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Assessment of groundwater availability in the Milan Province aquifers

Stima della disponibilità idrica negli acquiferi della Provincia di Milano

BONOMI T. (*), DEL ROSSO F. (*),
FUMAGALLI L. (*), CANEPA P. (*)

ABSTRACT - Management programs often give less importance to groundwater because it is less visible than surface water, but this invisible resource, drawn from wells and springs, makes up about 10% of the requirements for irrigation and 95% of the water needed for civil use (drinking water, water for non-drinking purposes, fish-farming, etc.) in Lombardy. This study aims to provide a quantitative evaluation of the potential of the groundwater reservoir in the Milan province, through the integrated use of databases and models which permit the simultaneous management of large amounts of data. In fact, information on more than 7000 wells in the Milan province has been coded and stored in a special hydrogeological database, which permits a three-dimensional definition of the geometrical and hydrogeological characteristics of the subsurface system. The parameterisation of hydrogeological properties, such as effective porosity, helps to estimate the potential quantity of water stored in subsurface deposits throughout the whole provincial territory (approximately 34 billion cubic metres of water). Only a part of this is made up of mobile water, that is, the water that permeates medium and coarse materials (porosity over 17%), for a total of about 13-15 billion cubic metres of water. The variations of this groundwater reservoir depend on the piezometric level, the system's reaction to the static and dynamic characteristics of the hydrogeological system itself and make up the net balance of the system.
The estimation of the quantities of available both free and stored water volumes, is considered the best approach for simulating the effect of different impacts on resources, whether natural and/or man-made.

KEY WORDS: data bases, Groundwater, plains, pumping, stratigraphies, three-dimensional models.

RIASSUNTO - L'acqua sotterranea è spesso poco considerata nei programmi gestionali perché meno "evidente" rispetto a quella superficiale, ma questa risorsa invisibile, prelevata da pozzi e sorgenti, costituisce circa il 10% degli usi irrigui e il 95% di quelli civili (potabile, non potabile, piscicolture, etc.) in Lombardia. Lo studio mira a dare una valutazione quantitativa della potenzialità idrica del serbatoio sotterraneo della provincia di Milano, mediante un uso integrato di banche dati e modelli, che consentono una gestione contemporanea di una mole elevata di dati. In una apposita banca dati idrogeologica sono stati infatti archiviati e codificati i dati di oltre 7000 pozzi per la provincia di Milano che consentono una definizione tridimensionale delle caratteristiche geometriche e, tramite quelli forniti di stratigrafia, anche delle caratteristiche idrogeologiche del sistema sotterraneo. La parametrizzazione delle proprietà idrogeologiche, come la porosità efficace, consente di stimare un potenziale quantitativo d'acqua stoccato all'interno dei sedimenti del sottosuolo (all'incirca 34 miliardi di m^3 d'acqua). Solamente una parte costituisce volumi d'acqua mobili, cioè quelli che permeano materiali medi e grossolani con classi di porosità media e medio alta (sopra il 17%), per un totale di circa 13-15 miliardi di metri cubi d'acqua, nell'intero territorio provinciale. Le oscillazioni di tale serbatoio sotterraneo dipendono dal livello piezometrico, risposta del sistema alle caratteristiche statiche e dinamiche del sistema idrogeologico stesso, e costituiscono il bilancio netto del sistema.
L'approccio di stimare quantitativamente i volumi idrici disponibili, liberi e stoccati, si ritiene possa essere la strada migliore per simulare variazioni negli impatti sulla risorsa, naturali e/o antropiche, all'interno di scenari logici e plausibili.

PAROLE CHIAVE: Acqua sotterranea, banca dati, modelli tridimensionali, pianura, prelievi, stratigrafie.

(*) Dipartimento di Scienze dell'Ambiente e del Territorio, Università degli Studi di Milano-Bicocca, Piazza della Scienza 1, 20126 Milano

1. - INTRODUCTION

The groundwater of the Milan Province supplies the whole residential and commuter population, almost all industrial needs and part of agricultural requirements. This means that for the Milan province and for its capital, Milan, groundwater is currently the most important resource and will become even more so in the future. The conservation of this resource demands programs targeted to prevent quantitative and qualitative depletion. In order to be efficient, all measures aiming to save water resources must be based on accurate information: this refers to the entity of the reserves, their variations and their uses, as well as their quality. This means that it is essential to have detailed knowledge of the hydrogeological structure and the characteristics of groundwater aquifers, but also to have an efficient groundwater monitoring network and information on the volumes extracted throughout the territory.

Management programs often give less importance to groundwater because it is less visible than surface water, but this invisible resource drawn from wells and springs constitutes about 10% of the requirements for irrigation and 95% of the water needed for civil use (drinking water, water for non-drinking purposes, fish-farming, etc.) in the entire Lombardy region. (REGIONE LOMBARDIA, 2006) (fig. 1).

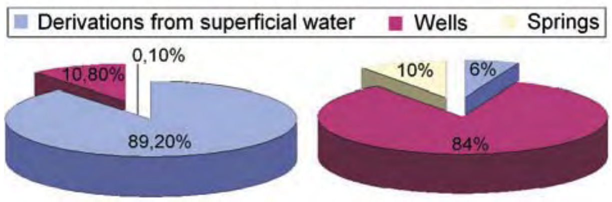

Fig. 1 - Water distribution for irrigation (left) and civil use (right) according to origin, in the Lombardy Region.
- *Distribuzione dell'acqua per usi irrigui (a sinistra) e civili (a destra) in funzione della provenienza, in Regione Lombardia.*

2. - STUDY AREA

The study area is located in the Po Plain in Italy (fig. 2), which is characterized by a very high density of urban, industrial and agricultural activities. The Milan Province, which covers 1989 km^2, contains 189 municipalities, and 71% of the land is used for agriculture. The area also has a natural hydrographic network, as well as a man-made one. The natural network is made up of the Adda and Ticino rivers, the eastern and western boundaries, of the area respectively. Both rivers drain groundwater.

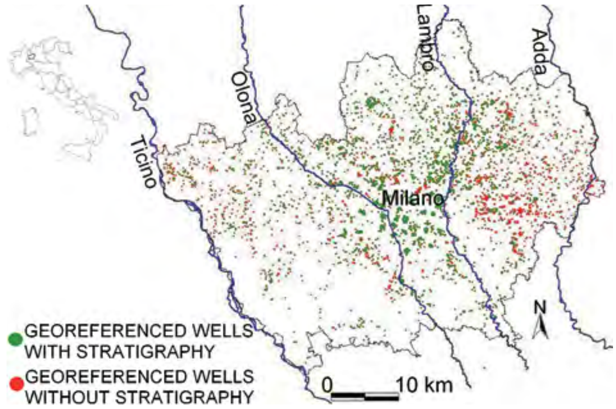

Fig. 2 - Location of Milan Province and wells georeferenced with stratigraphy (3493 in green) and wells georeferenced without stratigraphy (2114 in red).
- *Ubicazione della Provincia di Milano e dei pozzi georeferenziati con stratigrafia (3493 in verde) e pozzi georeferenziati senza stratigrafia (2114 in rosso).*
-

The main hydrogeological system consists of fluvial and fluvio-glacial deposits, mostly gravel and sand with discontinuous confining layers of silt and clay. From the hydrogeological point of view, an unconfined shallow aquifer is underlain by deeper semi-confined and confined aquifers (POZZI & FRANCANI, 1981; AVANZINI *et alii*, 1995; PROVINCIA DI MILANO *et alii,* 1995; PROVINCIA DI MILANO, 2001). The last description of the stratigraphical sequence of Pleistocene and Quaternary deposits separates them in four Aquifers Groups, on the basis of a multidishiplinary studies (REGIONE LOMBARDIA, 2002), called A, B, C and D, from the youngest to the older. The Traditional Aquifer (A and B) consists of a hydrogeological system of the unconfined aquifer within a system of very heterogeneous layers, which has been traditionally used in the plain. The deep aquifers (C and D) have not been included in the study.

3. - UNDERGROUND SUPPLY SOURCES

Information concerning the aquifer systems in the Milan area is well documented (AVANZINI *et alii*, 1995; CAVALLIN *et alii*, 1984). In particular, research carried out by the Hydrogeology Unit at the Department of Environmental and Territorial Sciences at the Bicocca University in Milan aim to estimate groundwater availability through a 3D parameterisation of the subsurface. This research is performed through integrated use of databases and models which permit the simultaneous management of a large amount of data (BONOMI, 2009; BONOMI *et alii*, 2007).

The starting point is the collection of data concerning water wells, in particular the stratigraphic logs. Although these may not be accurate, they have the advantage of providing large amounts of information. In the Lombardy Region, data pertaining to over 21.000 wells has been stored and processed in a special hydrogeological database for this purpose (www.tangram.samit.unimib.it, BONOMI *et alii*, 1995) (fig. 3).

The use of groundwater instead of surface water supplies dates back to the second half of the 19th century (1887) and is linked to the local abundance of groundwater resources. Since then, more than 10,000 well-drillings have been estimated in the province. During research work carried out in recent years, 7617 wells in the Province of Milan have been recorded in the database. Among them 5607 are georeferenced and 3493 have appropriately coded stratigraphic data (fig. 2). More than 5000 are private wells and the remaining 2100 are public (fig. 4). A large number of problems arising in recent decades, especially in relation to groundwater quality, have led to abandonment of about 30% of the wells. They are still an important measuring reference, but at the same time, may also be a possible contamination path towards the aquifers.

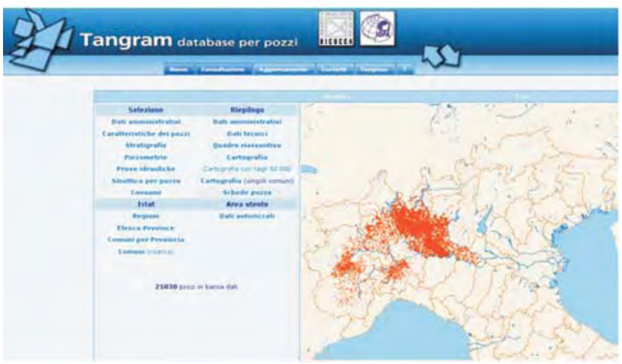

Fig. 3 - Home page of the Tangram hydrogeological database: www.tangram.samit.unimib.it. The screen capture shows data typology ("*Selezione*"), synopsis of data types and maps ("*Riepilogo*"), public data available ("ISTAT") and the users' site ("*Area utente*"). 25030 water wells are available in the database.
- *Schermata dell'*homepage *della banca dati idrogeologica Tangram: www.tangram.samit.unimib.it. La schermata mostra le tipologie di estrazione ("Selezione"), sinossi della tipologia di dati e delle carte ("Riepilogo"), dati pubblici ("ISTAT") e la zona utente ("Area utente"). Nella banca dati disponibili 25030 pozzi per acqua.*

4. - 3-D PARAMETERIZATION OF THE GROUNDWATER RESERVOIR

The large amount of coded and georeferenced data enabled us to integrate previous work defining some relevant geometries (topographic surface and base of the phreatic aquifer system) and introducing the 3-D parameterisation of the groundwater reservoir (MARCHETTI, 2001; REGIONE LOMBARDIA, 2002). The geometries help to define the thickness of the groundwater reservoir (fig. 5),

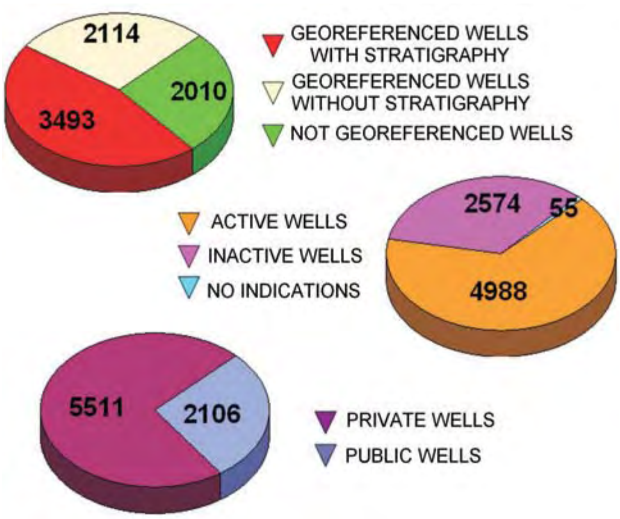

Fig. 4 - Breakdown of wells stored according to georeferencing, the presence of stratigraphy, status and type in the Milan Province.
- *Suddivisione dei pozzi archiviati secondo la georeferenziazione, la presenza di stratigrafia, lo stato e la tipologia, in Provincia di Milano.*

which varies between a minimum of approximately 2 metres in the north-eastern zone and a maximum of approximately 190 metres to the south, and to calculate the volume of the aquifer that makes up the area, estimated at about 250 billion cubic metres of material.

Scientific literature recognises the importance of reconstructing the heterogeneity of the conceptual model when determining water flow, and has led to the development of methodologies, starting from extensive gathering of stratigraphic information, in order to achieve this purpose. MARTIN & FRIND (1998), MALLET J.L. (2002), used 3D geostatistics to reconstruct hydrogeological systems through the interpolation of the boundaries

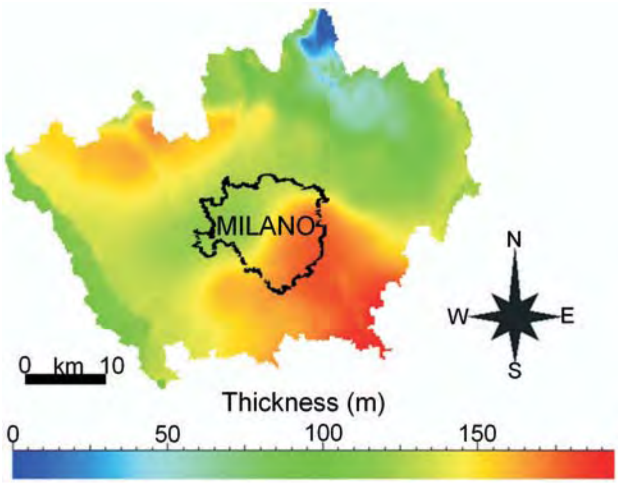

Fig. 5 - Thickness of the hydrogeological system under investigation (m), in the Milan Province.
- *Spessore in metri del sistema idrogeologico in esame, in Provincia di Milano.*

of the aquifer bodies and of their conductibility defined on the basis of stratigraphic and literature data

On the other hand FLECKENSTEIN *et alii* (2006) made a geostatistical analysis of the transition probabilities between the textural types characterized from conductivity data from scientific literature, and analysed the modelling results of different heterogeneity configurations.

In this work, parameterization is performed through the definition of a three-dimensional calculation grid into which the hydrogeological properties of the wells are entered, such as textural properties (coarse, medium and fine grain-size, BONOMI *et alii*, 2007) and hydrogeological properties (hydraulic conductivity and effective porosity).

It is possible to extract these characteristics from the database for selected depth intervals, using conversion textural – conductivity – effective porosity tables, previously entered in the reference database. Figure 6 shows the processing layout of the stratigraphic data, from the coding and storage stage, to the extraction stage.

The viewing of the point data, imported and projected into the 3D space is shown in figure 7: a close-up of a portion of aquifer can be seen, and the wells are included within the two bounding surfaces (topographic surface in red and the aquifer base in grey); percentages of coarse terms are shown as an example. It can be easily noted that the abundance of coarse-grained units can vary between 40%-60% at the surface, and gradually decreases in depth, down to values of about 3%, with the exception of lenses with high relative abundance of coarse sediments corresponding to deep confined aquifers.

These textural quantitative evaluations constitute the base to obtain the quantitative estimation of groundwater resources.

A powerful software was used to construct the three-dimensional calculation grid (fig. 8): Gocad (Geological Object Computer Aided Design) developed by a Research Consortium (Gocad Research Consortium), currently composed of numerous university research centres and industrial companies (*http://gocad.ensg.inpl-nancy.fr/www/consortium/index.xhtml*).

CODIFIED STRATIGRAPHY DATA

DEPTH from 0.00 m	ALPHA NUMERIC CODE	STRATIGRAPHY DESCRIPTION
2	C0000000	Topsoil
6	60050000	Yellow sand
13	605M0200	Grey medium-size sand with few pebbles
14	60004000	Sand with gravel
20	600M0000	Grey sand
30	A00A0000	Grey clay
38	A00B0000	Green clay

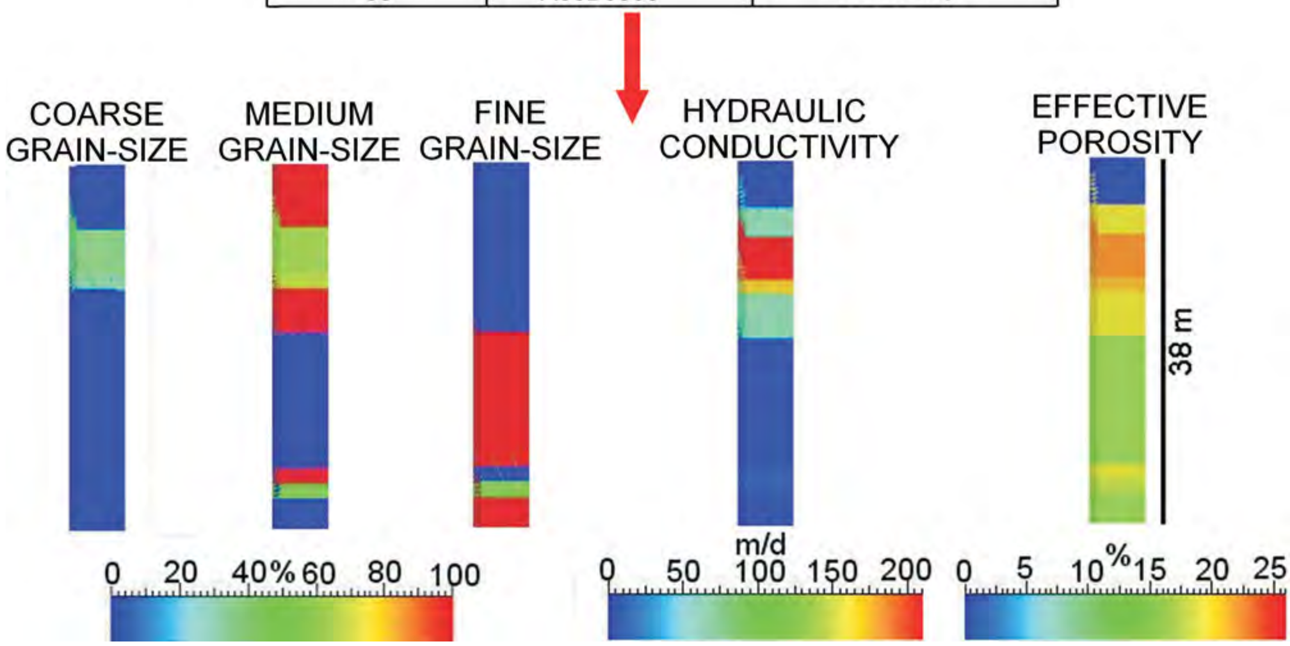

Fig. 6 - Parametrization of stratigraphic data codified in the database (table) and allocation of its textural and hydrologeological properties (columns).
— *Parametrizzazione dei dati stratigrafici nella banca dati (tabella) e attribuzione delle relative proprietà tessiturali ed idrogeologiche (colonne).*

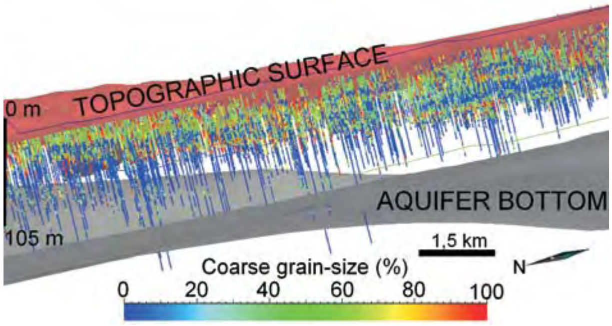

Fig. 7 - Close-up of a portion of the system: wells are shown between the topographic surface (pink) and the base of the aquifer (grey); gravel abundance (%) is shown.
- *Zoom su una porzione del sistema in esame: pozzi visualizzati tra la superficie topografica (in alto, in rosso) e la base dell'acquifero (in basso, in grigio); come proprietà sono visualizzata i termini grossolani.*

The grid was divided into 202 layers and is composed of 256 columns and 215 lines; each cell is 250 m x 250 m in size and has a thickness that varies around 2 metres since the grid was modified in proportion with the distance between the two surfaces. A total of 11,508,950 cells form the 3D calculation grid (fig. 8) and a property can be associated with each individual cell.

The data-points were interpolated by kriging; in this manner the properties are estimated in non-sampled points by means of a weighted linear combination of known values. The weights assigned to existing data are calculated by analysing the variogram relative to the initial information. In this way their correlation is examined according to distance and direction. The final result is a reconstruction of the textual characteristics and hydraulic parameters inside the total volume of the aquifer, aimed at reproducing vertical and areal he-terogeneity, which is known to have a considerable influence on the flow direction as well as the contaminant transport (PECK *et alii*, 1988).

As an example, the distribution of effective porosity is shown (fig. 9), which varies in the subsurface (between 6% and 26%) conditioning the sediment capacity to store and release water. In particular, figure 10 shows, for instance, the volumes that have an effective porosity of 12%, 14% and 22% inside the calculation grid.

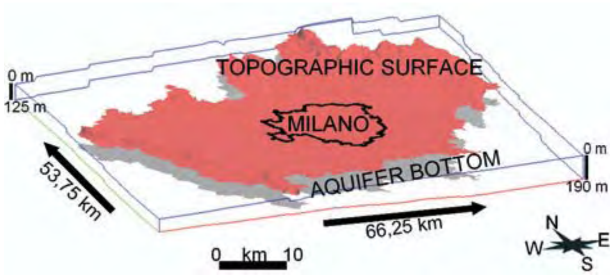

Fig. 8 - 3D computation grid: topography in red and basal aquiclude in grey (202 layers, 256 columns and 215 lines, cells 250m X 250m X 2m).
- *Griglia 3D di calcolo, con all'interno le due superfici: in rosso il* top *e in grigio il* bottom *(202 strati, 256 colonne e 215 righe, celle 250m X 250m X 2m).*

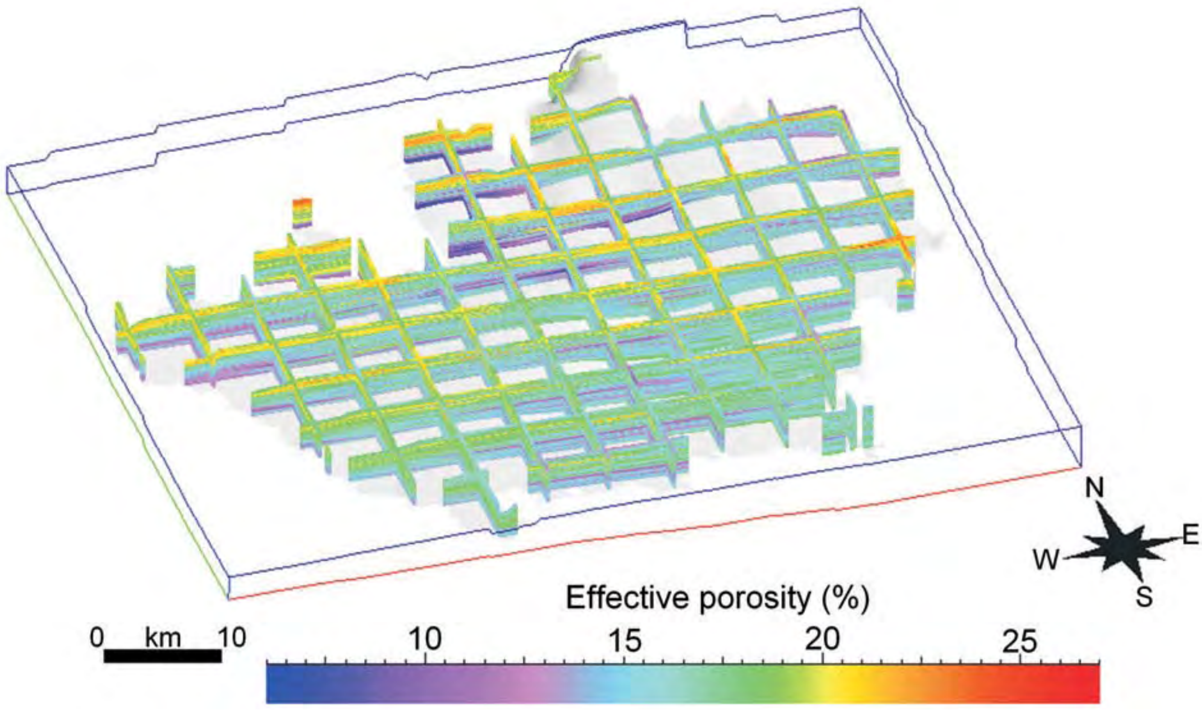

Fig. 9 - Cross-sections of effective porosity (%) distribution in the Milan Province. The scale ranges from a minimum of 5% (clay) to a maximum of 28% (coarse gravel).
- *Sezioni incrociate della distribuzione della porosità efficace (%) nella Provincia di Milano. La scala varia da un minimo del 5% (argilla) ad un massimo del 28% (ghiaia grossolana).*

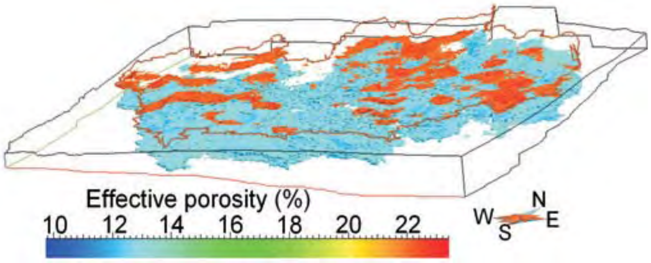

Fig. 10 - Volumetric representation of effective porosity: 12% (light cyan, 14% (dark cyan) and 22% (orange) are represented.
- *Volumi delle classi percentuali di porosità efficace del 12% (azzurro chiaro), 14% (azzurro scuro) e 22% (arancione).*

5. - ESTIMATE OF GROUNDWATER AVAILABILITY

The evolution of the piezometric level shows how the system reacts to the water balance since its oscillations make up the net balance. The prevalent balance category in strongly urbanised impervious areas, like the city of Milan and its hinterland, is groundwater extraction, which has a strong influence on piezometric levels and water reserves when replenishment does not occur (BONOMI *et alii*, 2008). An example relative to an eastern zone in the city of Milan is shown in figure 11. If extractions were measured accurately, the correlation between them and levels on a provincial scale would provide an estimate of anthropogenic impact on groundwater resources. An evaluation of the history of this impact in relation to socio-economic development would help in setting up management programs.

A reconstruction of the piezometric areal evolution was performed for the 1979 – 2005 period, to determine the changes in water availability (fig. 12).

These changes are shown by variations in the saturated volume within the aquifer over a period of time, corresponding to a difference in water content resulting from changes in the effective porosity of the aquifer. Figure 13 shows modal classes of effective porosity; the value for sand and sandstone are between 15% and 19%. Furthermore, over the years the saturated pore volume of the aquifer was evidently subject to change, mainly for the highest values of porosity, concerning medium and coarse-grained deposits. In fact, these occur in the upper part of the aquifer where the height of the water table varies over time. On the other hand, the lowest porosity values (between 6% and 10%) relate to the finer deposits which occur at greater depths. Values between 23% and 26% are related to a very low saturated pore volume size.

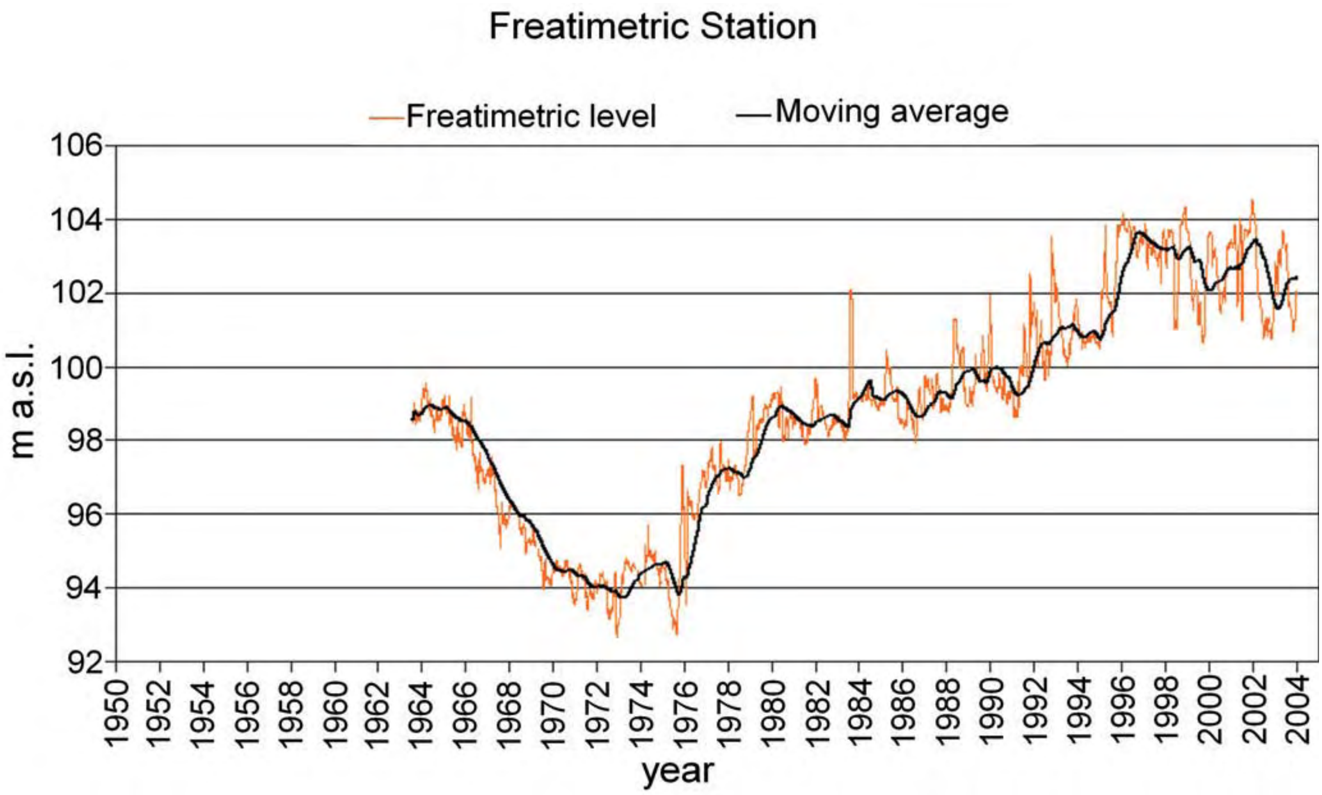

Fig. 11 - Historical evolution of the phreatic surface in a piezometer of the Milan municipal network, between 1964 and 2005. The moving average line over 12 months is shown in black.
- *Andamento freatimetrico storico in un piezometro della rete comunale di Milano, dal 1964 al 2005. La linea nera indica la media mobile su 12 mesi.*

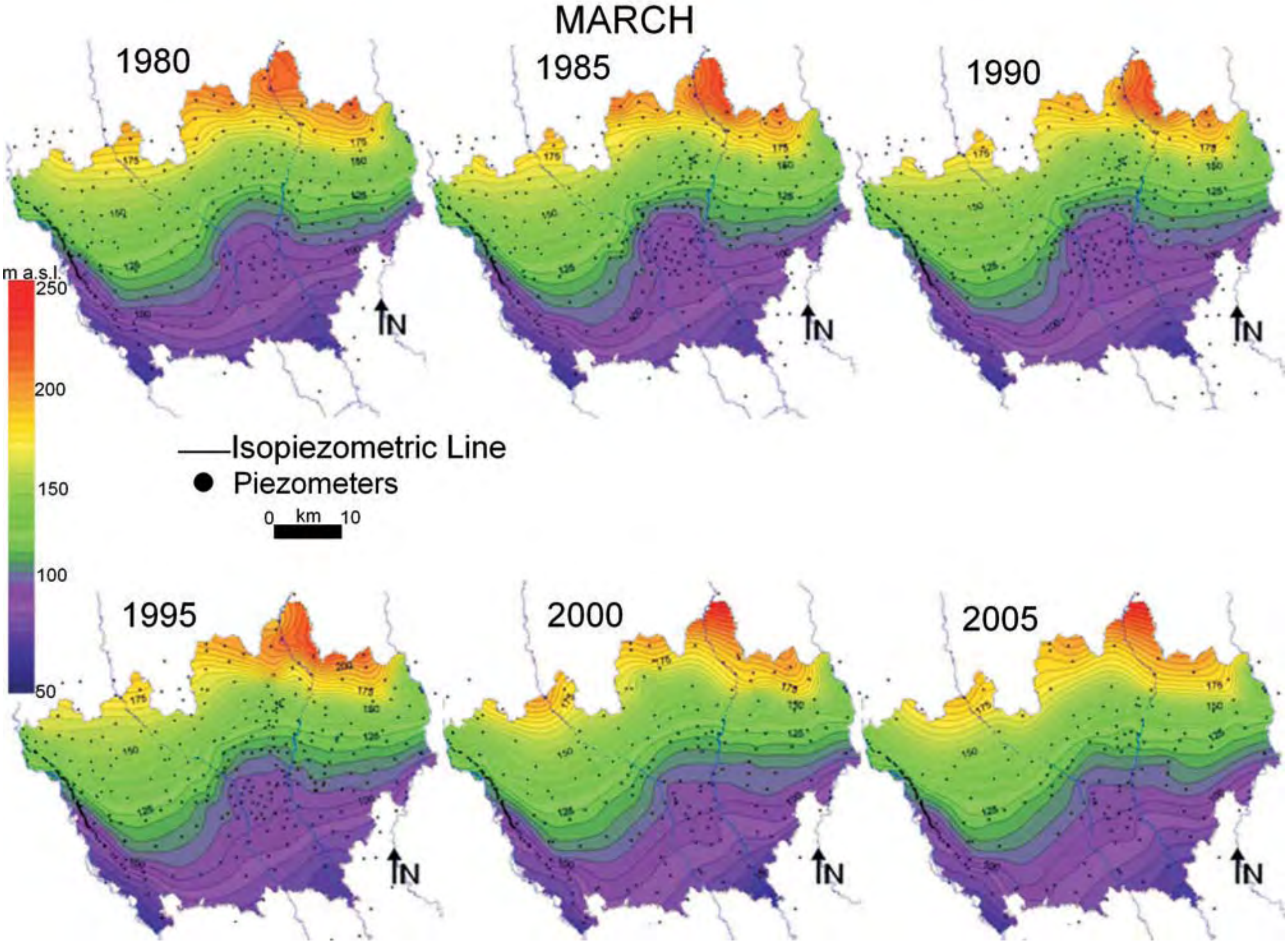

Fig. 12 - Piezometric surfaces in the Milan Province between 1980 and 2005 (m. a.s.l.), interpolating the data of the monitoring network. - *Ricostruzione piezometrica nella Provincia di Milano dal 1980 al 2005 (m s.l.m.), interpolando i dati della rete di monitoraggio.*

The volumes of the aquifer have been calculated for each porosity classification and multiplied by the value of corresponding effective porosity to provide an estimate of the actual water volume available for the current year. Figure 14 shows the relative calculation of the saturated aquifer volume (brown bars) and the corresponding water volume it contains (blue bars) in relation to the period between 1979 and 2005.

The theoretical calculation of the water volume stored in the subsurface for the whole Milan province yields approximately 33-34 billion cubic metres (fig. 14). Only part of this volume is mobile water, which permeates medium and coarse-grained deposits (porosity over 17%) for a total of about 13-15 billion cubic metres of water. Naturally these volumes vary according to the evolution of the piezometric level which saturates or drains different portions of aquifer with varying water storage capacity (fig. 15).

The difference between these estimated annual values compared to the average in the period 1979-2005 (about 14.420.000 m^3/y, red line in the figure 15), provides an idea of the variation of water availability over a period of time. The oscillation represents the result between recharge and extraction. For example, provincial water withdrawal estimated in some publications is approximately 1 billion cubic metres of water (BERETTA *et alii*, 1985; BONOMI, 1995). A positive variation in water availability indicates that the replenishment of the system has succeeded not only in balancing the withdrawals, but also in providing a water surplus. A negative variation indicates that the replenishment has not been able to compensate the withdrawals, and the subsoil system is in deficit. Water availability estimation is a basic evaluation to be correlated with the evaluation of the minimum piezometric level sustainable by a system, which means the minimum water availability sustainable.

In the same area and for the same period, the aquifer recharge due to the precipitation has been estimated in about 370 million m^3/year, varying between 830 million m^3 (1980) and 106-121 million m^3 (1981-2005); it represents about 1% of the total water reservoir and 2.7% of the mobile water, (FUMAGALLI, 2010, in press). The annual recharge rate is consistent with the groundwater oscillations,

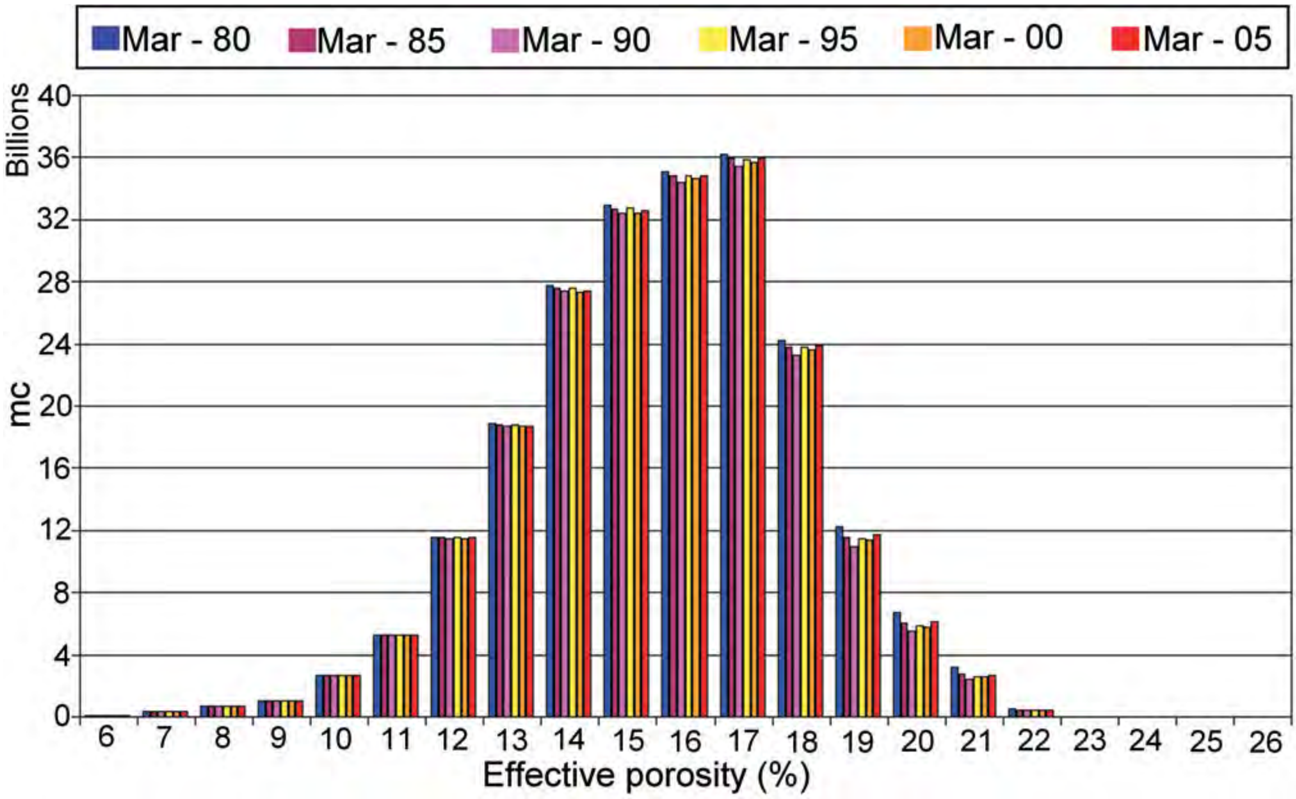

Fig. 13 - Histogram showing the saturated volumes for each effective porosity (%) classification over a period of time. The examples show values for the years: 1980, 1985, 1990, 1995, 2000 and 2005.
- *Istogramma dei volumi saturi per ogni classe di porosità efficace (%) al variare del tempo. Come esempio sono riportati gli anni 1980, 1985, 1990, 1995, 2000 e 2005.*

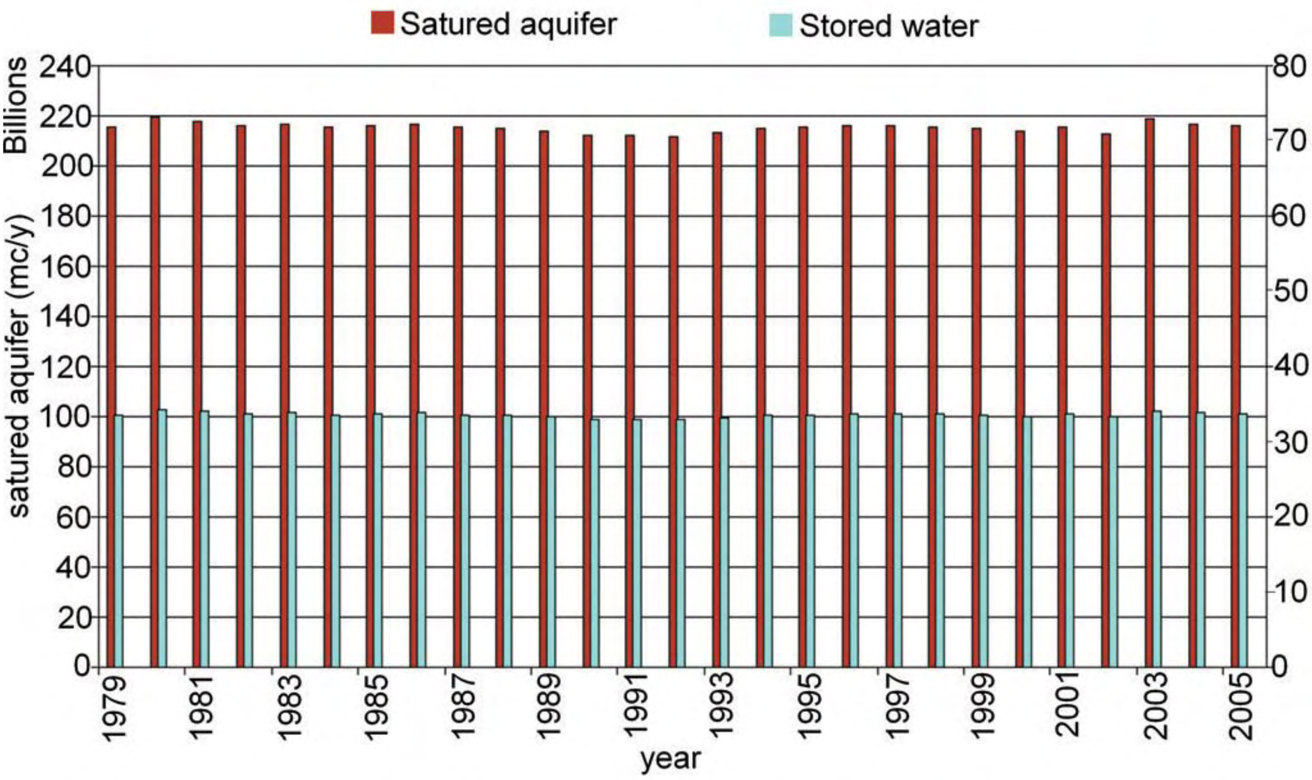

Fig. 14 - Histogram showing the saturated volume (brown bars) and the volume of stored water (blue bars) between 1979 and 2005 in the Milan Province.
- *Istogramma della variazione nel tempo del volume saturo (barre marroni) e del volume d'acqua immagazzinata (barre blu) dal 1979 al 2005 in Provincia di Milano.*

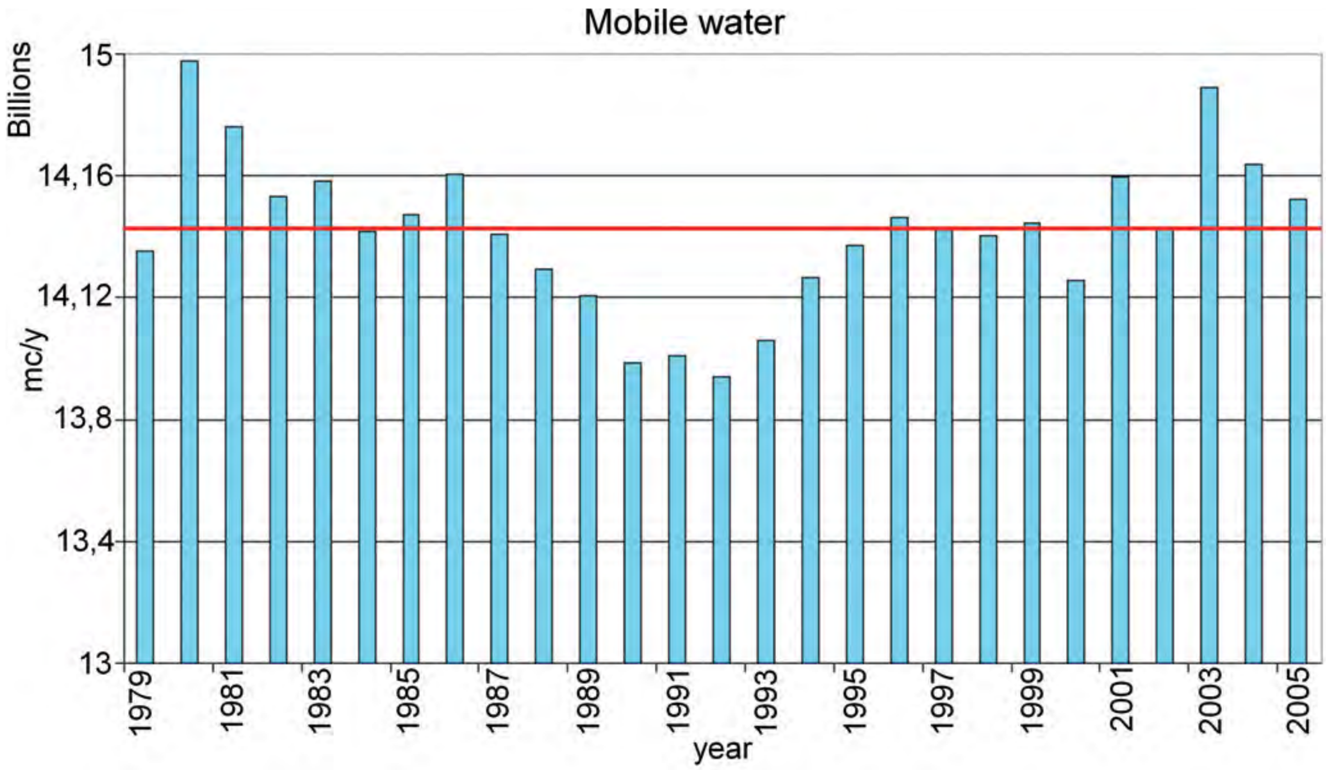

Fig. 15 - Histogram showing the volume of mobile water between 1979 and 2005 in the Milan Province (porosity over 17%). The red line shows the annual average over the period.
- *Istogramma della variazione nel tempo dei volumi d'acqua mobile dal 1979 al 2005 in Provincia di Milano (porosità maggiore del 17%). La linea rossa indica la media annuale sul periodo considerato.*

that are however delayed of some months.

These data refer to the results of soil water balance simulations (MACRO model, JARVIS, 1994) that have been done for the soil profiles of the province area, taking into account an average climatic and agricultural scenario and the waterproof urban area extension.

6. - FINAL REMARKS

The results of this study for resource management can be summarized as follows:

- quantification of the volume of water stocked in the Milan Province by estimating the effective porosity of the aquifers;
- estimates of the mobile water fraction according to the textural characteristics of the system.

There is no doubt that the groundwater reservoir is the best water reserve available and the best natural strategic storage throughout the territory. Variations between one year and the next represent the net water balance of the hydrogeological system, equal to the result between the recharge of the system (efficient rainfall, efficient irrigation, draining from canals and drainage systems, feeding from rivers, etc.) and withdrawal (well pumping, springs, feeding to rivers, etc.). If accurate information concerning these factors were available, it would be possible to compute the groundwater balance and even water availability with good precision. Unfortunately, so far it has not been considered necessary to monitor the volume of water outflowing from the aquifer on a provincial scale.

The next step of the research will be the evaluation of the quantities that could be reasonably used according to sustainability parameters.

In this evaluation, another factor that must not be ignored is the porosity variation to which a sediment is subject due to variations of water content, and therefore it is necessary to introduce a corrective factor when attributing effective porosity to textural percentages.

The qualitative-quantitative information relative to this reservoir is a useful instrument at waterworks level (GIUDICI *et alii*, 2000; GIUDICI *et alii*, 2003), but it could be used to manage consumption increases, both continuous and sporadic also at a provincial level. The computation of the groundwater reservoir variations could be useful for Milan during Expo 2015, for example, when millions of tourists are expected. We consider that a quantitative estimate of available water volumes is an efficient approach for simulating the effect of diverse impacts on resources, both natural and/or anthropogenic.

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