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Three-Dimensional Model of the Aquifers of the Lombardian Po Plain

Modello tridimensionale degli acquiferi della pianura lombarda

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Abstract - The Po Plain is the widest alluvial plain in Italy where the industrial and civil demand for water resources is very high. Getting to know the structure of the aquifers is one of the targets of a number of administrations and companies working on this research field. The collaboration between the Office of Geological Cartography of the Lombardia Region, which elaborated a number of papers and maps of the Po Plain aquifers, and the Laboratory of Information Technology for Earth and Environmental Sciences of the University of Urbino, allowed to build a three dimensional model of the structure of the four groups of the aquifers of the Lombardian alluvial Plain.

In order to prepare the files for 3D elaboration the contour maps of the bottom of each of four groups of aquifers, the maps of the cumulative content of sand and other maps (i.e. the boundary between fresh and salt water), already derived from the processing of geophysical data (i.e. seismic reflection profiles), borehole data, well logs, and hydrogeological research integrated with the DTM and the land use map of the area have been imported in CAD/GIS environment (Microstation by Bentley, ArcView by ESRI, Sharc and ThreeX by Terranova). The surfaces of the bottom of each group of aquifers have been built using a 3D modelling software (3DMove by Midland Valley Exploration Ltd.), in order to process a visual and numerical analysis of their morphology and, consequently, to evaluate the total volume actually available (and with the integration of the sand-content maps the effectively available one). A preliminary analysis of fluid migration has also been integrated with the maps of recharge areas and land use in order to assess the aquifers vulnerability at a regional scale.

This sort of pilot project showed that a 3D model can provide highly accurate information which can be integrated with other data and used for many purposes so as to develop a sort of 3D GIS for expert users. On the other hand, a 3D model of easier use could spread the geological knowledge lay men such as politic administrations in order to develop a conscious way of thinking and of managing precious water resources.

Key Words: 3D Model, CAD/GIS, Aquifers, Water Resources, Lombardian Po Plain.

Riassunto - La Pianura Padana è la pianura alluvionale più ampia presente in Italia. In quest'area la domanda di risorse d'acqua per scopi civili ed industriali è estremamente elevata. La conoscenza della struttura degli acquiferi è quindi uno degli obiettivi sensibili di molti amministratori e compagnie che lavorano in questo settore della ricerca. La

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collaborazione tra l'Ufficio di Cartografia Geologica della Regione Lombardia e il Laboratorio di Informatica applicata alle Scienze della Terra e Ambientali dell'Università di Urbino, ha permesso di costruire un modello tridimensionale della struttura profonda di 4 gruppi di acquiferi presenti nell'area lombarda.

Per lo sviluppo del modello 3D sono stati importati in ambiente CAD/GIS (Microstation by Bentley, ArcView by ESRI, Sharc and ThreeX by Terranova) per essere rielaborati: (i) le carte delle isopache del limite inferiore per ogni gruppo acquifero, (ii) le carte del contenuto cumulativo di sabbia, (iii) altre carte (come ad esempio quella del limite tra acqua salata e acqua dolce), già ottenute dall'elaborazione di dati di geofisica (profili di sismica a riflessione), dati di pozzo, stratigrafie di pozzo e indagini idrogeologiche, integrati con DTM e carte dell'uso dei suoli. Con l'applicazione di un software per la modellizzazione in tre dimensioni (3DMove della Midland Valley Exploration Ltd.) sono state costruite le superfici corrispondenti al limite inferiore di ogni gruppo acquifero. Ciò ha permesso un'analisi numerica delle strutture profonde e di conseguenza la stima del volume totale effettivo disponibile. Un'analisi preliminare della migrazione dei fluidi è stata integrata con le carte dell'uso dei suoli della zona in esame, per stimare la vulnerabilità degli acquiferi a scala regionale.

Questa sorta di progetto pilota ha dimostrato che un modello 3D può fornire informazioni molto accurate che possono essere integrate con qualsiasi altro dato e per qualsiasi scopo, sviluppando una sorta di 3D-GIS per utenti esperti del settore. D'altro canto, un modello 3D di facile comprensione può diffondere le conoscenze geologiche tra le persone non addentro all'argomento, tra cui gli amministratori politici, per sviluppare un modo di pensare "cosciente" nella gestione di risorse preziose quali l'acqua.

Parole Chiave: Modello 3D, CAD/GIS, Acquiferi, Risorse idriche, Pianura Padana lombarda.

1. - INTRODUCTION AND AIMS

The study of the alluvial plains is particularly important for the geological and hydrological knowledge, as these are areas where the concentration of the population and of the antropic activities is very high (Martinis *et alii*, 1976). This study focuses in particular on the Lombardian Po River Plain (fig. 1). With an extension of about 17.500 Km² (corresponding approximately to the 38% of the whole Po River Plain and of the Venetian Plain), the Lombardian Plain is bounded by the Alps to the North, by the Apennines and by the border of the Emilia-Romagna Plain to the South, by the border of the Veneto Plain to the East, and by that of the Piedmont Plain to the West.

The Lombardia Region has been engaged for years in basic and applied research on the territory of the Po Plain under its jurisdiction (Carcano & Piccin, 2002). In recent years, the Region has started a collaboration with the Laboratory of Information Technology for Earth and Environmental Sciences (LINEE) of the "Carlo Bo" University of Urbino, where techniques for the construction and analysis of 3D models in virtual reality are applied (De Donatis *et alii,* 2002), in different research fields of the Earth Science. The above mentioned collaboration produced this study, which allowed an advanced visualization system and a three dimensional analysis of the main aquifers groups of the Lombardian Plain.

A 3D model of the subsurface and the location of permeability barriers of basinal extent are extremely important to the Regional authorities involved in preserving and developing the ground-water reservoirs. The present work was carried out in order to:

1 . develop a 3D model of the subsurface by the integration of seismic and stratigraphic data;

2 - provide a tool for the computation of the subsurface water reservoirs and of the water balance of the Po River Plain;

3 - define the flow-pattern from recharge areas to the deepest part of the aquifers;

4 - locate new, deep and sealed aquifers that might ensure strategic water reserves.

2. - GEOLOGICAL SETTING

Ground waters of the central-eastern Po River Plain are located mostly in the continental and marine strata of Plio-Pleistocene age. This sedimentary sequence is overall regressive and consists of basal turbiditic sands and clays, overlain by a prograding fluvio-deltaic sedimentary wedge, capped by continental sediments (Regione Emilia-Romagna & ENI-AGIP, 1998; Carcano & Piccin, 2002).

Three progradational directions of the wedge

Fig. 1 - Map of the Po River Plain and adjoining areas. The red polygon indicates the study area.
- *Carta della Pianura Padana e zone circostanti. Il poligono rosso delimita l'area di studio.*

can be recognized on seismic profiles:

1 - Eastward, axial, low-angle progradation, originated by the paleo-Po river delta system;

2 - South-eastward, transversal, high angle progradation fan delta systems originated by the Alpine Rivers;

3 - North-eastward, transversal, high angle progradation fan delta systems originated by the Apennine Rivers.

Slope, outer-shelf, inner-shelf, deltaic, coastal and alluvial deposits are identified within wedges by means of seismic and well data interpretation. Depositional systems of the Alpine Rivers are strongly affected by the late Pliocene morphology. During the Upper Miocene – Pliocene, a sequence of tectonic phases mainly developed in the Apennine domain tilt southward the basin and this, joined with the Late Miocene sea level fall, results in the excavation of deep and narrow submarine canyons. Canyons are then filled by turbidites on which prograde Alpine Rivers delta fans; along the frontal section, they interfere with the paleo-Po river axial system. The Po river system is characterized by slope and outer shelf deposits, mostly clay, covered by coarse littoral and inner platform sediments that evolve upward into continental alluvial plain.

Along the Alpine and Apennine piedmont areas, Plio-Pleistocene reservoirs reach the surface. Coarse grained marine deposits are very deeply flushed by fresh water (e.g. –750 m b.s.l. AGIP well "Lambrate", eastward of Milano and –720 m b.s.l. AGIP well "Tollara1", southward of Piacenza).

Four main Surfaces of Stratigraphic Discontinuity (S.S.D.), of basinal extension, have been identified and mapped (tab. 1). The most prominent of them (point 3) was recently redefined by means of magnetostratigraphy integrated with new biostratigraphic data (MUTTONI *et alii*, 2003). The palaeogeography corresponding to each discontinuity is summarized as follows:

1 - S.S.D. 1.700.000 years before present (y B.P.): Po Valley is a marine basin, the slope extends along the northern margin of the basin from the Maggiore to the Iseo lakes, and on the southern margin along the front thrust of the Apennines from S. Colombano along the Emilian folds.

2 - S.S.D. 1.200.000 y B.P.: the less subsiding portion of the basin is filled by the fan delta deposits of the Alpine rivers (Ticino, Adda) and the Po system. The slope moves East of Cremona. The mid-west Lombardia section of the area is a marine shallow platform. At this time the important northward movement of the Apennine thrust starts. In the next 330.000 years the uplift and associated erosion of the Ferrara area occurs together with a reduced subsidence in the Bologna-Ravenna piggy-back basin.

3 - S.S.D. 870.000 y B.P.: the Po River Plain records a general increase of sediment coarseness. The transition from sand bearing fluvial systems, mainly flowing longitudinally parallel to the southalpine belt, to a rapidly prograding alluvial fans and coarse-grained braided fluvial systems, is related to the MIS22, the first prominent glacioeustatic lowstand of the Pleistocene. Climatically driven devegetation, eustatic lowstand, and erosion were responsible for this new basin-wide scenario.

4 - S.S.D. 450.000 y B.P.: the Po Valley acquires continental sedimentary conditions. The fresh-brackish water contact (FBC) is related to the sedimentary history of the basin. Along the Po River system, characterized by mostly thin sediments, the FBC is rather shallow: 300 to 400 m b.s.l.. Because of fresh water flushing, in the areas where coarse sediments of the Alpine rivers fan deltas exist, the FBC is as deep as 750 m b.s.l.

The Surfaces of Stratigraphic Discontinuity were originated both by the combined effects of tectonic uplift and by sudden isostatic subsidence of the basin. The superposition of eustatic sea level rise and climatic de-activation of fluvial systems on such a basinal subsidence resulted in 8 to 20 m of thin sediment (mostly clay) spread over most of the basin. These layers are outstanding vertical seals and allow to define four Aquifer Groups (D to A from bottom to top), bounded by the cited S.S.D.

3. - FIELD AND CARTOGRAPHIC DATA

The field data that have produced the cartographic elaborations (CARCANO & PICCIN, 2002) result from the analysis of:

1) 40.000 km of seismic lines, acquired by ENI-AGIP for hydrocarbon exploration (fig. 2a);

2) 330 AGIP wells bored for hydrocarbons exploration and production (fig. 2b);

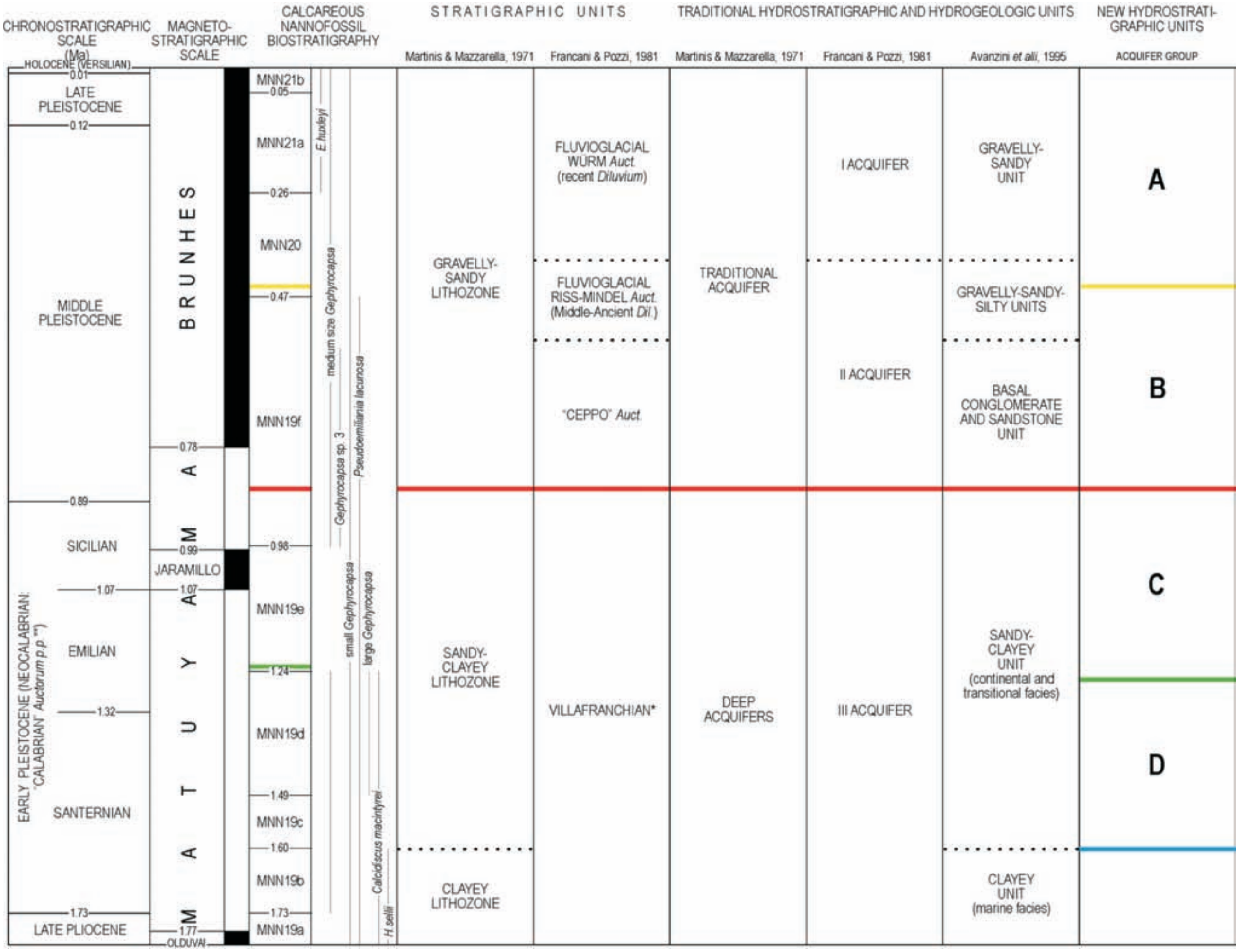
3) 5000 stratigraphic columns of water wells (fig. 2b);

4) 11.000 m of continuous cores from boreholes drilled specifically for the Regione Lombardia (fig. 2b);

5) Geological field mapping at 1:10.000 scale of the Alpine and Apennine piedmont area.

The maps used for the three dimensional reconstruction of the Lombardian Plain subsurface have been generated by the Regione Lombardia, and are made up of:

Tab. 1 - *Stratigraphic position of Aquifer Groups A, B, C and D.*
- Posizione stratigrafica dei Gruppi Acquiferi A, B, C e D.



- *maps of isobaths*: in "two-dimensional dxf" format relative to the base of the four groups of aquifers;

- *maps of sand-contents*: in "dxf", relative to the four aquifers;

- *maps of the interface fresh/brackish water*: for the C and D Aquifer Groups.

These maps show a different data quality because of the poor quality of the seismic data in the more superficial layers, as they had been processed for the study of deeper objectives (hydrocarbons). In the maps of sand contents (fig. 3), each contour represents the cumulative thickness of sediments having a permeability that make them potentially useful aquifers; therefore the grain size classifications taken into account for the computation of the so called sand content range from cobble (64-256 mm) to very fine sand (0.063-0.125 mm).

Other maps relevant to the computer model are:

- DTM of the Lombardian Plain area, available in "ascii Grid" of Arcinfo;

- land use map, in "shp" format of ArcView;

- toponyms map, in "shp" format.

4. - THREE DIMENSIONAL MODEL CREATION

The three dimensional reconstruction of aquifers was made possible by combining different information systems: for the hardware, Windows and Linux-operated workstations and powerful graphics accelerators. The combinations of software employed are CAD/GIS systems (Microstation V8 by Bentley, ShArc 4.0 and ThreeX 2.2 by Terranova and ArcView GIS 3.2 by ESRI) and software for modelling in two and three dimensions (2Dmove and 3Dmove by Midland Valley Exploration).

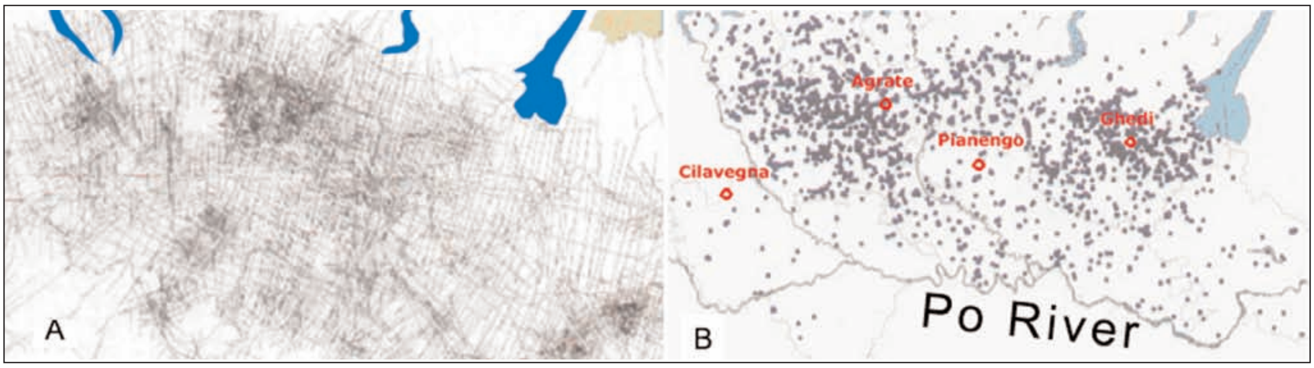


Fig. 2 - Location of data sets: A) reflection seismic lines; B) water and hydrocarbon exploration well stratigraphies and four continuous core log boreholes.
- Distribuzione dei dati: A) tracciati delle linee sismiche a riflessione; B) pozzi esplorativi per la captazione dell'acqua e degli idrocarburi e quattro sondaggi a carotaggio continuo.

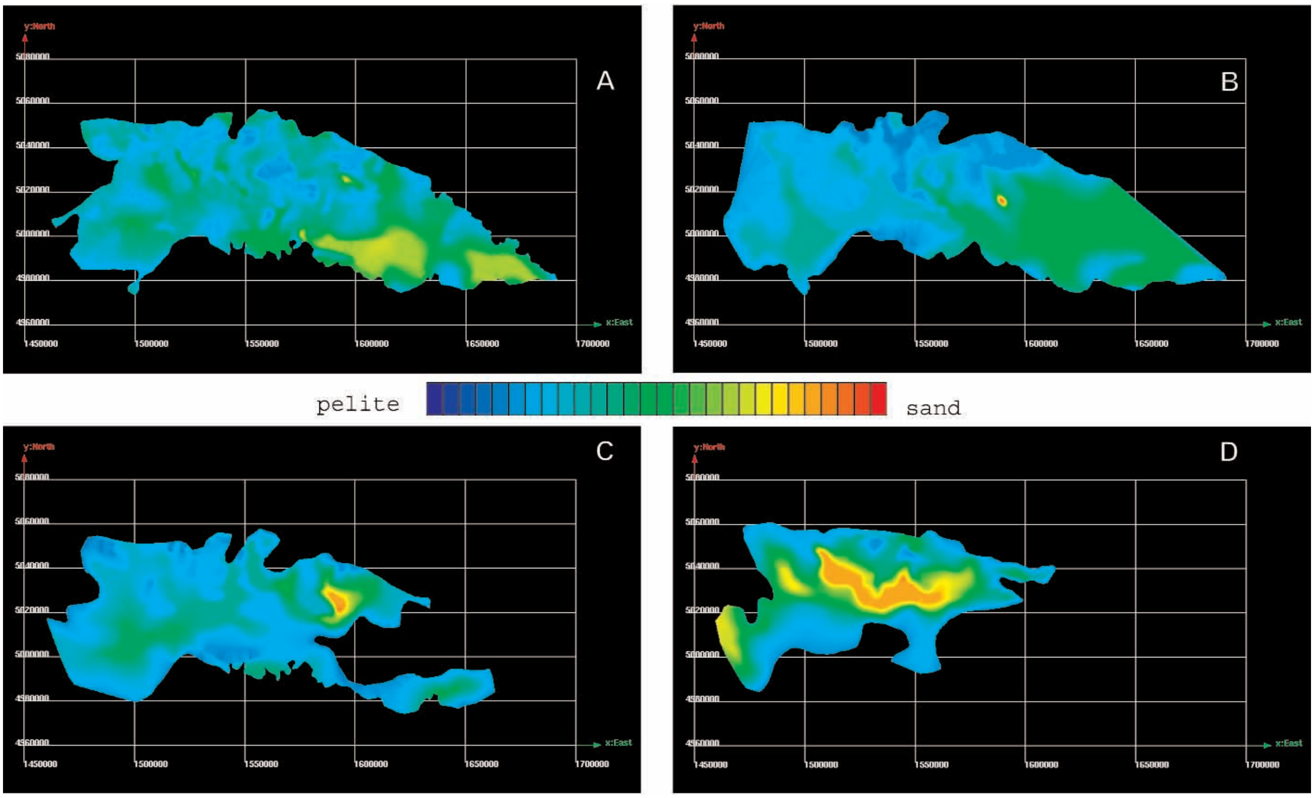


Fig. 3 - Maps of the sand content of Aquifer Groups A, B, C and D (cf. table 1). Red colour indicates sand, dark blue colour pelite.
- Mappa del contenuto in sabbia dei diversi Gruppi Acquiferi: A, B, C e D (c.f tab. 1). Il colore rosso indica zone a più alto contenuto in sabbia, il blu quello in pelite.

The contours maps of the four Aquifer Groups boundaries, georeferenced in the UTM coordinate system (example in fig. 5), have been imported in Microstation to provide each line with the altitude/depth attribute (z), necessary to positioning the whole map in the three dimensional space.

These files of points have been imported in 3DMove, where they have been interpolated by means of an appropriate algorithm to obtain three dimensional surfaces (fig. 6).

This algorithm (tesselation algorithm) uses each given point to build a surface made up of triangles (TIN) whose vertexes are original points. The density of triangles shaping the new surface is directly proportional to the density of points that have originated it.

The operations so far described have been applied to the four maps of the four aquifers bases (fig. 6), and the surfaces obtained in this way have been positioned in a single virtual space, in order to get a first 3D model. Also the Digital Elevation Model (DEM) has been converted and imported in 3Dmove through: TN3D, TNShArc,

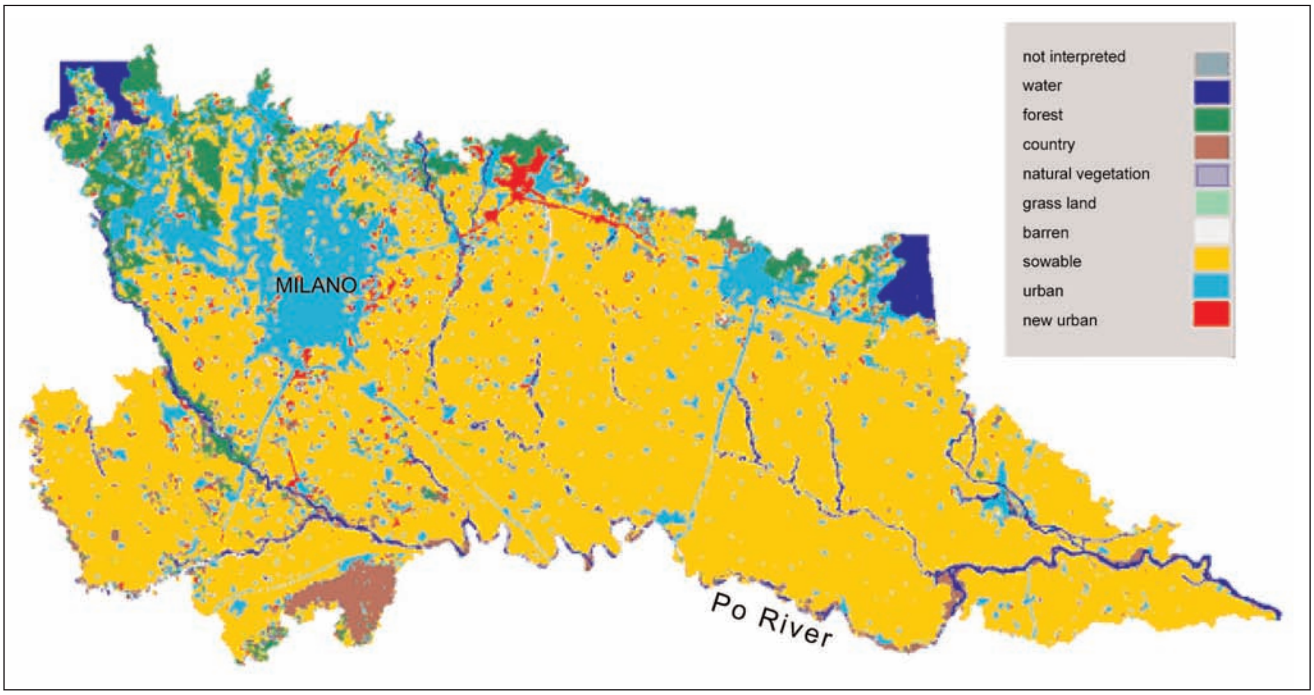


Fig. 4 - Land use map of the studied area; urban areas are in red and blue (cf. figure 1).
- Carta dell'uso del suolo (cf. fig. 1).

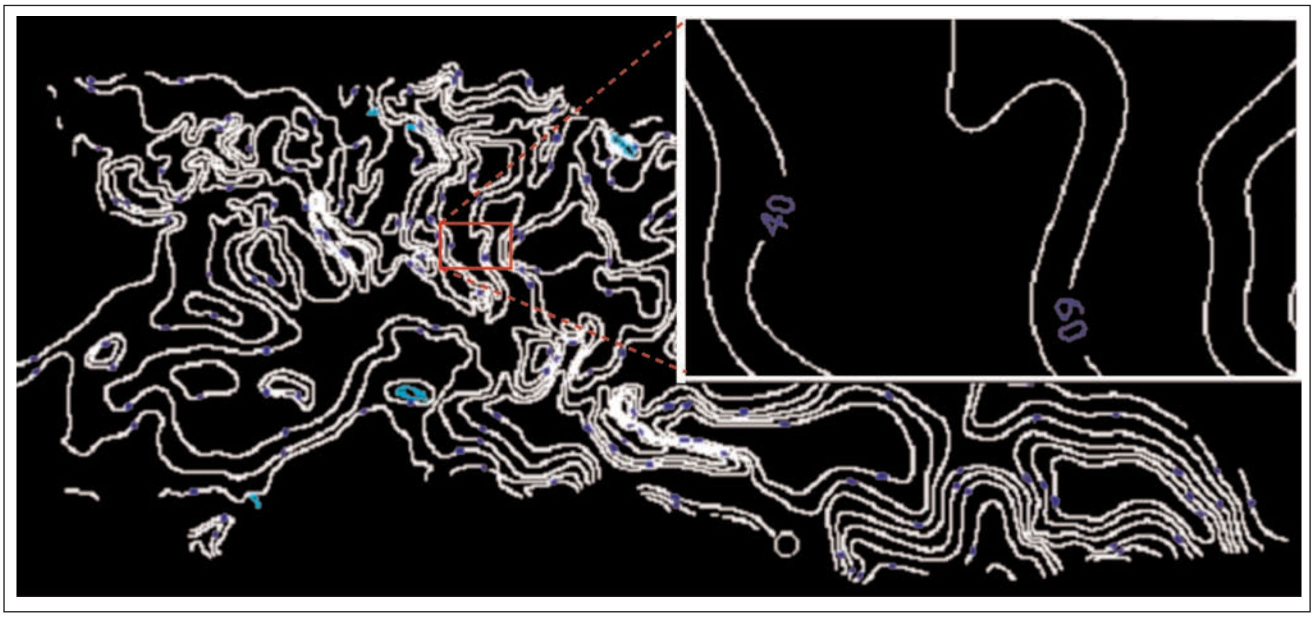


Fig. 5 - Example of contour map of the base of Aquifer Group B. In the inset a detail of contours.
- Esempio di mappa ad isolinee della base del Gruppo Acquifero B. Nel riquadro un dettaglio delle isolinee.

Microsoft Excel. Through the TN3D, it has been possible to create a TIN, starting from the ascii Grid file that has been subsequently exported as "file of points" (shape file of points).

With the Terranova ShArc, it has been possible to convert the DTM in "shape" format, elaborated in TN3D, in "*.txt", and then in "*.dbf", modified by Microsoft Excel. In this way a "*.txt" file has been obtained, importable in 3DMove so as to complete the three dimensional model (fig. 7). The 3DMove software allows to manage both vector and raster georeferenced data. These latter cannot be directly imported, but can be used as "texture" on pre-existing surfaces. Therefore it was impossible to apply the map of the land use (fig. 8), carried out through TN ShArc to the DEM of the three dimensional model.

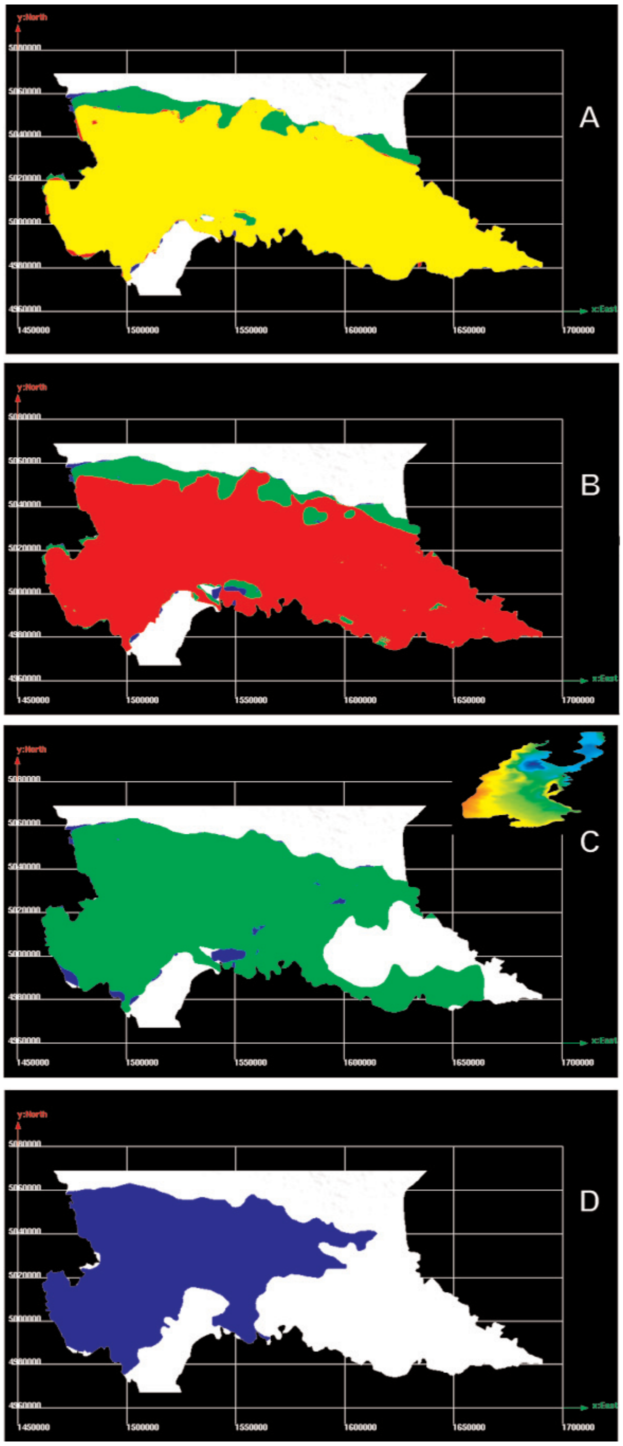


Fig. 6 - Areal distribution of the aquifer boundaries from A to D; the detail is a view from SW of the C/D boundary.
- Distribuzione areale dei limiti tra i vari Gruppi Acquiferi: da A a D. Nel dettaglio vista da SW del limite C/D.

Eventually, a volumetric model of the aquifers has been built in 3DMove (fig. 9). In this way it is possible to calculate the volume between two superimposed surfaces, generating and filling in the space between them with tetrahedrical elements which do not need to be regularly shaped.

5. - AQUIFERS CHARACTERIZATION

The three dimensional model of the aquifers in the Lombardian Po Plain allows a general outlook of the structure of the area under study together with qualitative and quantitative hydrogeology.

5.1. - Morphological description of aquifers

By increasing the scale of the depth with a vertical exaggeration equal to 10, the lateral variations in shape can be better highlighted (fig. 8). The shallower Aquifer Group (A, in yellow) is characterized by a gently increasing thickness moving from North towards South, where deposits reach the greatest thickness. The same happens when moving from West towards East. The B Aquifer Group, too, is characterized by a general thickening of the deposits in the southeastern area of the model. The deepest Aquifer Groups (C and D), conversely, are more influenced by the tectonic structures affecting the substrate and show a number of lateral variations in shape and thickness.

Through software, both 3D contour maps, exportable as three dimensional DXF files, and sections in any spatial direction can be obtained.

The creation of geological sections on the model allowed to highlight more carefully the geometry of deep basal surfaces. Fig. 9 shows cross-sections orthogonal to the deposition axes and a longitudinal section extracted from the model. In these sections the geometries that grow thins towards North-West, and the irregular geometries of the deepest aquifers groups base connected to the shortening structures existing in the substratum are clearer.

5.2. - Calculation of volumes

The three dimensional definition of the surfaces bounds of aquifers groups allows to easily reconstruct the volumes included between the horizons and the volumetric computation (tab. 2). By using the sand content maps previously described, it was possible to calculate the aquifers' useful volume that can be exploited, a value that may be used in hydrogeology to go back up to the aquifers' potential storage capacity.

In table 2 the volumes of a useful aquifer and the minimum and maximum thickness for each Aquifer Group are represented. The biggest volumes in sands and gravels belong to Aquifer Group A; in particular, the largest cumulative thickness is found in the areas of the Cremona and Mantova provinces. On the other hand, deep aquifers groups contain a quantity of sand hardly negligible, which allows a wider exploitation of their water.

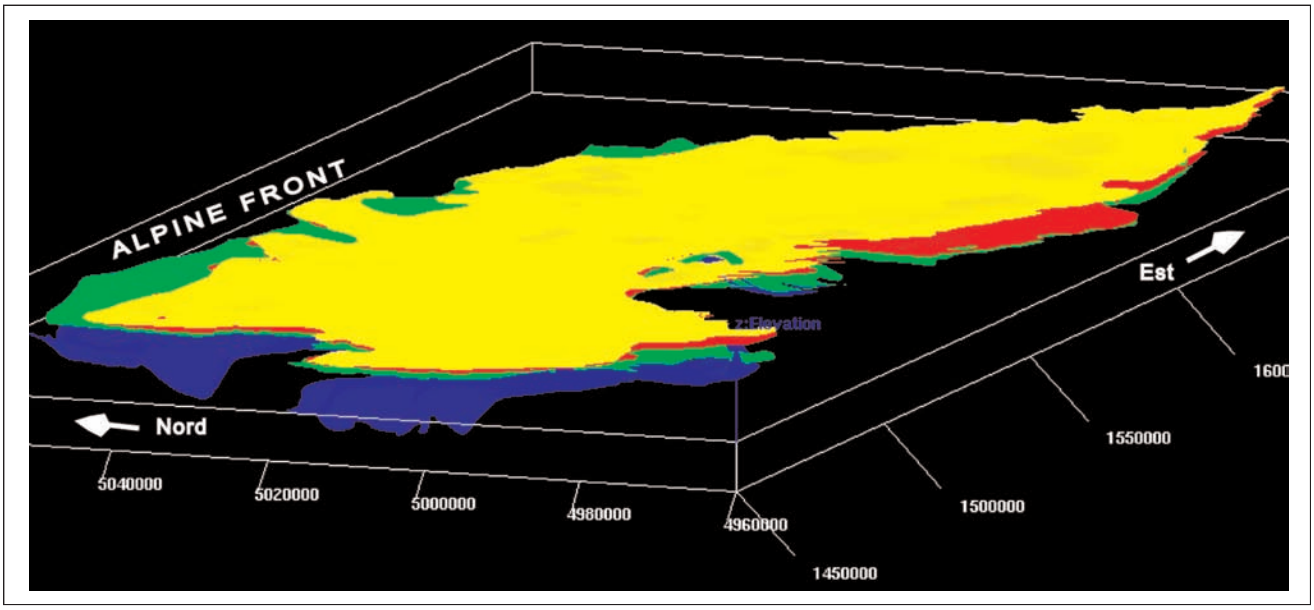


Fig. 7 - The three dimensional models of the boundaries between the four Aquifer Groups (view from W, vertical exaggeration 10x).
- Modello tridimensionale dei limiti tra i quattro Gruppi di Acquiferi (vista da W, esagerazione verticale 10x).

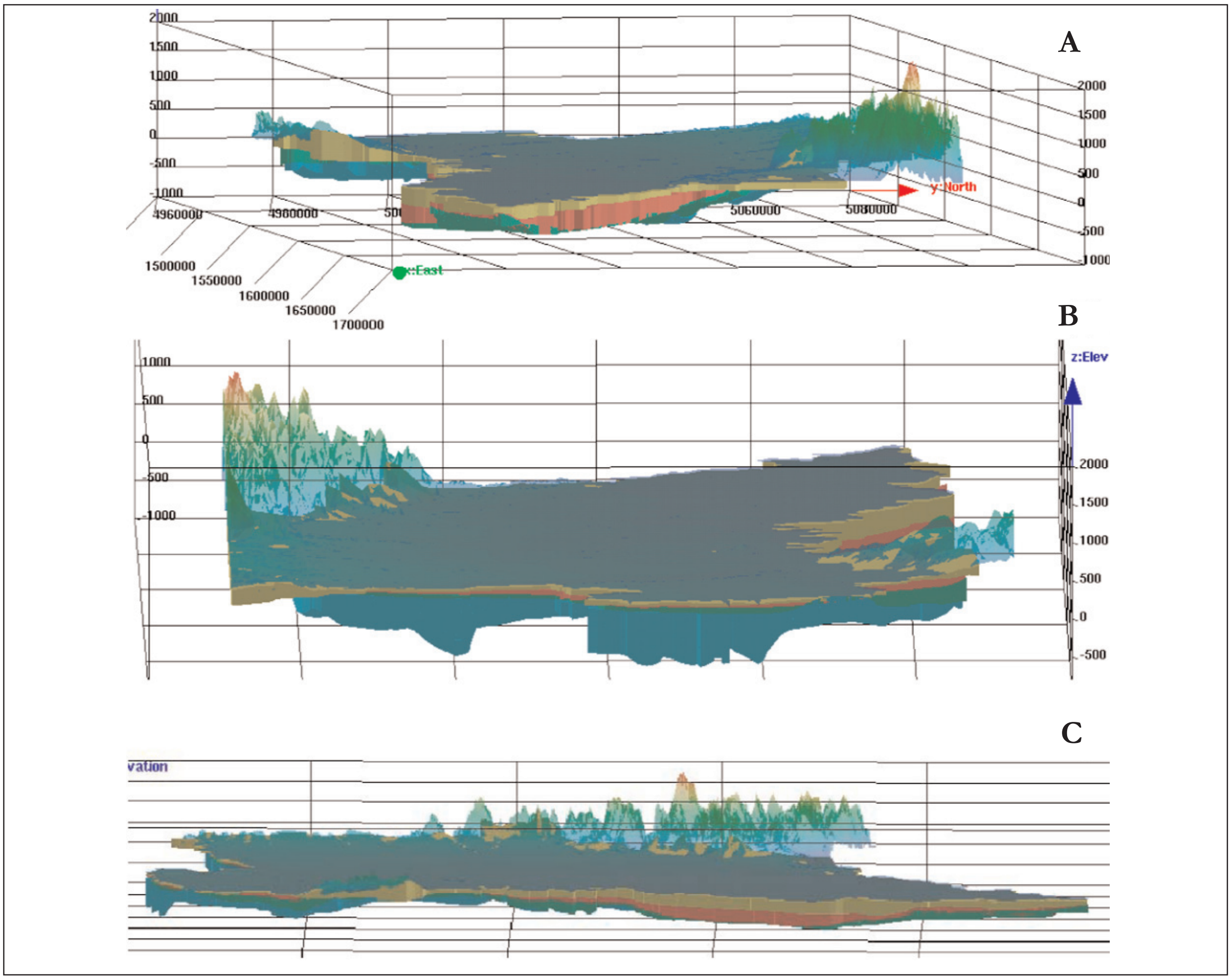


Fig. 8 - Volumetric model: A) view from East; B) view from West; C) view from South.
- Modello volumetrico: A) vista da Est; B) vista da Ovest; C) vista da Sud.

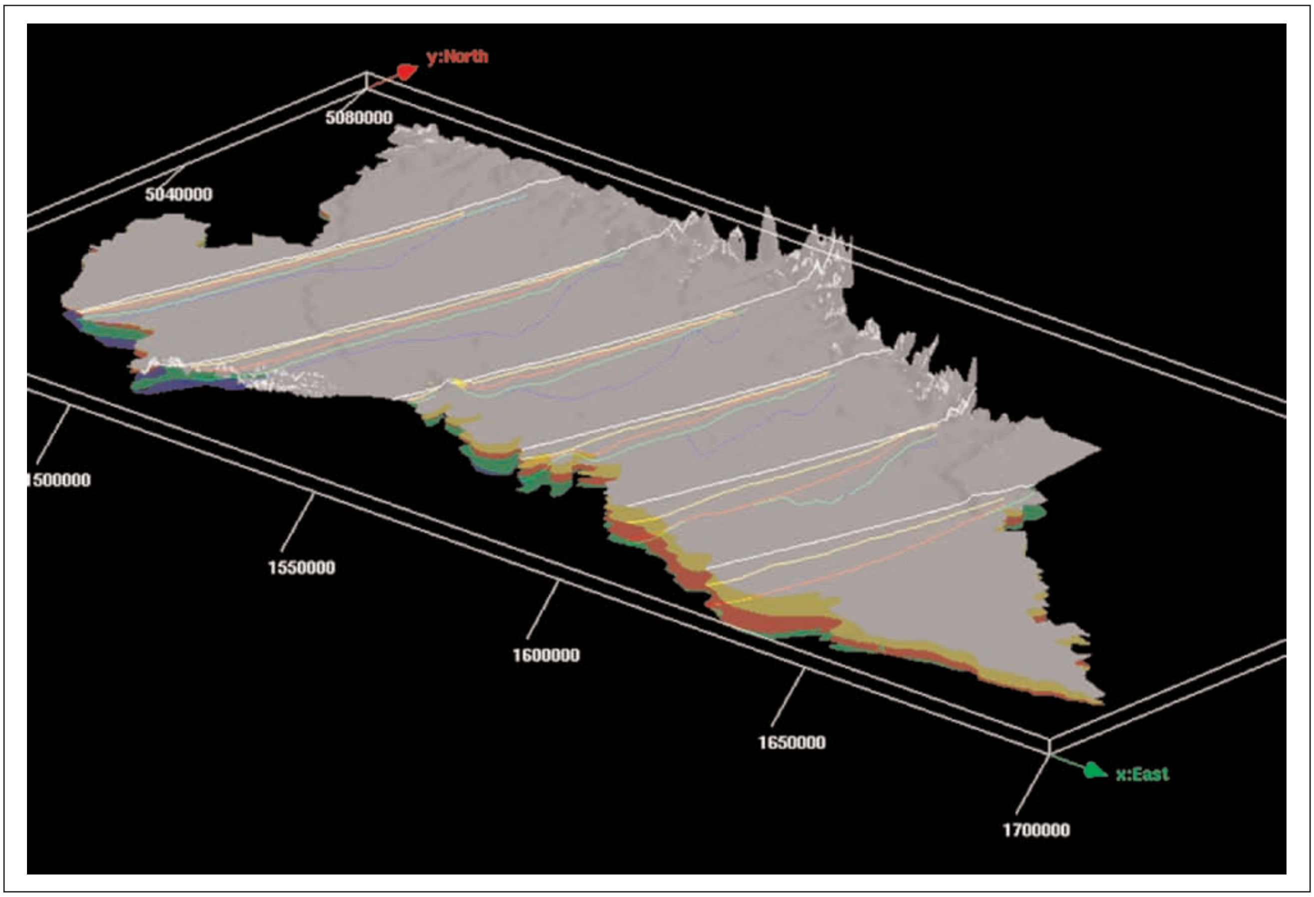


Fig. 9 - Location of the SSW-NNE oriented transverse sections derived from the model.
- Sezioni trasversali, orientate SSW-NNE, estrapolate dal modello 3D.

By comparing the total sedimentary volumes of each Aquifer Group (tab. 2) with the volumes of the sands alone (tab. 2), an estimate of the total volumes of aquitards and /or aquicludes bodies is obtained. The results, in percentage volume of the pelitic deposits, are shown in table 2.

5.3. - Analysis of water flows

In spite of the shortage of detailed information and of data available (e.g. the detailed distribution of areas with a bigger or smaller permeability in the different aquifers groups), we tried to

Tab. 2 - *Total volume, Effective volume due to sand content and Percentage volume of the pelitic deposits of the four Aquifer Groups.*
- Volume totale, Volume effettivo dovuto al contenuto in sabbia e Volume percentuale dei depositi pelitici nei quattro Gruppi Acquiferi.

	Aquifer Group **A**	Aquifer Group **B**	Aquifer Group **C**	Aquifer Group **D**
Bottom surfaces (Km2)	10671	10379	9462	6692
Total volume (Km3)	1790	1616	1070	1515
Min thickness (mt)	10	0	0	0
Max thickness (mt)	160	220	210	210
Useful volume (Km3)	659	538	348	462
Percentage volumes of the pelitic deposits	63%	66%	67.5%	69.5%

reconstruct some flow maps, with an adequate approximation. For this purpose, it has been used the "Fluid Migration" algorithm of 3Dmove, which allows to visualize and analyse the potential path of a fluid on a three dimensional surface. The "Migration" Toolbox needs to specify the surfaces to map and the seed points. Flow lines start from the seed points. The blue lines in fig. 10, represents the potential path of the fluids and follow the direction of maximum slope of the surface, as far as they reach the local depocentres, where the waters accumulate.

As far as the deep aquifers are concerned (groups B, C and D), the water sources are located along the foot hills areas of the Alps and Apennines which correspond with the direct recharge areas of these aquifers (fig. 10B, C, D; cf. FRANCANI, 1980). For the Aquifer Group A (fig. 10A), on the contrary, taking into consideration the recharge extended to the whole topographic surface, the points forming the whole DTM have been used as seed points.

5.4. - AQUIFERS VULNERABILITY

The integration of the use of land map with the three dimensional model of aquifers, and with the flow models in particular, allows some considerations. The level of urbanization, industrialization and agricultural development achieved in Lombardy is such, that a number of the more superficial aquifers result heavily polluted (GIULIANO *et alii*, 1998). It is clear that some of the main lombardian cities and industrial centres are located within the recharge areas of deep aquifers as can be seen comparing figures 4 and 10. Cities like Bergamo and Brescia, in particular, have experienced in recent years a heavy growth (red areas in fig. 4), which has surely increased the pollution load of antropic origin.

In the foothill areas of the Apennines, on the contrary, the exploitation of the land is mainly agricultural. The risk of contamination of the deep layers thus depends on the percolation of chemical and biological products used in agriculture. In this case, the restriction operated by the buried structures limits the diffusion of polluting agents towards the entire layer.

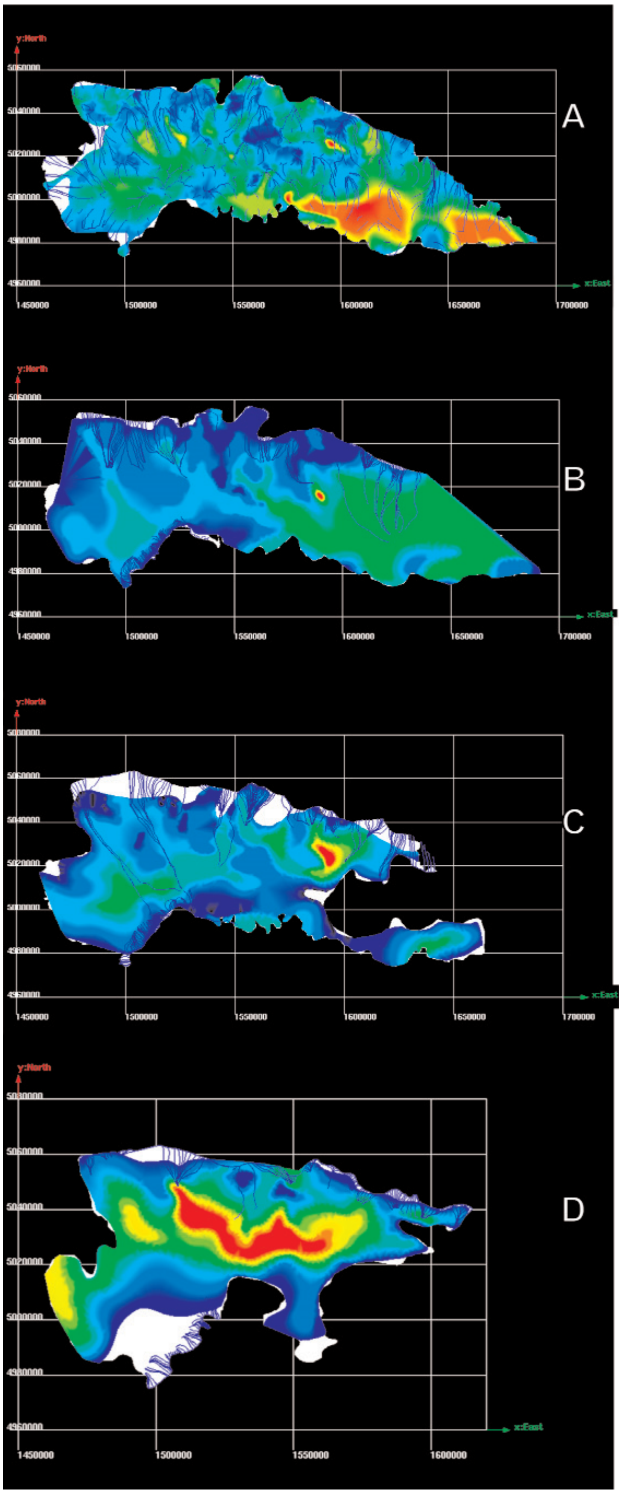


Fig. 10 - Fluid flow models for each Aquifer Group (A, B, C and D).
- *Modello della circolazione dei fluidi per ogni singolo Gruppo Acquifero (A, B, C e D).*

6. - CONCLUSION

This work, carried out in collaboration between the research group of LINEE (University of Urbino) and the Office of Geological Cartography of the Lombardia Region, allowed to build a three-dimensional model of the hydrogeological basin of the Lombardian Po River Plain.

The main results of the 3D model can be summarized as follows:

1 - The 3D model shows the morphology of the surface boundaries of the four main groups of aquifers. The deepest ones (C and D) are affected by tectonic structure of the substratum. Some new

geological cross sections from the model allow a better visualization.

2 - Volumes calculation was carried out very easily following the 3D volume creation. Also the effective disposal volume, assessed by the maps of sand content in each aquifers group, was calculated.

3 - The maps of water flow were elaborated: the flow paths from recharge areas to the deepest part for each aquifers group are shown.

4 - The integration of the 3D model with the land use map (from the Alpine limit to the Apennines foothills) can suggest different strategies for ground water exploitation and protection.

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