points out overflow phases connected to subsidence events (GUERRERA *et alii*,

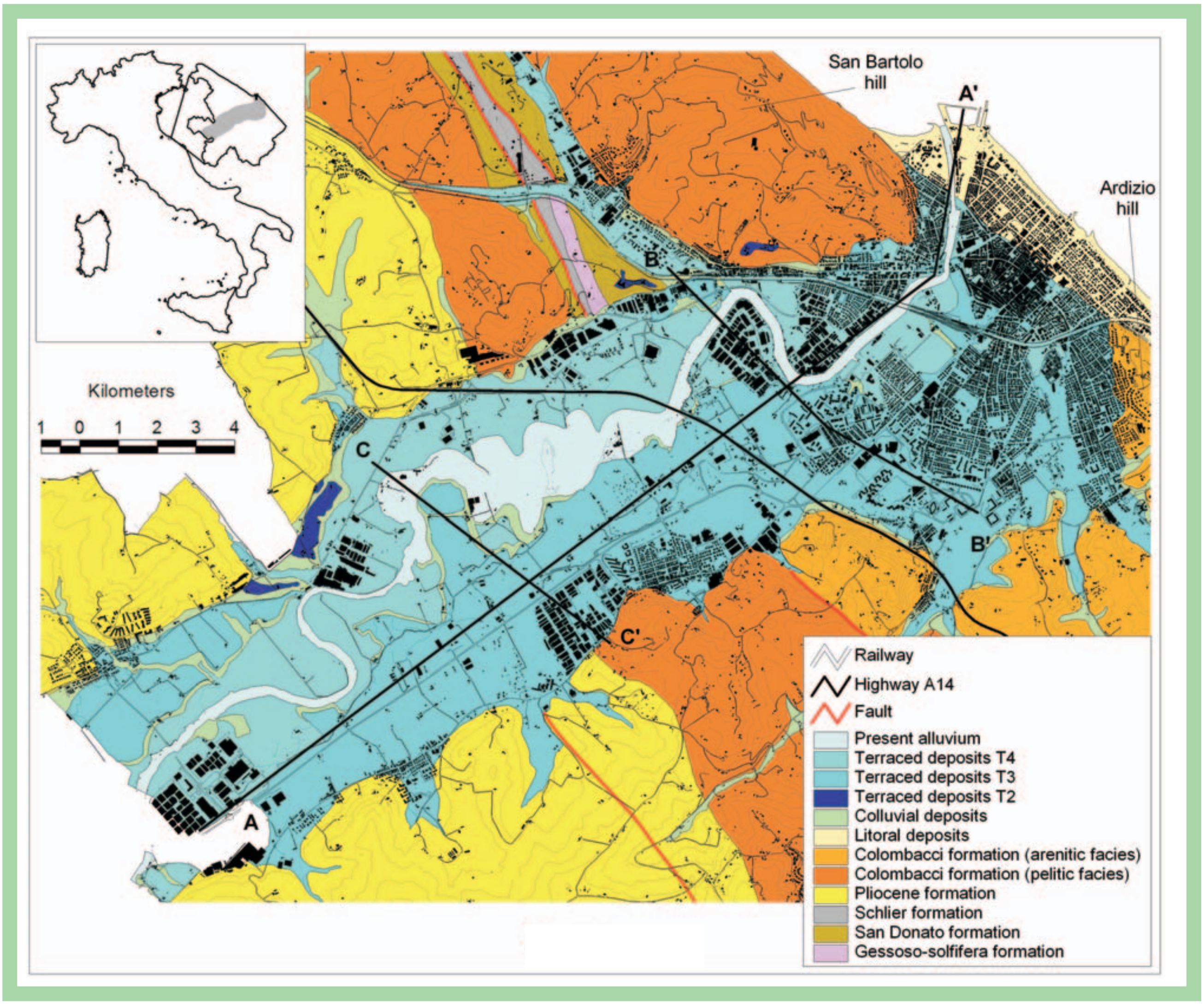

Fig. 1 - Geolithologic map of the study area and trace of the cross-sections (courtesy of Pesaro Municipality).
- *Carta geolitologica dell'area di studio e traccia delle sezioni (cortesia Comune di Pesaro).*

1978). A dextral strike-slip fault (NW-SE oriented), with a mesured slip of 2 km, displaces the course of the Foglia River toward North cutting the 4th order terrace in the terminal part of the valley (GUERRICCHIO, 1990).

The fluvial body of the low Foglia valley consists mainly of fluvial deposits of the third order terrace, within which the actual river bed is engraved (ELMI *et alii*, 1983). The substratum is constituted by the Umbria-Marche succession from middle Miocene to middle Pliocene age deposits. The oldest formation in the study area is the Schlier (lower middle Miocen in age). It is constituted by marls with variable contents in carbonates and clays with various thickness layers. The upper Miocene Colombacci formation consists of two different turbiditic facies. The arenitic prevalent facies outcrops widely in the Ardizio hill south-east of Pesaro and partially in the south hillside of San Bartolo. The pelitic prevalent facies outcrops in the north hillside of San Bartolo and it constitutes the base of the unit. The Pliocene formation is mainly constituted by clay with rare intercalations of sand and silt thin bedded turbidites (pelitic lithofacies). In this area the Pliocene arenitic facies is not present.

3. - DATA

Data related to geognostic surveys and wells have been collected and recorded. The first activity has been the choice of the data. If direct and indirect surveys were available for the same site, only direct ones have been considered and digitized, because more detailed, reliable and devoid of interpretation factors. In general the order of preference has been as follow: (1) drilling, (2) static penetrometry and (3) dynamic penetrometry and geophysical survey.

Many geognostic investigations have been realized for geothecnical purposes; 1006 surveys have been gathered on the whole municipal territory of Pesaro, of which 764 drillings, 159 static penetrometries, 20 dynamic penetrometries, 5 geophysic prospectings and 58 wells with stratigraphy. About these, 714 focus on the Foglia River alluvial deposits: 494 drillings, 150 static penetrometries, 17 dynamic penetrometries, 5 geophysic inquieries and 48 wells with stratigraphy. The distribution of the investigations (fig. 2) interests sites involved in the planning of new urban areas and in the renovation of the historical center.

3.1. - Data validation

The lithological data collected differ for subsoil investigation technique, year of execution and geologist sensibility regarding editing and stratigraphy description. Therefore the data were affected by a variation in detail and accuracy. No comparison was possible, neither geological nor stratigraphical correlations were possible using the data as they were and obviously neither sedimentological nor geo-environmental interpretations could be carried on. The difficulty is related essentially to two problems.

First, the collected geognostic data belong essentially to two categories of tests: direct (drillings) and indirect ones (penetrometric and/or geophysical surveys). The differences of the stratigraphical reconstructions (more or less reliable)

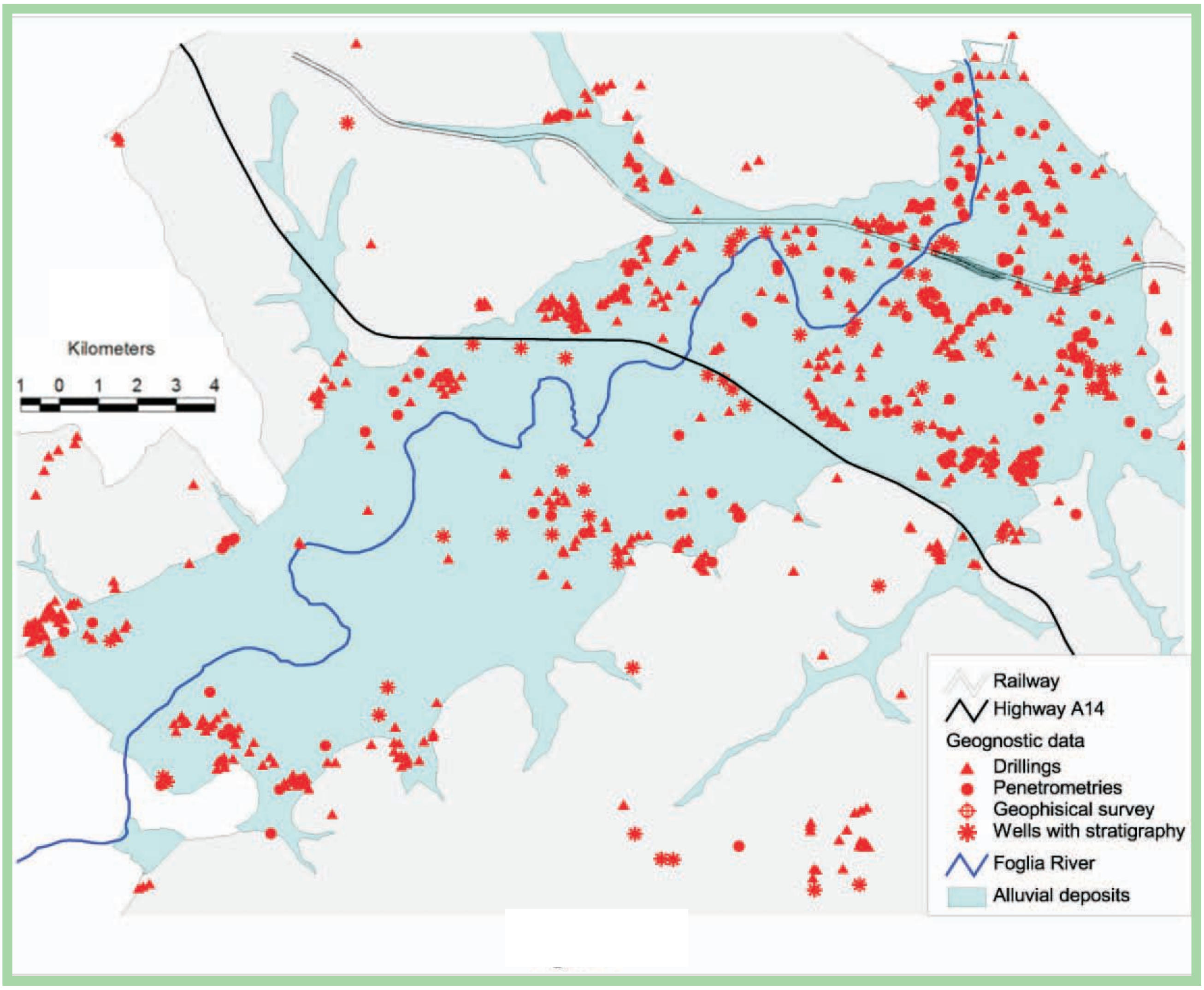

Fig. 2 - Areal distribution of the alluvial plan and location of the geognostic data.
- *Distribuzione delle indagini dirette e indirette lungo la valle alluvionale.*

are implicitly and etymologically related to the kind of geognostic test conducted.

Second, the collected data cover a period of time ranging from 1960 (oldest recorded survey) to 1998; moreover, direct survey stratigraphies show lithology descriptions deeply different from one another (from scarce and concise to detailed descriptions, with pictures attached, completed with drill tests, laboratory tests and pocket instrument tests). Finally concerning indirect surveys, the interpretation of geophysical survey or penetrometric tests often depends on the geologist's knowledge of the area rather than on an accurate application of abacus and/or conversion formula.

Simplifications are made, and structural rules are defined both in the conceptual and data model to solve the uncomparable problems and to obtain homogeneous and correlatable geognostic data files, least affected by subjectivity. A "degree of interest" and a "degree of quality" have been assigned to each individual stratigraphical column. The "degree of interest" is defined as the geological significance of the data compared to the geologic setting where the geognostic survey has been conducted. For example in this project, considering alluvial deposits, the data interest is high when the investigation reaches the substratum and then runs through and characterizes the whole alluvial body; the interest is medium if the top of gravel deposit is reached, and it is considered low if the top of gravel deposit is not reached. The "degree of quality" is defined according to the reliability of the data, evaluating the conditions in which the data have been obtained and so depending on which kind of investigation was used and on the degree of interpretation necessary to "translate" the raw data obtained from the indirect survey into stratigraphic lithological data. For example, data obtained by a core recovered well are qualitatively superior to a cutting recovered well; data obtained by a static penetrometry with piezocone are better than ones using a static penetrometry and these latter are qualitatively superior to data obtained by a dynamic penetrometry.

The definition of "degree of interest" and "degree of quality" to assign to each individual geognostic datum can be fixed freely, according to the aims of the study, the geologic stratigraphic structure of the area assessment, the goals of the project, or depending on particular standards which enable an homogeneous evaluation of the data interest/quality. This methodological step allows a data control and data verification in data entry activity and solves the comparison problems described above offering a reliability filter to geognostic data.

The data processing starded by running queries and comparisons in order to detect the data affected by error or by a high degree of uncertainty.

The stratigraphic and lithologic descriptions of the investigation were very different if we compared one to another and sometimes there were doubts about the reliability of the data because no granulometric analysis were conducted. To solve this problem a simplification has been made concerning the lithological descriptions. All possible drillings descriptions and/or interpretations of indirect tests have been assembled in the following classes: O: Covered soil; N: Natural soil; C: Clay and silt; S: Sand, muddy sand, sand and clay; G: Gravel, sandy gravel, gravel and mud, gravel and clay; SUB: Substratum.

The reason for creating these classes is the need for uniform and easily comparable lithological descriptions of drillings carried out by geologists with different sensibilities and degrees of detail and of quality (as pointed out before). The suggested classes are less numerous than the original descriptions used by geologists. This apparent limit must not be considered as a loss of data/details, but as a choice to provide stratigraphy with an extra value, because it allows the comparison and uniformity of the whole set of recorded data. The "degree of interest", "degree of quality" and the uniform lithological classes are the essential conditions that allow for the inquiry and comparison of stratigraphic data and permit subsequent data base implementation and data processing for the creation of new informative levels.

4. - THE GEOLOGICAL GIS

All geognostic investigations have been georeferenced on the aerophotogrammetrical cartography drawn to the scale of 1:5.000 by the Municipality of Pesaro; the surveys have been inserted in the GIS Microstation Geographics by Bentley System. Corographies and detailed planimetries have been used to georeference subsoil investigations (big scale map 1:500 - 1:1000) with a positional accuracy of 5 meter. The absolute height of each investigation has been calculated by a digital terrain model (DTM) using the height point of the technical map. The Microsoft Access relational database software was used to manage the geological database.

The basic feature of the GIS systems lies in the association of information (stored in database tables) to geographic data. The point is the topologic element in the geological GIS and it represents the geognostic investigation. The GIS software can show all the data related to each geometric element (location, stratigraphy, interest and quality of data, *in situ* and in laboratory tests, phreatic depth). Moreover, it is possible to query the database and display which geognostic data fulfill the conditions required (e.g. which drills have a substratum deeper than 35 meters; which geognostic investigations present a gravel thickness higher than 5 meters, etc.).

The dataset (filtered point samples) can be spatially interpolated using specific algorithms commonly used in geostatistics (linear interpolation, distance-weighted method, kriging method etc.) to obtain a statistical surface. Following this procedure it is possible to produce substratum depth maps, top gravel maps, gravel or sand or fine deposit thickness maps, fine to total deposits percentage vertical distribution maps, prevalent unsaturated lithology maps and many other maps depending on available data and project tasks. Also some maps can be used to evaluate groundwater vulnerability to contamination potential using specific methodology as DRASTIC model (US-EPA, 1985).

Such elaborations, even if useful and fast, do not provide new information about the deposit structure. It is very difficult to represent and to imagine the deposit assessment, lateral distribution and continuity, thickness, eteropic contacts using only isarithm maps and geological sections, above all if we are studying particolar geological contexts such as alluvial plains. The next step of the work is to delineate a new strategy, a different methodology to implement the lithological data stored in the database, to obtain new elaborated information useful for the reconstruction of the stratigraphical and hydrogeological assessment of the study area, supported by 3D potential.

5. - DATA IMPLEMENTATION

Geological data management in the last 10-15 years works using and integrating Database and GIS features for data implementation and data output. The limits of these software elaborations consist mainly of 2D representation of the geological complexity: only contour lines, surfaces and sections can be produced. For a more integrated approach towards a realistic geological representation, digital models have been developed in the last years; making use of three dimensions, the digital model can better represent geologic structures (JONES, 1989). The introduction of 3D models and their observation considerably increases the capability to analyse deposit assessment and to obtain new and detail stratigraphic information.

REQUICHA (1980) has identified six schemes to define methods representing rigid solids. Three schemes apply to the construction of geometric primitives, the other three fit the construction of geological models (JONES, 1989). The first scheme, called spatial occupancy enumeration, is based on the definition of a list or set of spacial cells that are occupied by the objects to be represented. These cells have a cubic shape and are grouped in a regular grid called voxel. The second scheme, cell decomposition, shares with voxel a similar approach, but with a difference: the polyhedric body may be represented by a series of separated voxels, so that each side of the voxel matches a side of the irregular object to be represented. Requicha's last scheme, called boundary representation, provides the reproduction of a solid through the representation of one of its outline surfaces. It is typically represented by two polygonal faces with vertexes corresponding to those of the solid being represented.

In this work, the implementation of the recorded geological data is carried out using the software Voxel Analyst by Intergraph. The application is based on voxel-type (spacial occupancy enumeration) processing model that it gives the name to the software. This program can read ASCII data, graphic CAD data (Dwg by Autocad and Dgn by Microstation) and can process them using different techiques. The two main ones consist in surfaces interpolation (representing the horizons of lythological contact), and in geostatistical elaboration of exact data (technique used in this experimentation).

6. - 3D GEOSTATISTICS

The spatial (or geostatistic) interpolation is a technique used to determine the values of a quantity in mean points, among points where that quantity is known or, as defined by BURROUGH & MCDONNEL (1998), the procedure which allows to predict the value of attributes of points in areas not sampled from measurements carried out in separate points. In the three dimensional geostatistic analysis shown in figure 3 the space is not divided into squares (cells) but in irregular cubes (voxels). The lower Foglia River valley has been analysed in this study using Voxel Analyst software. The voxel matrix is 11.600 metres wide, 7.200 metres long and 82 metres high. Each side of the parallelepiped is 116x72x0,82 meters, the volume of each voxel is 6850 cubic meters.

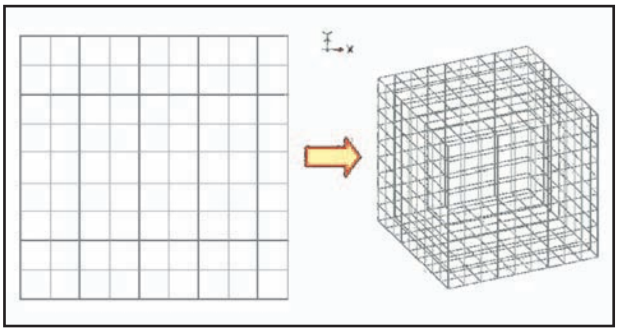

Fig. 3 - Subdivision of space in 2D cells and in 3D voxel.
- Discretizzazione dello spazio in celle 2D e in voxel 3D.

6.1. - Interpolation

There are many interpolating functions and they can be grouped in the two following categories.

Global interpolators: they use all available data to make the prevision on the whole interested area (cell matrix or voxel). The surfaces obtained are highly prone to the edge effect, and it is easy to get incorrect representations right out of the area covered by data; local interpolators: they operate on small areas, near the point to be interpolated, to guarantee that the estimate would be released only with data localized in the proximity and that the measure would be as precise as possible.

There is a difference between exact and approximate interpolators: the first release the true value of the information (e.g. the Kriging is the exact interpolator most widely used in 2D geostatistics). The Voxel analyst program algorithms are exact interpolators based on the distance, and so they use the distance as a base measure for interpolation. The Metric (fig. 4A), the Multiquadratic (fig. 4B) and the Spline (fig. 4C) are the commonly used methods. For the 3D geostatistic processing of the stratigraphic data of this work, a number of runs have been carried out to achieve a geologically coherent elaboration. The choice of the interpolator has been in favour of the Multiquadratic Method. The latter uses a function which respects the spacial variation (the gradient) of the input data. The result tend to follow the trend of incoming data (fig. 4B);

7. - 3D MODEL OF THE FOGLIA RIVER ALLUVIAL DEPOSITS

The geological database allows the storing of geognostic data and the acquisition of a dataset from selection criteria. The geological GIS allows (the geologist) to georeference the data and to localize the information and the query results. But

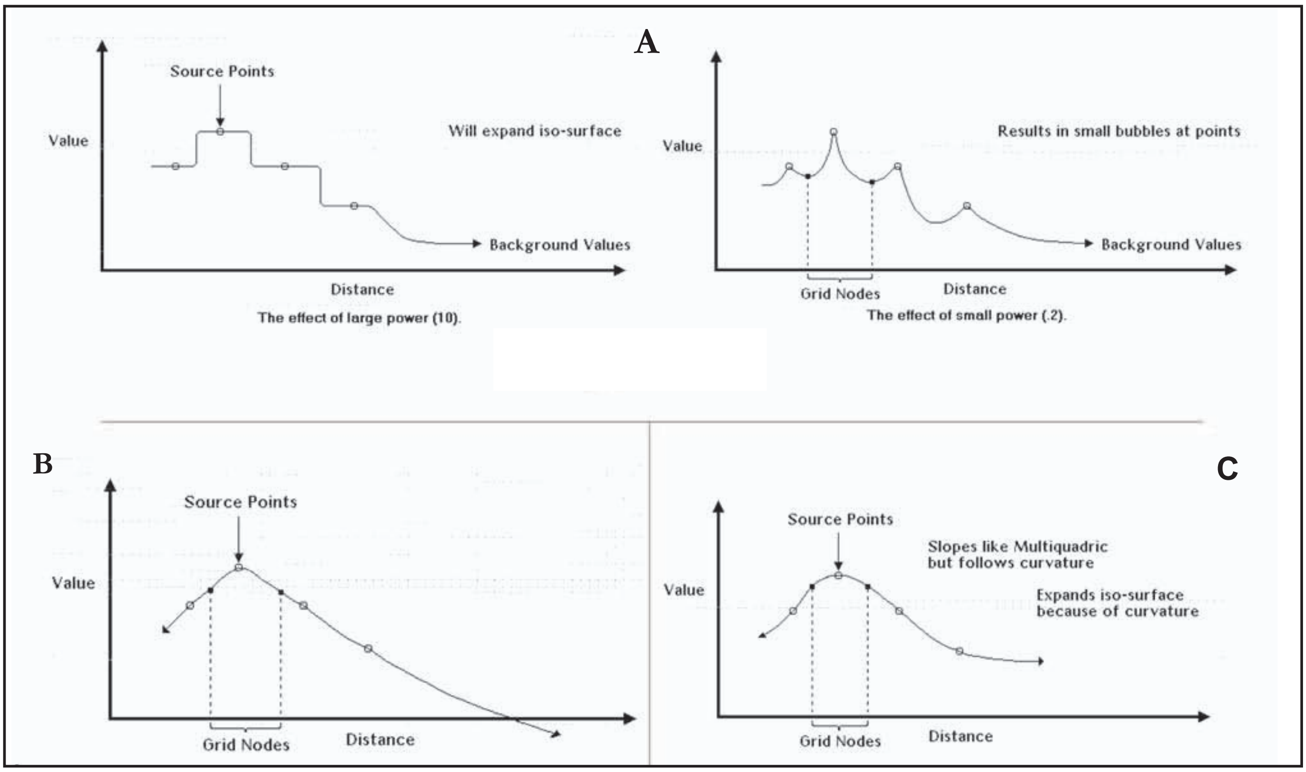

Fig. 4 - A: Variations of Metric operator with power factor; B: Metric operator Multiquadratic variation; C: Metric operator Spline variation.
- A: Variazione dell'interpolatore Metric al variare del power; B: Andamento dell'interpolatore Multiquadratic; C: Andamento dell'interpolatore Spline.

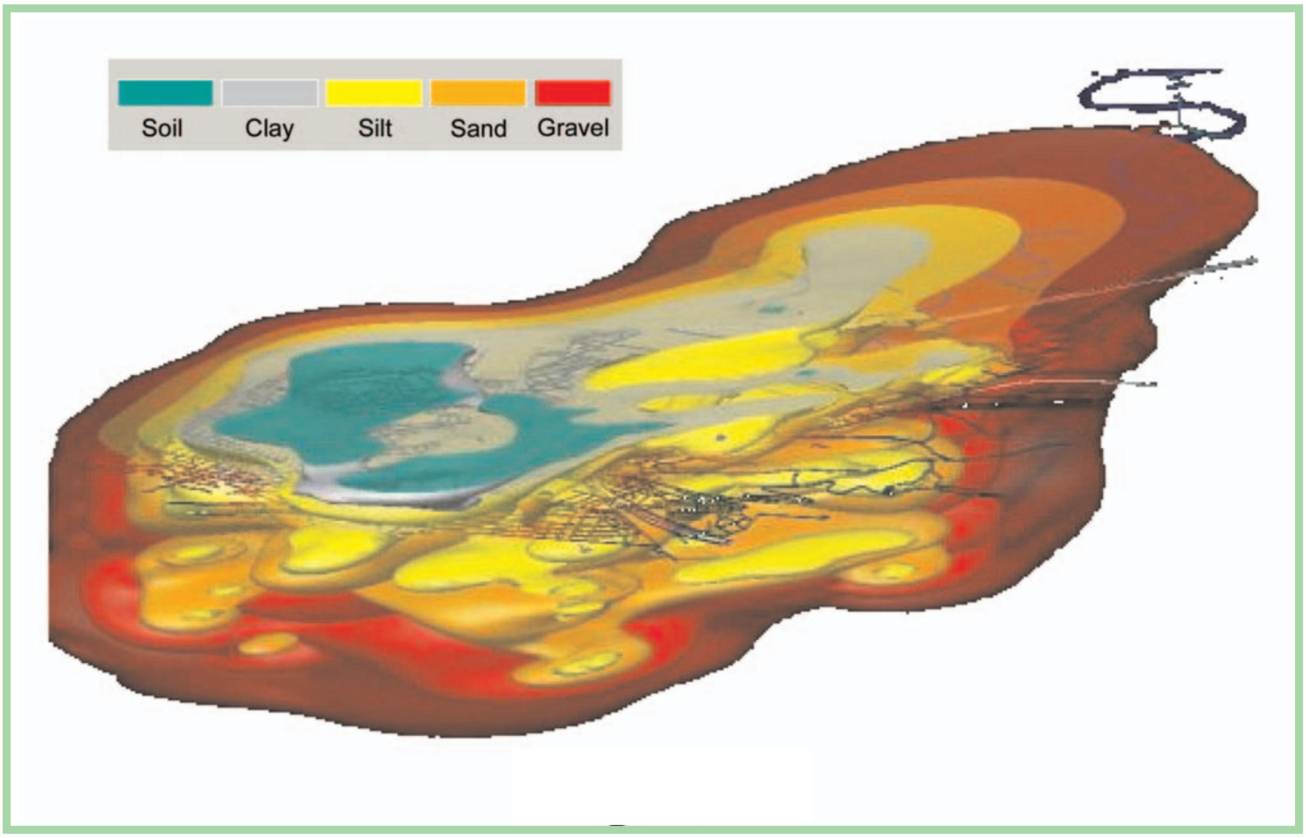

Fig. 5 - 3D geologic model of the lower alluvial plain of Foglia River; view from NE toward SW.
- *Il modello geologico tridimensionale della bassa valle del Foglia, vista da NE verso SO.*

the most interesting implementation of the data is carried out by the construction of a 3D geological model of the lower Foglia River valley using Voxel Analyst. BAIOCCHI & GUERCIO (2000, 2002), using the same software, presented a methodology based essentially on a pre-elaboration phase, which consists in a homogenization of the data input. It consists on a simplification of the stratigraphic succession through the reduction of the number of layers noticed in the subsoil. Afterwards, the horizons of the lythologic contact between formations and/or the lythologic differencies have been imported and interpolated in Voxel Analyst, obtaining a geologic 3D model.

This work presents a different methodological approach. As described above, the data homogenization phase conformed lithologies without any reduction in the number of layers. The construction of the 3D model is obtained by the geostatistical interpolation of all data according to specific criteria. According to the data validation assumption and to the definition of interest and quality degree assigned to each investigation, only medium (up to the top of gravel) and high (up to the substratum) interest data have been selected and medium - high quality data (direct investigation and only static and heavy dinamic penetrometries) are set as criteria to select the investigation useful for the construction of the model. Another selection criteria, based on investigation more than 10 meters deep, has been imposed on the database, obtaining a dataset of 1142 lithological data.

In order to keep the interpolation confined within the sedimentary basin (defined by the substratum) and prevent it from greatly suffering of the so-called "edge effect", 340 ficticious points have been inserted along 55 verticals distributed along the alluvial valley boundary according to the Mio-Pliocene stratigraphic units outcrops. The resulting dataset of 1197 lythological data have been imported in Voxel Analyst, interpolated using the Multiquadratic Method; the lithologic classes (according to the data validation step) have been represented using iso solid graphic objects (provided with different transparency degrees) and encoding an appropriate legend.

The elaboration carried out is accettable on the whole (fig. 5), even if it suffers from some imperfections and forcings. The "edge effect" has been reduced near the valley boundaries, but the result obtained towards the coast line is not acceptable. In fact, the geostatistical elaboration tends to amplify the distribution of deposits towards the sea (overall gravel) generating an evident 3D "bull eye" effect, because no data were available. Moreover, the uneven results between alluvial deposits and substratum particularly evident along the transversal sections (fig. 6A and 6B) are not geologically acceptable even if the amplification effect is considered (Z axis is scaled 15 times). The analysis of sensibility is often carried out to check the reliability of a geostatistic elaboration. It consists of a geostatistic elaboration leaving out some data points to see if the calculated output complies with the known data not considered in the elaboration. In this application, the analysis of sensibility has not been executed because the fluvial environment is characterized by strong facies variations, with a lot of layers distributed all over. Therefore, a much more reliable result can only be obtained by using all available data.

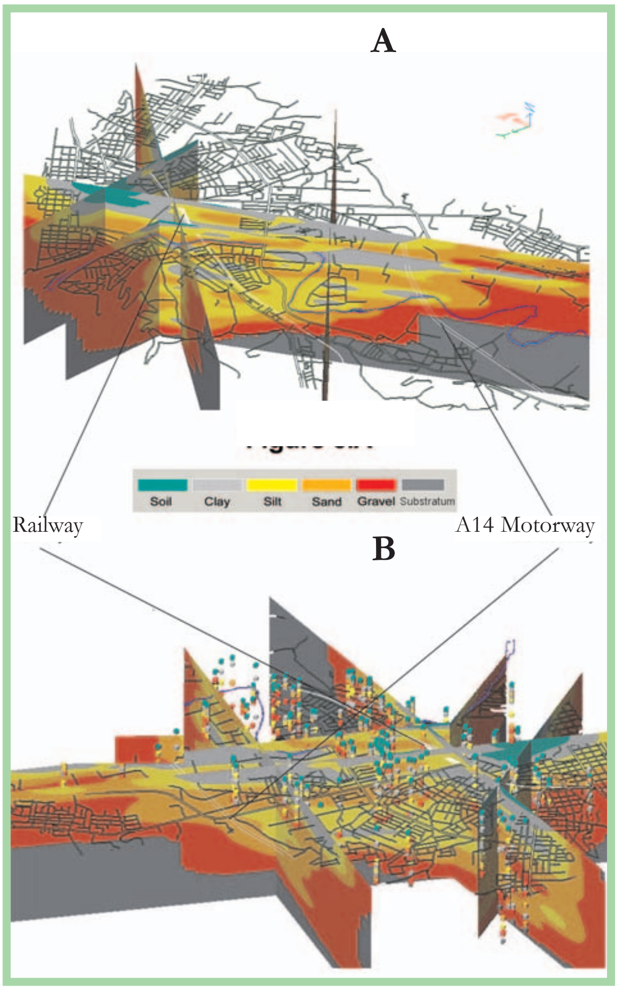

Fig. 6 - A: Longitudinal and trasversal section, view from NW to SE; B: Longitudinal and trasversal section, view from S to N.
- *A: Vista delle sezioni longitudinali e trasversali da NW verso SE; B: Vista delle sezioni longitudinali e trasversali da S verso N.*

7.1. - Comparison with traditional sections

The cross-sections extracted from the 3D model are coherent with elaborations carried out according to the classic interpretative methodologies (fig. 7A). In fact, using the same data input, a comparison of the "traditional" sections with those supported by geostatistical investigation was carried out and the geological settings and the information obtained were rather uniform. Figures 7B and 7C present two portions of "traditional" sections compared with portions of sections from the 3D geologic model on adjacent areas. Although it is difficult to try to represent the sections obtained by the model on the same axes on which the sections have been made following the manual technique, because of sections representation are 3D space and not on level, and considering that 3D sections are amplified 15 times along Z axis while the manual sections are amplified 10 times, it is clear at a glance how both sections provide the same geological meaning.

The cross-section of figure 7B, oriented SW-NE, shows the prevailing gravelly deposits with lenses of clay and clayey silts that are laterally discontinuous and become mainly made up of fine materials ending with bodies of rough granulometry. Figure 7C displays the section of alluvial deposits in direction NW-SE. In this case too, the geological meaning is substantially identical, even if problems of proportions and dimensions of the bodies make themselves not well visible. The gravels sediments are deeper and continuous in contact with the substratum and the fine sediments, essentially muddy and clayey, are very much widespread. The alternations of sandy, muddy-clay and muddy-sand bodies towards SE are represented in extended lens structures, which indicates a variation in energy during the sedimentation event.

8. - NEW KNOWLEDGE FROM THE 3D MODEL

The 3D geological model of the lower Foglia River valley allows some considerations about stratigraphy and sediments assessment. In fact a 3D model offers an integrated approach and a more realistic geological representation of the site assessment. The visualization tools (different kind of 3D object, different trasparency degree) allow the geologist to see, to move, to rotate and to go through the alluvial bodies that characterized the geological assesment of the study area.

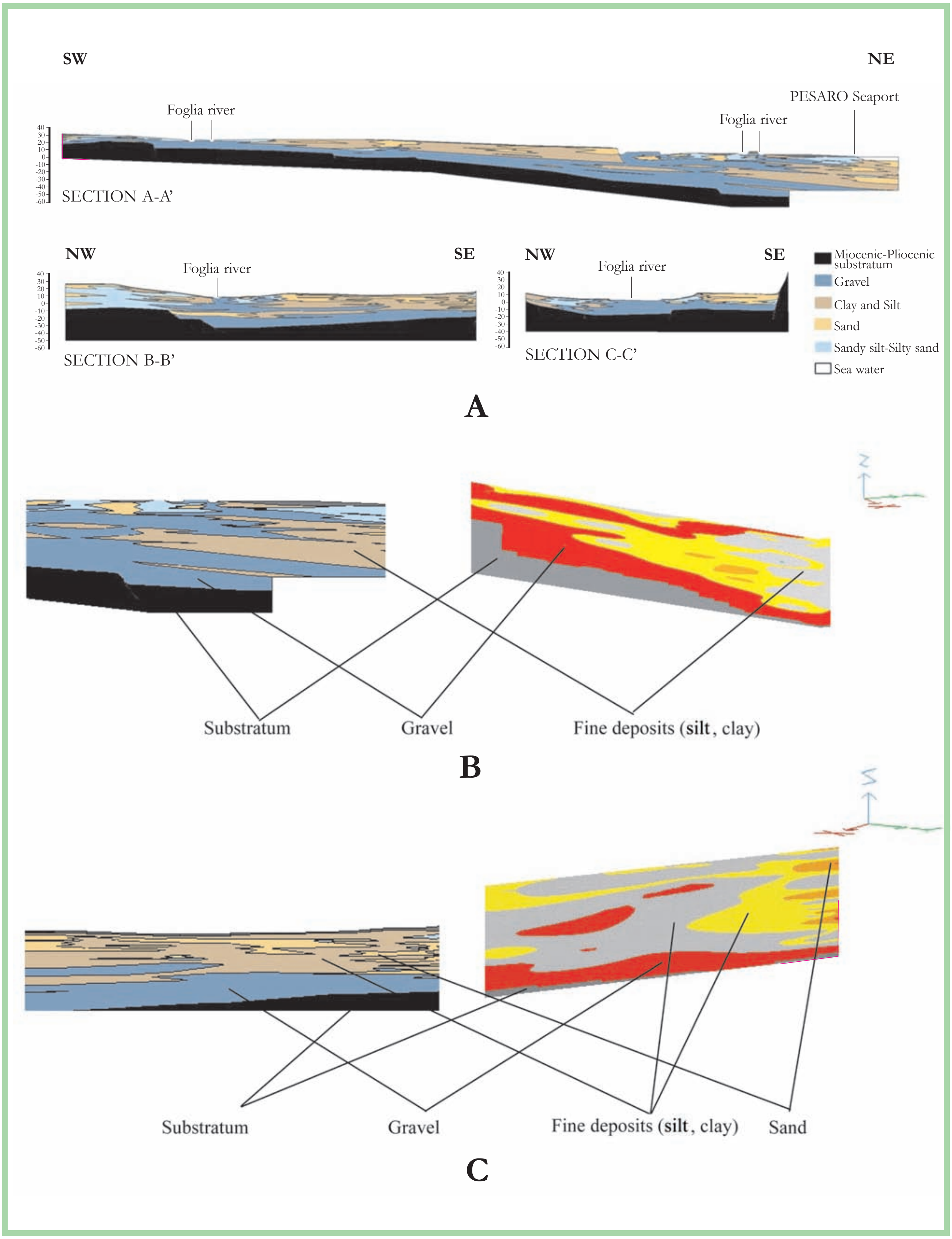

Fig. 7 - A: "Traditional" geologic cross-sections (courtesy of Pesaro Municipality); B: "Traditional" geologic cross-section and geologic cross-section obtained by 3D model oriented SW-NE; C: "Traditional" geologic cross-section and geologic cross-section obtained by 3D model oriented NW-SE.
- *A: Sezioni geologiche "tradizionali" (cortesia Comune di Pesaro); B: Sezione geologica "tradizionale" e sezione geologica dal modello 3D orientata SW-NE; C: Sezione geologica "tradizionale" e sezione geologica dal modello 3D orientata NW-SE.*

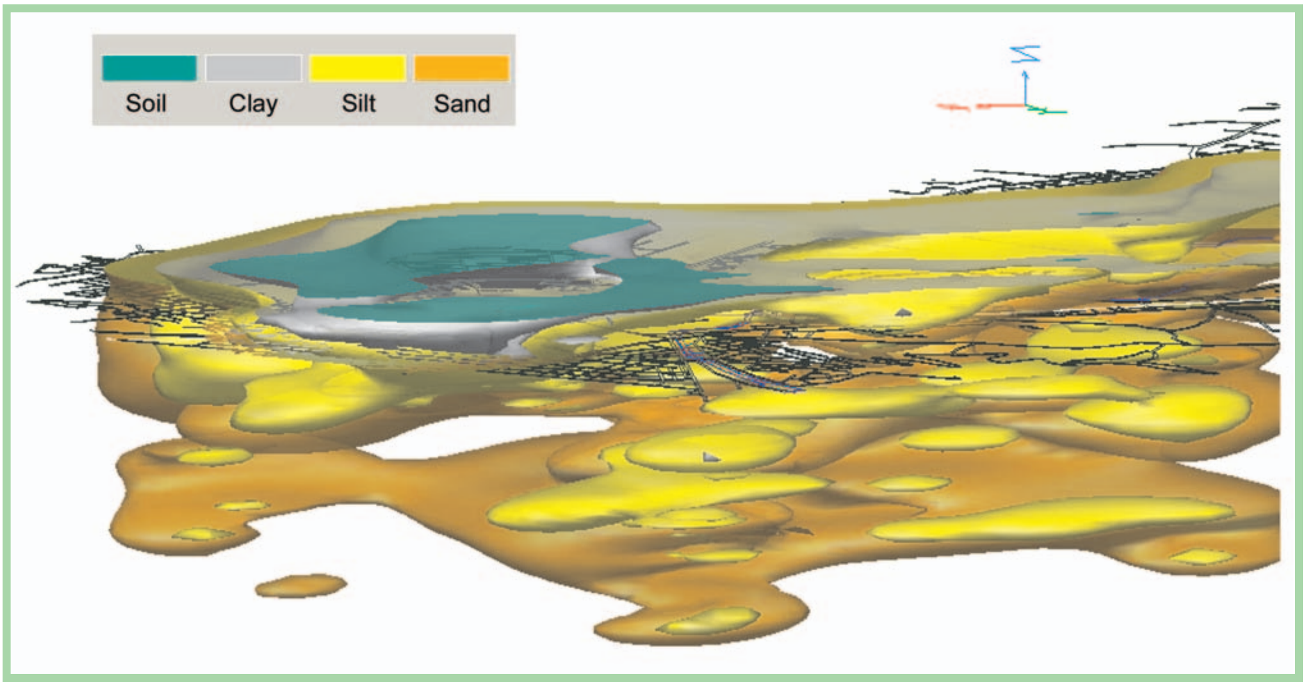

Fig. 8 - Representation of the fine-grained deposits, view from N to S.
- *Vista dei corpi fini (limi e argille) da N verso S.*

The 3D views offer a unique representation of the model that different people can see at the same time, suggesting different considerations and a discussion opportunity.

8.1. - PHYSICAL STRATIGRAPHY

The alluvial body is mainly made up of gravelly-sand and presents a reasonable continuity in depth with intercalation of muddy-clayey layers sometimes of relevant thickness, but laterally discountinuous (fig. 6A and 6B). Moreover, two significative levels of muddy-clayey sediments stand out: the first, superficial, about 20 meters thick, is particularly visible in the SE area of Pesaro between the A14 Motorway and the railway; this assesment and these deposits can be connected to a flood plain environment (ELMI *et alii*, 1983). The second level subdivides the main gravelly-sand body towards the mouth, in two/three levels, without a clear separation. The clayey-muddy levels come closer to the surface near the mouth, according to fining upward sequence connected to the succession of erosional/depositional cycles (ELMI *et alii*, 1983).

The rough sediments are well distributed both on the right and on the left sides of the alluvial basin. Fine sediments (clay and mud) are particularly developed on the hydrographic right, connected to the third order terrace. Their distribution looks compact and uniform laterally up to 6 meters depth, with lenticular bodies, eteropic, without lateral countinuity and alligned mainly in a SW/NE and W/E direction (fig. 8). The geological-structural features of substratum, charaterized by the presence of a fault covered by quaternarly deposits (fig. 1), the current structure of Foglia River (binding strongly on the hydrographic left), the alluvial terraces assessment and the depositional setting of fine sediments (more developed on the hydrographic right and on the surface), allow to reconstruct the following paleographic evolution of the study area:

Depositional phase of T3. It is characterized by a high-energy phase that progressively tends to diminish, leaving fine sediments on the right and rough deposits on the left (the raising begins);

Depositional phase of T4. The raising is more evident and the erosive-depositional phase (NESCI & SAVELLI, 1991) is affected by this difference in altitude. T3 is re-shaped on the right, while sediments remain on the left.

The considerable extension of T4 in the last stretch of the river indicates aggradation phase, probably caused by subsidence (GUERRERA *et alii*, 1978). The morphology of deposits indicates a recent active tectonic phase, developed along a N-S to NW-SE direction, confirmed by tectonic evidences right transform, having two kilometer displacement below the alluvial deposits (GUERRICCHIO, 1990).

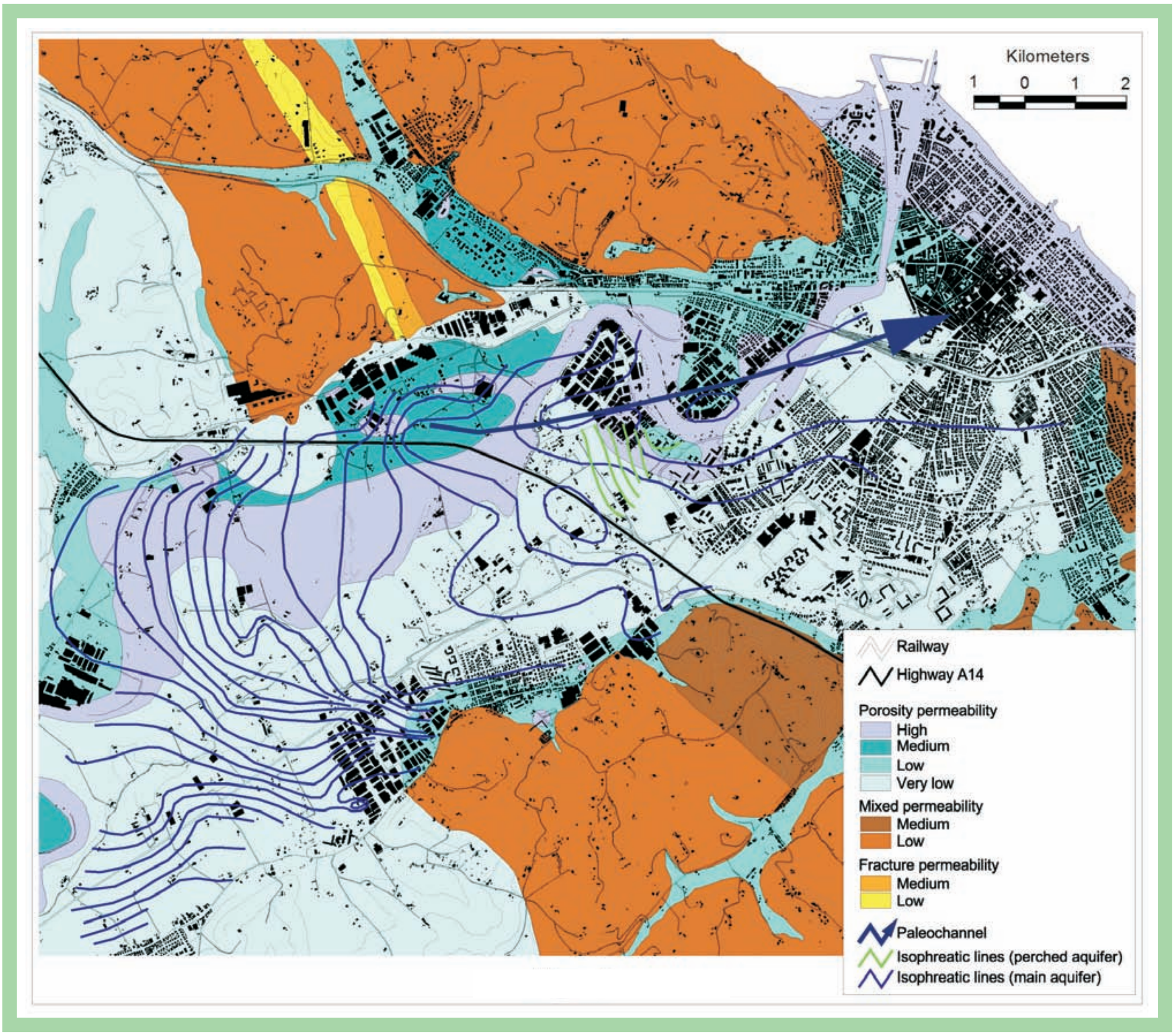

Fig. 9 - Hydrogeologic map showing the position of the paleo-channel (courtesy of Pesaro Municipality).
- Carta idrogeologica con evidenziato il tracciato del paleoalveo (cortesia Comune di Pesaro).

8.2. - Hydrogeology

The alluvial Foglia deposits are the site of a phreatic aquifer. It is subdivided in three bodies by silt, clay and clay silt deposits but without a complete separation of it (semiconfined aquifers) as shown in the 3D model. These levels, thicken towards the coast line, allowing exchange of water in the main aquifer do not strictly define a confined aquifer. The main aquifer is mainly constituted by gravel and sand, enough isotropic and homogeneous and it is highly vulnerable; large and muddy-clayey bodies near the surface are important for its protection, limiting and delaying the increase in hydrodiffused pollutants (fig. 6A, 7A). The water table lies, on average, between 12 and 14 meters below the ground surface.

Also clay levels are present at shallow depth (4-6 m) having enough thickness to keep groundwater originated by meteoric waters infiltration (perched aquifer) isolated but with no exploitation interest (fig. 9). The clayey levels are important to locally protect groundwater, because they limit and retard the transport of pollutants, but their extension is not sufficient to protect the main aquifer. Local discontinuity and heterogeneity are present and these are typical of braided river environment.

The most important erosive depositional event is, undoubtedly, the T3 formation which has shaped the sedimentary and hydrogeological setting of the Foglia River valley. A paleo-channel about 4 km long between the motorway and the railway axes in WSW/ENE direction is present in T3 deposits. This geological feature is quite visible in 3D model (fig. 6A, 6B) and it is also confirmed by hydrogeological evidences such as piezometry and conductivity data (fig. 9; ELMI *et alii*, 1983).

9. - CONCLUSION

This work presents a new methodology technique to visualize and analyse geological data. It allows the execution of query and extraction of data useful for the elaboration of a new thematic map and to realize new themes for GIS application. This approach consists of several steps:

1. Data validation: it consists of an attribution of a "degree of interest" and a "degree of quality" to each datum (stratigraphy obtained by investigations);
2. Data simplification: it consists of reducing the different descriptions of strata in few main classifications;
3. GIS: it consists of building up a Geodatabase for georeferencing all data (stratigraphy, drill typology, in-situ and laboratory tests, depth of water table);
4. 3D Geostatistics: using this elaboration technique we have realized a geological three dimensional model of the low Foglia River alluvial deposit.

The 3D model and the use of viewing and analysing tools help us to evaluate the mathematical elaboration obtained and to better understand the stratigraphic setting of the study area. In fact, the model and the cross sections obtained from the 3D model (also compared to "traditional" manual ones realized using the same data) show that the geostatistical elaboration works rather well where there are enough data but not in the boundary areas where a strong control to reduce the "edge effect" is needed. The 3D geostatistical model also allows some more accurate considerations on geology and hydrogeology:

1. The fluvial body of the low Foglia valley consists mainly of fluvial deposits of the third order terrace made up of gravelly-sand with a reasonable continuity in depth.
2. Lower Foglia River alluvial deposits are highly distributed. The thickness varies from 8/9 meters to 50 meters and more, going towards the coast.
3. Two main levels of fine sediments are evident: the first, superficial and about 20 meters thick, is particularly visible between the A14 motorway and the railway; The second level does not interely divide the main gravelly-sand body (where the main aquifer is located) in two/three minor levels.
4. The shallow fine sediment level is thick enough to isolate groundwater but is not laterally continous, and therefore it represents an important factor to protect locally the main aquifer from pollution.
5. The second deeper layer of finer sediments does not separate the permeable deposits in a multilayer aquifer, because they are semi-impermeable and not laterally continous.
6. There is evidence of an important paleochannel also confirmed by hydrogeological data.

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