Basin-scale hydrogeological, geophysical, geochemical and isotopic characterization: an essential tool for building a Decision Support System for the sustainable management of alluvial aquifer systems within the provinces of Milan and Monza-Brianza (Northern Italy)

Caratterizzazione idrogeologica, geofisica, geochimica e isotopica a scala di bacino: strumento essenziale per la costruzione di un Sistema di Supporto alle Decisioni per la gestione sostenibile dei sistemi acquiferi delle province di Milano e Monza-Brianza (Nord Italia)

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Riassunto: Il Gruppo CAP è un'azienda a capitale interamente pubblico, che opera come soggetto unico per garantire il servizio idrico integrato dei comuni delle province di Milano e Monza/Brianza (Nord Italia): 197 comuni serviti, più di 2 milioni di utenti, 887 pozzi, 154 serbatoi pensili e hub, più di 7500 Km di rete d'acquedotto, che generano un prelievo idrico annuo dell'ordine di 250 milioni di metri cubi. L'approvvigionamento ad uso idropotabile deriva esclusivamente da risorse idriche sotterranee, circolanti in più sistemi acquiferi sovrapposti.

La gestione delle risorse idriche a scala di bacino, come richiesto dalla Direttiva Europea sulle acque (2000/60/CE), risulta pertanto essere un compito altamente complesso. Alla luce di un tale quadro d'insieme, CAP sta attualmente sviluppando un progetto denominato Piano Infrastrutturale Acquedotti che si basa su un approccio di Decision Support System per la gestione sostenibile dei sistemi acquiferi nel bacino compreso tra Adda e Ticino. Il Decision Support System del Gruppo CAP si propone di rappresentare un sistema di analisi per la valutazione della disponibilità di risorse idriche sotterranee, l'identificazione delle condizioni ai limiti, il riconoscimento delle variabili climatiche e delle pressioni demografiche, lo sviluppo di modelli previsionali e il confronto di scenari alternativi di policy.

Il progetto è stato strutturato in step, che includono la costruzione di un Geodatabase, l'analisi geographic information system (GIS) (compresa la multilayer analysis) e la modellistica numerica. I dati raccolti nel Geodatabase sono stati analizzati per produrre mappe tematiche quanti-qualitative in ambiente GIS, così da poter condurre un'analisi multilayer dello stato attuale e futuro delle risorse idriche, nonché gli impatti agenti su di esse. Tale approccio operativo consente di restituire ai Decision Makers un quadro esaustivo del sistema idrico gestito. La multilayer analysis si affida ad alcuni specifici indicatori basati su dati quanti-qualitativi: idrogeologici, chimici, isotopici, di uso del suolo e rischio, climatici e demografici. Tutti i parametri appartenenti a queste macroaree sono stati omogeneamente raggruppati in 7 classi di rischio, assegnando un apposito peso a ciascuno di essi. Moltiplicando i valori delle classi per i rispettivi pesi sono stati calcolati degli indici sintetici, che sono stati gestiti con un'analisi multilayer e confrontati con altri modelli e strumenti (modelli: geologico, numerico di flusso idraulico delle reti, ecc.), così da ottenere degli indici di criticità. L'analisi di questi indici di criticità permette di valutare soluzioni alternative e strategiche per ottenere una gestione più efficiente e sostenibile del sistema idrico alla scala di bacino (approccio best choice). Attualmente, il team di progetto sta lavorando sulla multilayer analysis ed il passo successivo è il completamento e l'implementazione del modello numerico di flusso.

Parole chiave: Pianura Padana, Sistema Informativo Geografico, Decision Support System; Idrochimica, Gestione acque sotterranee.

Keywords: *Po Plain, Geographic Information System, Decision Support System, Hydrochemistry, Groundwater management.*

Abstract: *CAP Group is a public company, supplying the municipalities within the provinces of Milan and Monza/Brianza (Northern Italy) with the integrated water service: 197 municipalities and more than 2 million users served, 887 wells, 154 wall-mounted tanks and hubs, a water supply network of over 7500 km, from which approximately 250 million cubic metres of water per year are withdrawn. The drinking water supply comes exclusively from groundwater resources, circulating in several overlapping aquifer systems.*

Basin-scale water resource management, as required by the European Water Framework Directive (2000/60/EC), is an extremely complex task.

In view of this backdrop, CAP is currently developing a project called Infrastructural Aqueduct Plan that relies on a Decision Support System approach. The paper describes the preliminary steps concerning the design of a prototype Decision Support System aiming at the management of groundwater resources on a basin scale (Ticino and Adda rivers area). CAP Group Decision Support System is intended to be a package allowing for water resource assessment, identification of boundary

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Ricevuto: 7 giugno 2016 / Accettato: 23 settembre 2016
Pubblicato online: 3 ottobre 2016

conditions, climatic driving forces and demographic pressures, simulation and investigation of future forecasts and comparison of alternative policy measures. The project has been designed in steps including Geodatabase building, geographic information system (GIS) analysis (including multilayer analysis) and numerical modelling.

The data collected in the geodatabase were analyzed to design GIS quantitative and qualitative thematic maps in order to perform the multilayer analysis of current and future state and impacts, for providing the decision maker with a comprehensive picture of the water system. The multilayer analysis relies on specific indicators based on some quantitative and qualitative data: hydrogeological, chemical, isotopic, soil use and hazards, climatic and demographic.

Each parameter belonging to these macro areas were classified by 7-criticality classes scale and weights were assigned to each of them. For each macro area a synthetic index was calculated by multiplying class values with weights. These synthetic indexes were managed with a multilayer approach and compared with other models and tools (e.g. geological model, numerical groundwater model, distribution network model) in order to obtain criticality indexes. The assessment of these criticality indexes allow to evaluate alternative and strategic solutions to achieve a more efficient and sustainable water system management using a best choice approach.

Currently the project team is working on multilayer analysis. The next task will be the implementation of groundwater numerical model.

Introduction

CAP Holding S.p.A. (CAP Group, Assago, Italy) is a publicly owned company established in 1928, with local authorities as shareholders, supplying the Integrated Water Management (groundwater abstraction, distribution, sewage network and treatment) to nearly 200 municipalities of the Provinces of Milan and Monza/Brianza (Northern Italy).

Its main features are, in brief:

- 197 municipal authorities and 2 provincial authorities as shareholders serving for more than two million customers;
- 887 boreholes owned;
- 154 underground and above ground reservoirs;
- more than 7500 km of public water supply network.

CAP is currently developing a project called Infrastructural Aqueduct Plan (P.I.A.), which relies on a Decision Support System (D.S.S.) approach. The aim of the project is to foster a more efficient and sustainable management of water resources supplied and managed by CAP on a basin scale.

A D.S.S. is a computer-based information system serving the management, operations, and planning levels of an organization and helps people make decisions about problems that may be rapidly changing and not easily specified in advance (Power, 2002, 2003, 2004). This paper focuses on the development of a prototype D.S.S. for water management. This tool incorporates a Geographic Information System (GIS), a geodatabase and a complex set of model outputs. The D.S.S. is designed to manage environmental data and critical problems, based on a robust knowledge of hydraulic, hydrogeological and hydrochemical features of the aquifer systems within the provinces of Milan and Monza/Brianza (Gorla et al. 2016). Groundwater resources will play an increasingly strategic role in supplying fresh drinking water in the future, thus an efficient and sustainable withdrawal control and a correct water balance have to be achieved.

Conceptual framework

Study area

The case study proposed in this paper covers the whole metropolitan area of Milan (Fig. 1), analysing the environmental and infrastructural features of about 200 municipalities (Milan and Monza/Brianza provinces) and more than 2 million users. This highly urbanized and densely populated area suffers from problems mainly related to raw groundwater quality.

High concentrations of anthropic pollutants, both organic (mainly chlorinated compounds, such as Trichloroethylene TCE and Tetrachloroethylene PCE) and inorganic (nitrate, chromium, etc.) are detected. Therefore raw groundwater needs for suitable treatment (granular activated carbon - GAC – and reverse osmosis) before being supplied to users.

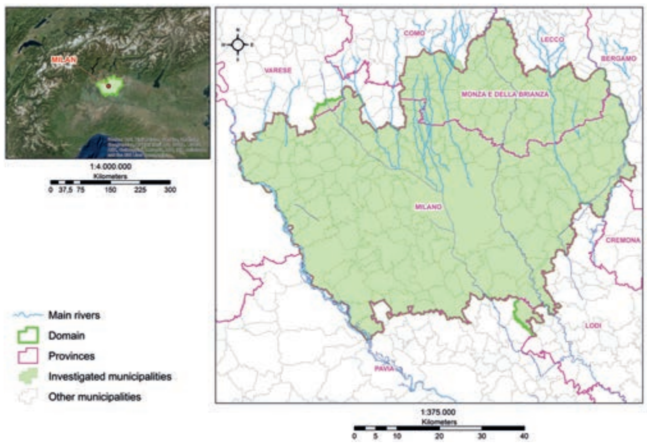

Fig. 1 - Study area.

Fig. 1 - Area di studio.

Geological setting

The first 200-300 m in depth present the following stratigraphic profile (CAP, 1995; Gorla, 2001a, 2001b); from bottom to top, the following lithological units can be distinguished (Fig. 2):

- Clayey Unit (Unità Argillosa). Made up of prevalent grey-blue clay and silt, with macro and microfossils (i.e. Hyalinea balthica and Ammonia beccarii) and thin cemented sandy levels. It derives from a shallow-deep marine palaeoenvironment, dating back to the Calabrian age. This unit can be observed up to depth of 280-300 m depth.
- Sandy-Clayey Unit (Unità Sabbioso-argillosa). This unit reflects a phase of marine regression (Lower Pleistocene) with lagoon, beach, palustrine and alluvial deposits and represents the bottom of the traditional unconfined aquifer. It shows a predominance of grey and yellow clay and silt (with frequent interposition of colour),

blended with peat, and locally lenses of gravel, sand and conglomerate. This unit generates confined groundwater reservoirs, recognizable within a depth range of 100 m to 160 (Eastern sector) up to 200 m (Western sector).

- Conglomerate and Sandstone Unit (Unità a Conglomerati e Arenarie – Ceppo). Made up of conglomerate and sandstone formations from the Lower Pleistocene age and, moving laterally and southwards, uncemented gravel and sand. This unit can be found mainly at the foot of mountains, at a depth of 50-100 m below ground level. Its maximum thickness is about 80 m. It derives from a palaeoenvironment of river channels.
- Sandy-Gravelly Unit (Unità Sabbioso-ghiaiosa). Composed of sand deposits, prevailing over the gravel ones, from the Middle Pleistocene age. Locally, silt-clay strata and arenite-conglomerate lenses are recognizable. Its thickness is 40-60 m. Within the city of Milan, this formation reaches a depth of 100-110 m below ground level.
- Gravelly-Sandy Unit (Unità Ghiaioso-sabbiosa). It indicates a fluvioglacial palaeoenvironment, when streams meandered across the alluvial plain during the Upper Pleistocene - Holocene. The gravel fraction generally dominates the sandy one, and there are rare clayey lenses with a limited spatial extension. The thickness of this unit is about 20-40 m.

Hydrogeological framework

From the hydrogeological point of view, there are three primary aquifer systems, called A, B and C (Fig. 2), respectively, with reference to the classification proposed by the Regional authority of Lombardy (Regione Lombardia – ENI Divisione AGIP, 2002):

- The first and second system (aquifers A+B), mostly in a phreatic unconfined condition, result from the coalescence of two and locally even three lithological/hydrogeological units. The bottom of this aquifer system is, on average, 100 m below ground level. It has a great yield, due to its high transmissivity (about 1-2·10^{-2} m^2/s or even greater) and saturated thickness (70-80 m). The potentiometric map clearly shows the flow pattern of this aquifer (Fig. 3). The hydraulic gradient diminishes from North to South, varying from 1% in the northern part of the province to 1-2‰ in its southern part.
- The third system (aquifer C), is a deep confined aquifer. Its transmissivity values mainly range from 1-2·10^{-3} m^2/s to 8-9·10^{-3} m^2/s. This deep aquifer is predominantly wedge-shaped, with thicknesses varying from 5-6 m, towards the south, to more than 20 m, in the highland zone, in the northern part of the province. The flow pattern on a provincial scale shows a principal flow direction from North to South (Fig. 4), with a hydraulic gradient varying from 5-6‰ upstream to 1-2‰ downstream.

The potentiometric map was carried out using the monitoring network designed by CAP in the 70s' and still working. Currently it includes more than 150 monitoring wells.

Hydrogeophysical setting

A hydrogeological and geophysical conceptual model of the study area has been developed by using ArcGIS 10.4 (ESRI®, Redlands, CA, USA). The conceptual model relies on a geodatabase which collects stratigraphic data, geographic coordinates, structural features of the boreholes (diameter, location and type of filters, etc.), static and dynamic potentiometric levels, pumping tests and geophysical logs. All these data were collected by CAP during the field surveys and the drilling of new public (CAP) and private boreholes (from 60s' to nowadays).

The analysis of hydrostratigraphic/structural data of public and private water wells (over 3,000 stratigraphic master logs and about 100 geophysical logs) was carried out.

Twelve North-South and West-East hydrostratigraphic sections (Fig. 5) were drawn by using Target for ArcGIS (Geosoft® Inc., Toronto, ON Canada).

The 2D hydrostratigraphic sections allow highlighting the main hydrogeological features (hydrofacies and aquifer) and the geophysical profiles for each well (e.g. Figs. 6 and 7).

The hydrostratigraphic surfaces of the aquifer systems A, B and C were reconstructed using geostatistical methods (Geostatistical Analyst, ESRI®).

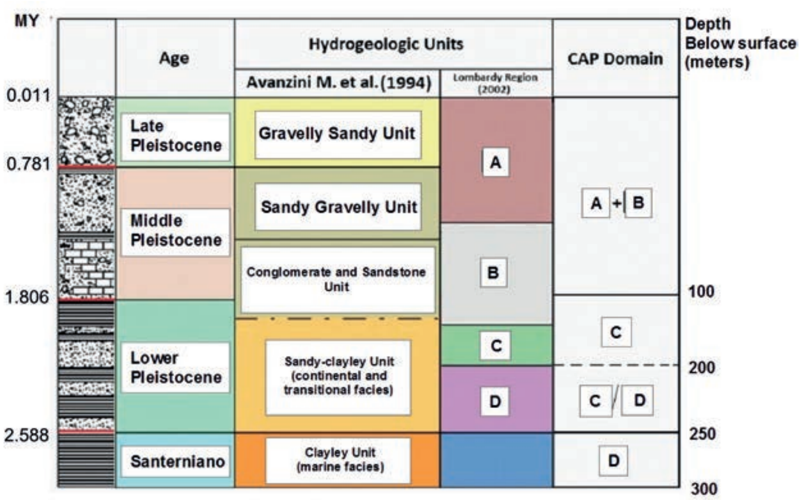

Fig. 2 - Stratigraphic profile of the quaternary deposits - provinces of Milan and Monza/Brianza.

Fig. 2 - Profilo stratigrafico dei depositi quaternari - province di Milano e Monza/Brianza.

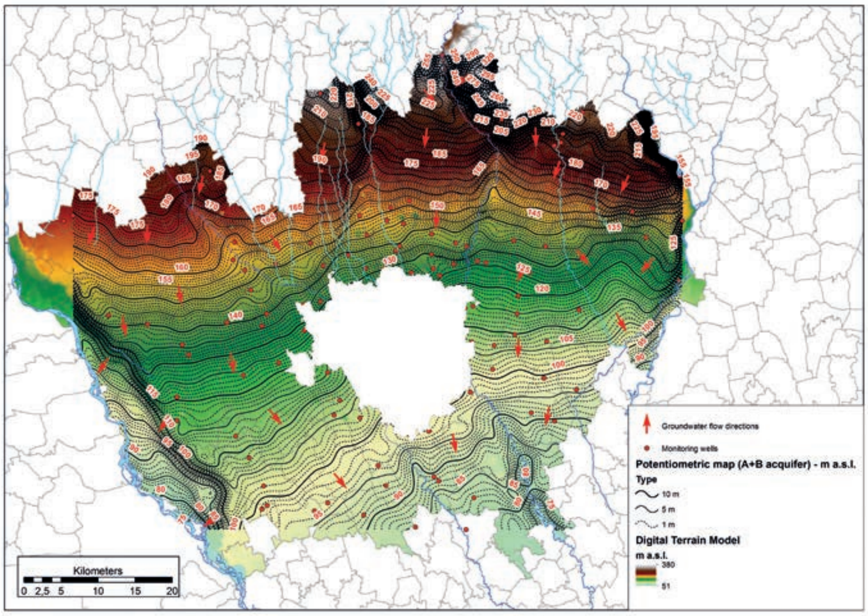

Fig. 3 - Potentiometric map (A+B aquifer).

Fig. 3 - Mappa delle curve isopiezometriche (Acquifero A+B).

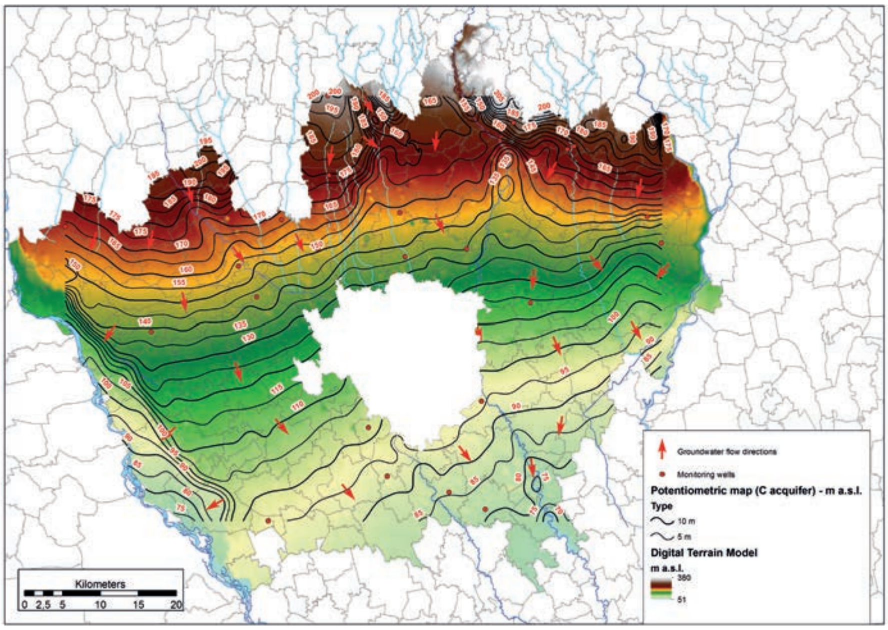

Fig. 4 - Potentiometric map (C aquifer).

Fig. 4 - Mappa delle curve isopiezometriche (Acquifero C).

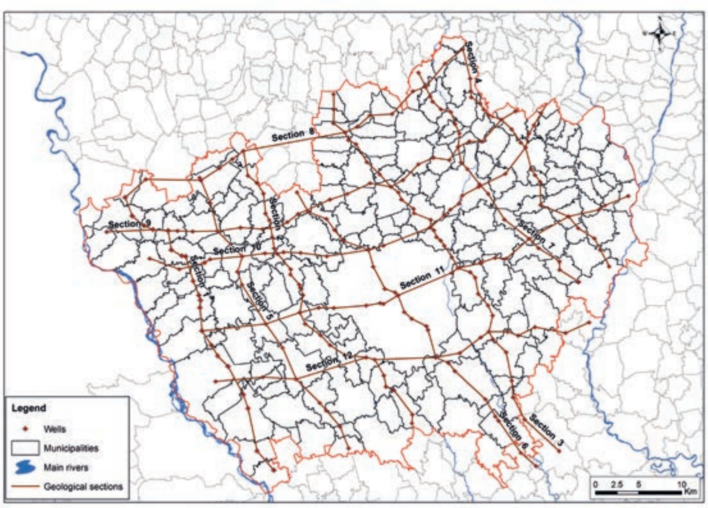

Fig. 5 - Hydrostratigraphic sections within the Ticino-Adda hydrogeological basin.

Fig. 5 - Sezioni idrostratigrafiche realizzate nell'area del bacino Ticino-Adda.

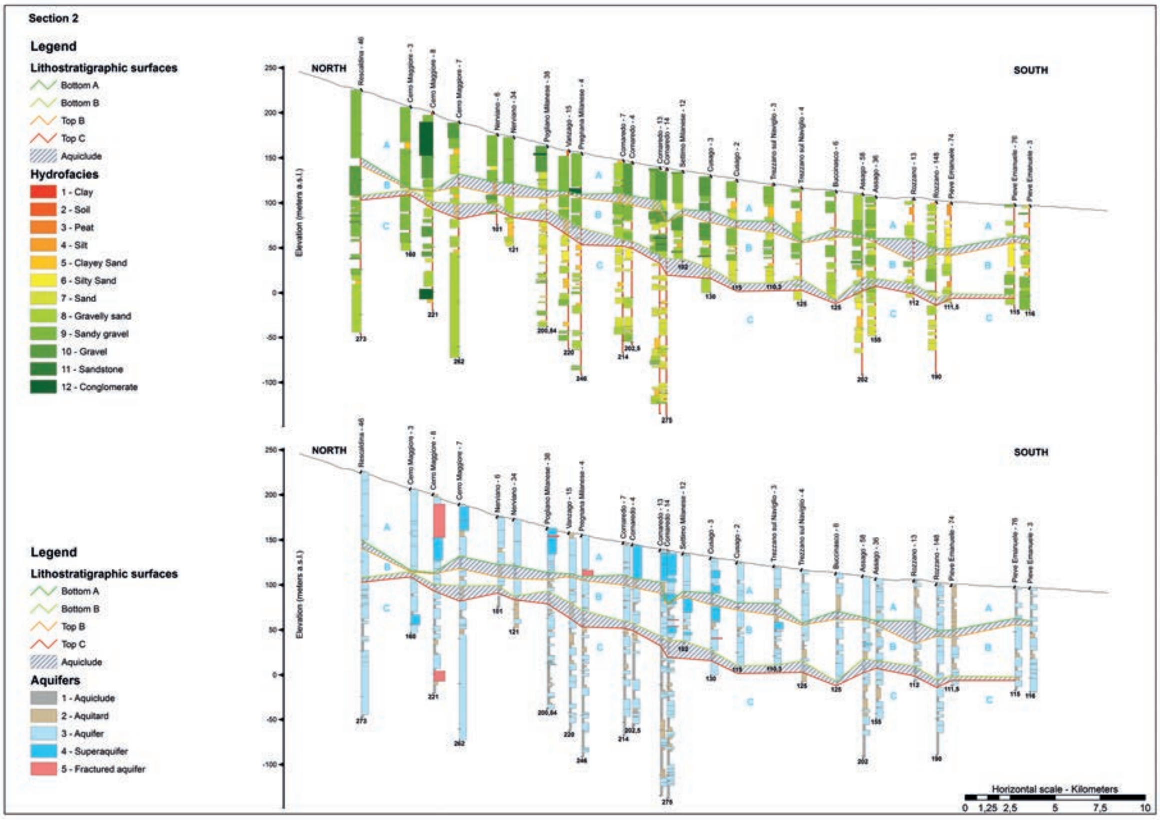

Fig. 6 - North-South hydrostratigraphic section.

Fig. 6 - Sezione idrostratigrafica Nord-Sud.

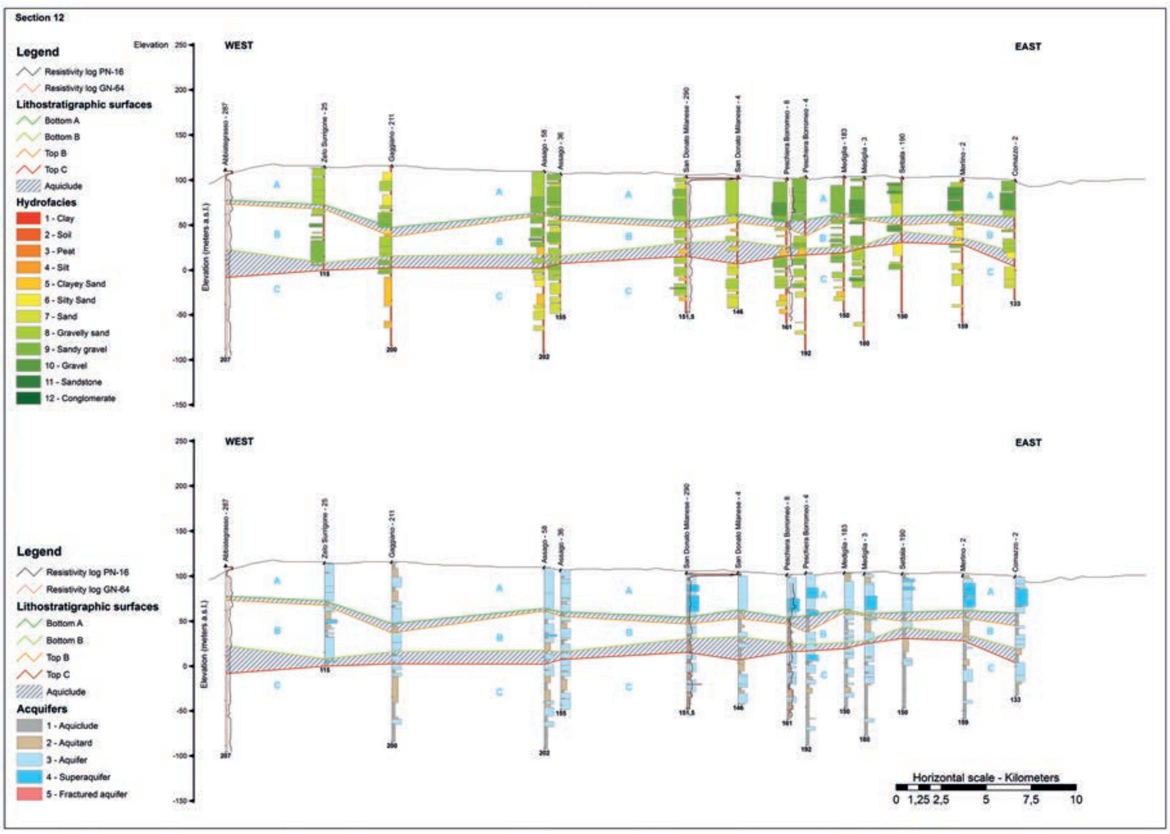

Fig. 7 - West-East hydrostratigraphic section.

Fig. 7 - Sezione idrostratigrafica Ovest-Est.

The aquifer C top boundary is about 120 m a.s.l. in the Northern area, with higher values in the Northeast, and deepens to around -10 m a.s.l. to the south. In the Northern part of the study area, there is an undifferentiated aquifer associated with the complete coalescence of aquifers A and B; the separation between aquifers A and B becomes evident Southward. The bottom of the aquifer B/coupled A+B system is at about 100-110 m a.s.l. in the North-western part of the study area, while it reaches lower depths in the North-eastern area and drops to about 0 m a.s.l. Southward.

Hydrochemical characterization

The hydrogeochemical characterization of the aquifers has been performed by creating a chemical Geodatabase. The GeoDB contains about 95,000 laboratory analyses of raw groundwater of nearly 2000 wells (period 2003-2016). For each well more than 100 chemical substances are periodically monitored by CAP Group.

Geostatistical maps have been carried out using about 48,000 analyses. These basin-scale thematic maps have been developed using 1133 monitoring wells (823 refer to aquifers A, B and A+B, and 310 to aquifer C).

A conceptual hydrogeochemical model, leaning on thematic maps, graphs and trends of the chemical parameters and ionic ratios (in compliance with the European legislation), has been carried out. This analysis allows achieving information concerning not only geochemical processes (ion exchange, degree of maturity, etc.), but also groundwater flow speed and age.

The hydrogeochemical characterization is a valuable tool to identify not only the water quality of supply sources but also pollutant loads generated by human activities and pressures affecting the aquifer system. This assessment has taken into account five main groups of parameters: chemico-physical properties, ionic compounds, inorganic and organic pollutants, new emerging contaminants. Thematic maps for each compound were designed (Fig. 8). *N.d.A.*: the chemical maps referring to raw water abstracted from water wells, and not to distributed water, which is always in compliance with national and EU laws concerning the quality of water intended for human consumption.

Isotopic characterization

On a basin scale isotopic markers naturally contained in groundwater represents a valuable tool to assess the origin, routes and age of groundwater, as well as the interactions and processes that take place in the subsoil between water, soil and any compounds of anthropic origin circulating in the aquifer (Clark and Fritz 1997; Gorla 2009). Multi-isotopic analysis takes into account not only the water molecule (Deuterium, Tritium, Oxygen-18) but also the main compounds and ions dissolved in the groundwater (Nitrogen-15, Sulfate-34, Chlorine-37), allowing to investigate the biogeochemical processes as well as physical and chemical ones.

In view of this backdrop, along with Sapienza University (Rome), several surveys (still in progress) were planned aiming at a complete isotopic characterization of the shallow and deep

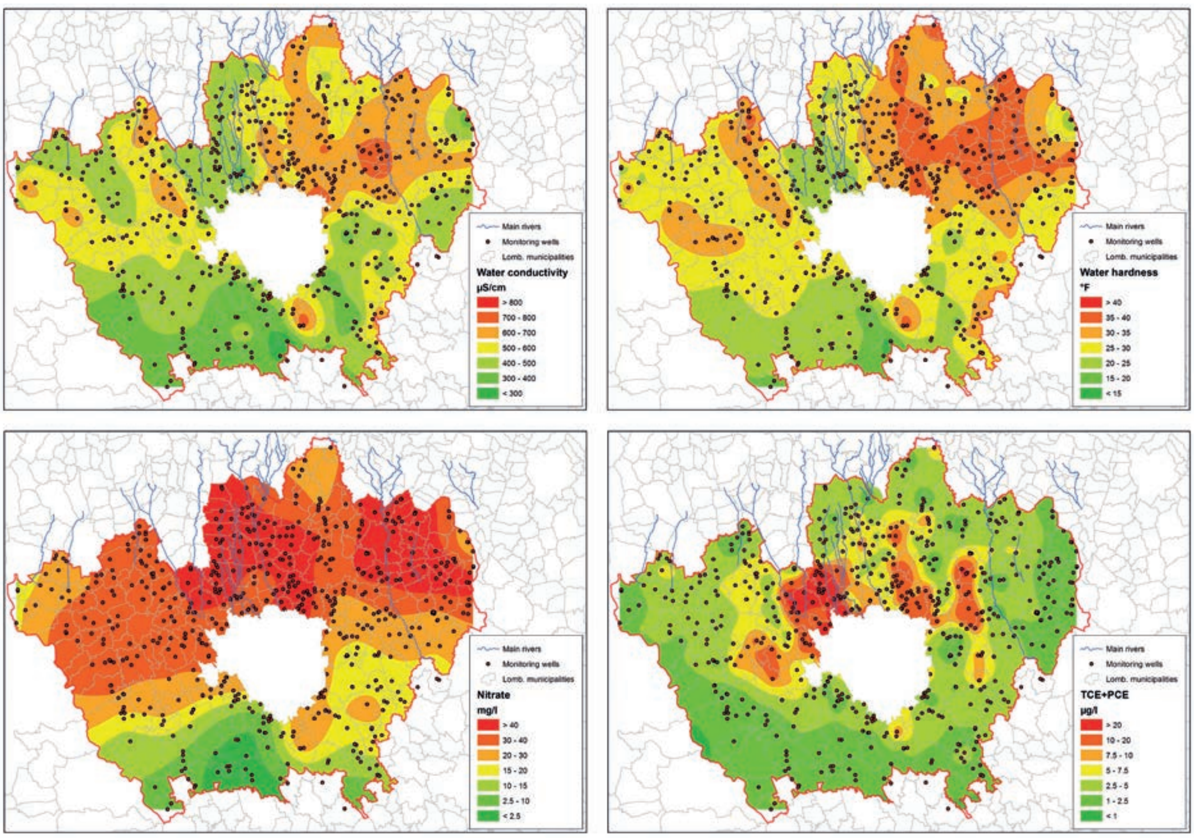

Fig. 8 - Hydrochemical maps: specific electric conductivity, hardness, nitrate, tetrachloroethylene+trichloroethylene.

Fig. 8 - Esempi di mappe idrochimiche: conducibilità elettrica specifica, durezza, nitrati e tetracloroetilene+tricloroetilene.

aquifers (Fig. 9) within the Adda-Ticino hydrogeological basin.

The isotopic study was undertaken considering the following environmental isotopes:

- Deuterium and Oxygen-18: to assess the origin of the groundwater.
- Tritium: groundwater age indicator.
- Nitrogen-15/Oxygen-18: to evaluate the origin and processes within the nitrogen cycle.
- Sulfate-34/Oxygen-18: to assess the origin, routes and processes of sulphates in shallow and deep aquifers.
- Carbon-13 and Chlorine-37 in the chlorinated solvents: to evaluate the evolution and potential degradation of the anthropic pollutants detected in groundwater.

All the analysed water samples have the same origin (meteoric water) and show very slight evaporation signals (interaction with other types of water, e.g. surface water).

In addition, the isotopic data presents a significant degree of variability (Fig. 10), which reflects the existence of several supply areas and groundwater discharge circuits, each of which with specific hydrogeological and hydrochemical features.

The sulphate content and sulphur isotopic ratio (δ34S) reveal an anthropic contribution, related to farming activities and, to a lesser degree, with urban activities (Fig. 11).

The nitrate concentrations and associated isotopic ratio values (δ15N) show more overlapping effects, probably due to farming and urban activities. The analysis highlights that the system does not allow a rapid elimination of nitrates (Fig. 12).

As for groundwater age, the whole basin reflects the existence of rapid but rather vulnerable circuits that requires careful management of the groundwater resources.

Decision Support System structure

The P.I.A. project goal is to build up a D.S.S. aiming at supporting Decision Makers and Water Managers in multi-objective planning of water resource systems based on simulation of alternative scenarios of water availability and water demand and the application of problem-specific policy measures (Peruffo and Todini, 2005).

CAP Group D.S.S. is a package that allows for water resource assessment, identification of boundary conditions, climatic driving forces and demographic pressures, simulation and investigation of future forecasts and comparison of alternative policy measures. It relies on a GIS, a Geodatabase and a complex set of model outputs (Fig. 13).

The project has been designed in steps including Geodatabase building, GIS analysis (including multilayer analysis M.L.A.) and numerical modelling.

The data collected in the geodatabase were analyzed to design GIS quantitative and qualitative thematic maps in order to perform the M.L.A.

The multilayer analysis of current and future condition and impacts implies the use of appropriate indicators, which objective is to provide the Decision Maker with a comprehensive picture of the water system. These indicators are based on the following quantitative and qualitative data:

- Hydrogeological features
- Chemical data
- Isotopic values and chemical ratios
- Soil use and hazards
- Climatic and hydrological parameters
- Demographic data.

Each parameter belonging to these macro areas were classified by 7 criticality classes scale. In order to reflect the relative importance of these parameters, weights were assigned to each of them. For each macro area a synthetic index was calculated by multiplying class values with weights. These synthetic indexes were managed with a multilayer approach and compared to other models and tools (e.g. geological model, numerical groundwater model, distribution network model) in order to obtain criticality indexes. The assessment of these criticality indexes allow to evaluate alternative and strategic solutions to achieve a more efficient and sustainable water system management using a best choice approach.

Currently the project team is working on M.L.A. The next task will be the implementation of groundwater numerical model.

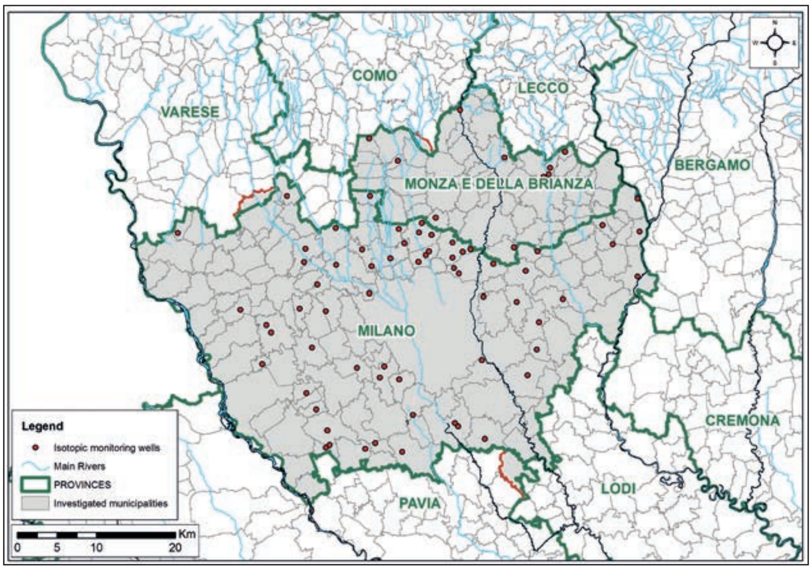

Fig. 9 - Location of wells sampled for the isotope analyses (November 2015 campaign).

Fig. 9 - Ubicazione dei pozzi campionati per le analisi isotopiche (Campagna novembre 2015).

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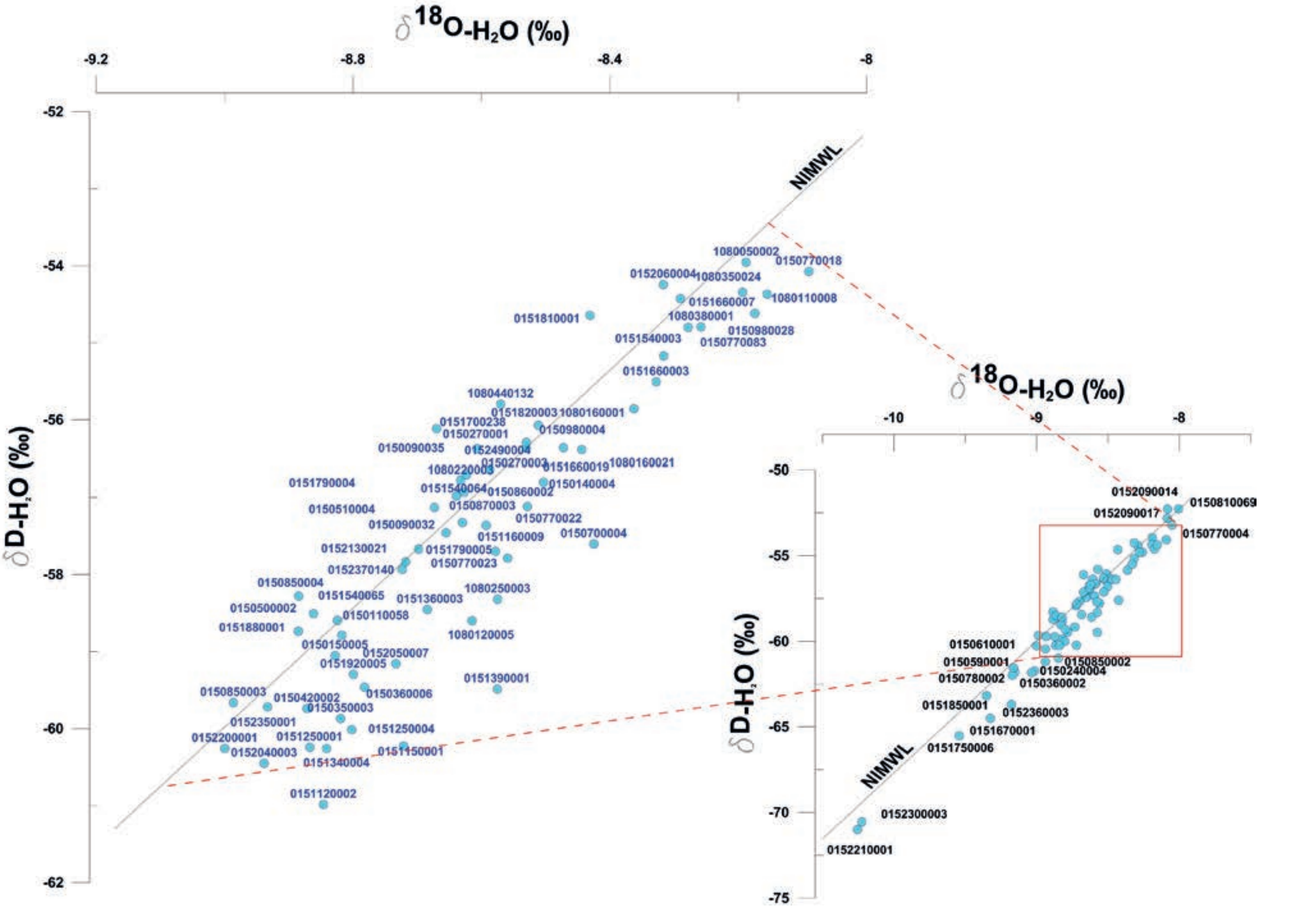


Fig. 10 - Deuterium/Oxygen-18 diagram of the water samples analysed (November 2015 campaign) (NIMWL = North Italy meteoric water line, Longinelli and Selmo 2003).

Fig. 10 - Diagramma Deuterio-Ossigeno 18 dei campioni d'acqua analizzati (Campagna novembre 2015) (NIMWL = North Italy meteoric water line, Longinelli e Selmo 2003).

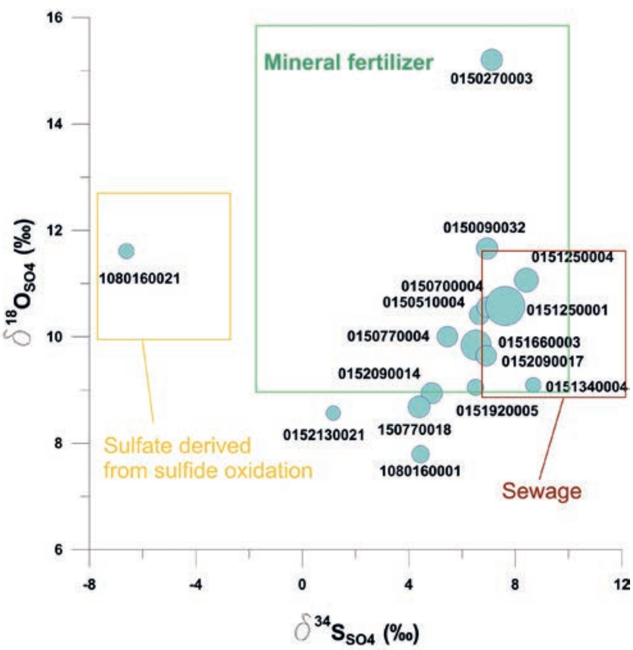


Fig. 11 - Sulphur 34/Oxygen-18 isotope diagram (November 2015 campaign).

Fig. 11 - Diagramma isotopico Zolfo 34/Ossigeno 18 (Campagna novembre 2015).

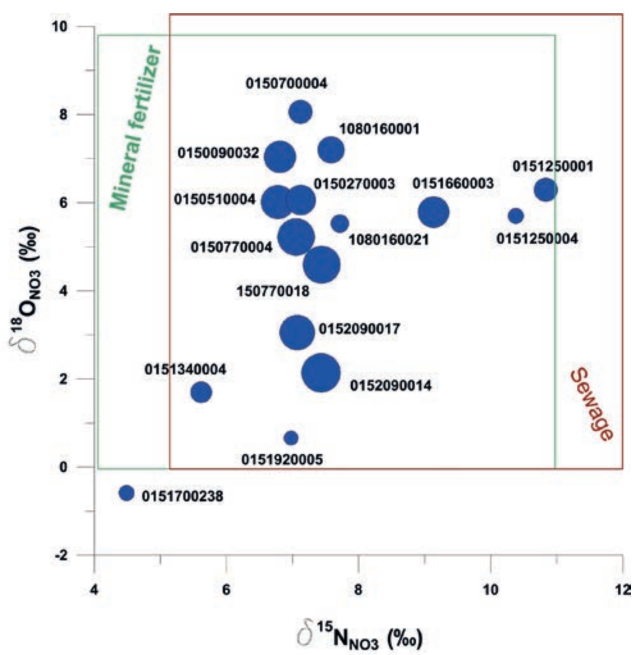


Fig. 12 - Nitrogen-15/ Oxygen-18 isotope diagram (November 2015 campaign).

Fig. 12 - Diagramma isotopico Azoto 15/Ossigeno 18 (Campagna novembre 2015).

Multilayer analysis: indexes and workflow

Multilayer Analysis consists in combining, with GIS tools, several levels of information, which can be used to develop a decision support system.

This multilayer analysis includes the following synthetic indexes (Fig. 13):

- IDX_IDR: quantitative index clustering main hydrogeological features with effective infiltration;
- IDX_QUAL: qualitative index based on the groundwater chemico-physical and chemical features (including the most representative pollutants on a basin scale);
- IDX_SOST: quali-quantitative index which takes into account groundwater geochemical features (ionic ratios and isotopic values and ratios) aiming at achieving a sustainable use of groundwater;
- IDX_SUP: qualitative index based on the nature of the soil, its end use and the presence of potential risk areas for the groundwater;
- IDX_CLIMA: quantitative parameter that takes into account the climatic factors that affect the hydrogeological water balance.
- IDX_DEMO: quantitative parameter considering percentage variation of population within the investigated area.

Warning thematic maps has been carried out by the analysis of each of these synthetic indexes and their overlapping in order to highlight possible critical issues concerning water management.

Hydrogeological index – IDX_IDR

This quantitative index takes into account: hydrogeological features (depth to water, hydraulic gradient, groundwater fluctuations), hydrodynamic (specific capacity) and geometric properties (thickness) of the aquifer, effective infiltration.

Within the investigated area the main critical issue concerns depth to water values (highest risk in the Southern areas of the basin where the aquifer is less than 2.5 m below ground level

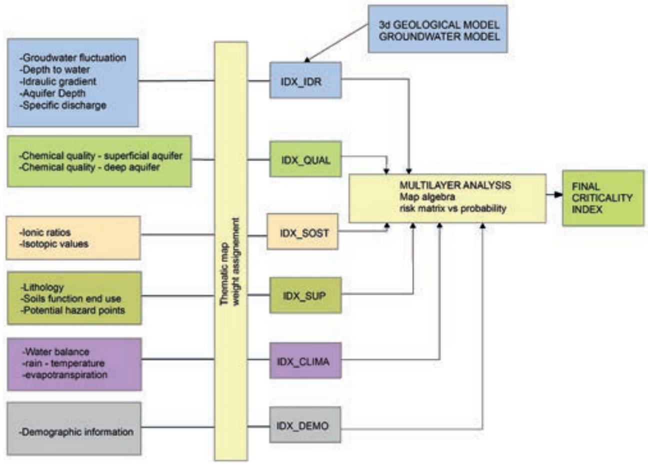


Fig. 13 - Prototype D.S.S. structure.

Fig. 13 - Struttura del prototipo di D.S.S.

(Fig. 14) and the seasonal fluctuation of groundwater (highest risk in the Northern areas of the basin where it exceeds 3 m) (Fig. 15).

IDX_IDR comes from overlaying IDX_GRAD (hydraulic gradient), IDX_Qs (specific capacity), IDX_SOGG (depth to water), IDX_OSC (groundwater fluctuations), IDX_Ie (effective infiltration) and IDX_GEOM (aquifer thickness) (Fig. 16).

Quality index – IDX_QUAL

IDX_QUAL refers to groundwater quality. This quality index takes into account the groundwater physico-chemical features (pH, specific electrical conductivity and hardness) and the main pollutants detected in the study area. With reference to the Drinking Water Directive (1998/83/EC) and to the knowledge of the groundwater quality investigated over the past decades, we focused our attention on:

- nitrates, sulphates, chlorides, solvents (tri- and tetrachloroethylene) and total pesticides detected in aquifers A and B;

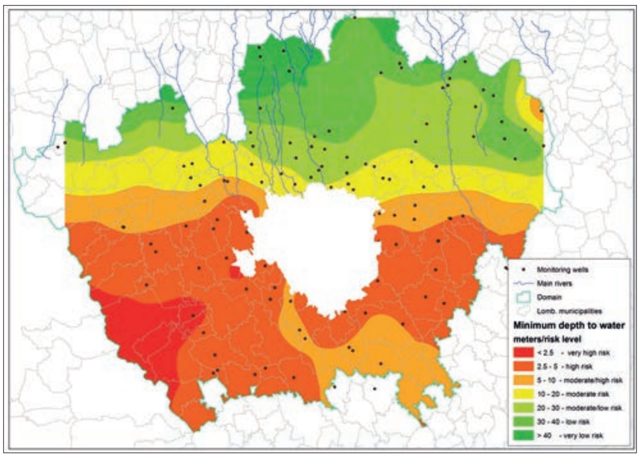


Fig. 14 - Minimum depth to water map (mean value, 2001-2015).

Fig. 14 - Carta della soggiacenza minima (valore medio, 2001-2015).

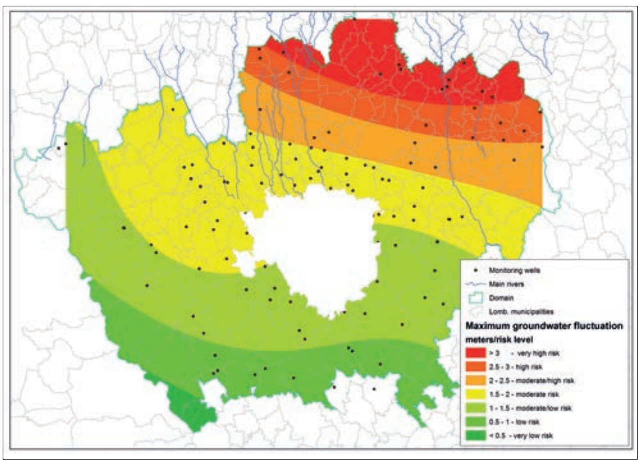


Fig. 15 - Maximum phreatic aquifer fluctuation map (mean value, 2001-2015).

Fig. 15 - Carta della massima oscillazione della falda libera (valore medio, 2001-2015).

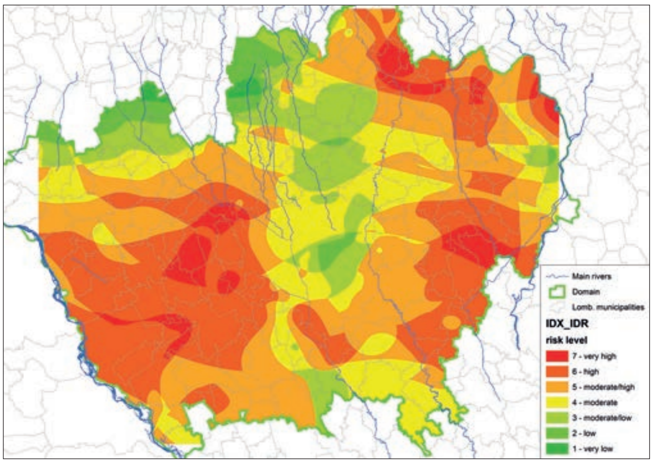


Fig. 16 - Hydrogeological index synoptic map (IDX_IDR).

Fig. 16 - Carta sinottica dell'indice idrogeologico (IDX_IDR).

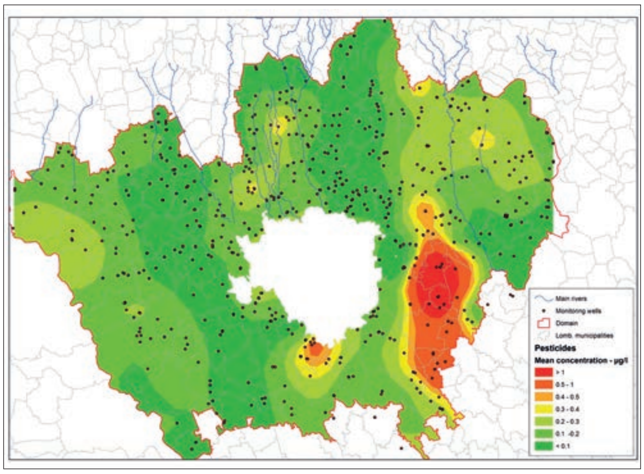


Fig. 17 - Pesticide map (mean concentration, 2006-2015).

Fig. 17 - Carta della concentrazione media dei prodotti fitosanitari (2006-2015).

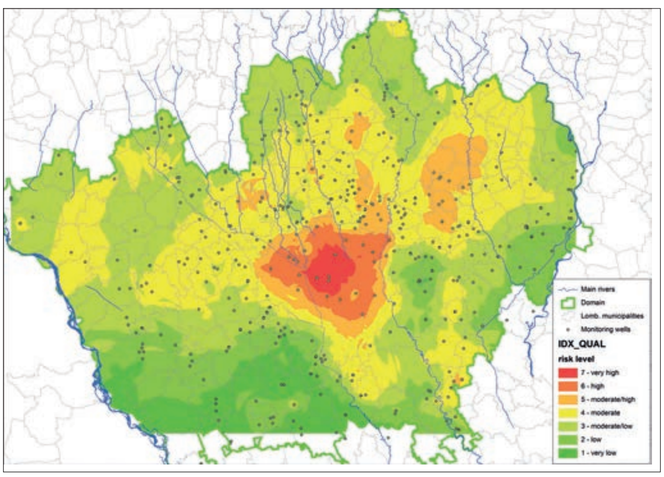


Fig. 18 - Quality index synoptic map (IDX_QUAL).

Fig. 18 - Carta sinottica dell'indice di qualità (IDX_QUAL).

- iron, manganese, arsenic and ammonium ions, with particular attention for deep aquifer (reductive environment).

Geostatistical analyses were performed to produce thematic maps for each chemical parameter (e.g. pesticide map, Fig. 17). As stated before, each parameter was classified and weighted in order to have a synthetic index. These synthetic indexes were managed with a multilayer approach in order to build up the IDX_QUAL map (Fig. 18).

Future implementation of this index will consider other 40 chemical parameters, including: hexavalent chromium, trihalomethanes, chlorofluorocarbons, aromatic solvents and N.E.C.s (new emerging contaminants), such as LM6 (4-(tertbutilammino)-6-idrossi-1-metil-1,3,5-triazin-2(1H)-one) and Mebicar (1,3,4,6-Tetramethyltetrahydroimidazo[4,5-d]imidazole-2,5(1H,3H)-dione).

Sustainability index – IDX_SOST

IDX_SOST is a quali-quantitative index, essential to rate the sustainability of groundwater withdrawal with respect to the values of some ionic ratios referring to aquifers A, B and C.

These ionic ratios can provide essential information such as: the relative age of groundwater (base-exchange index, I.E.B.), their degree of maturity (Mg^{++}+Cl^-/Na^++K^+ ratio); the presence of geochemical processes (ion exchange, Na^+/Cl^- ratio) and the speed of the circuit in the subsoil (SO_4^{--}/Cl^- ratio).

Future implementation of this index will take into account isotopic parameters.

The ionic ratios analysis (Fig. 19) shows that the water is relatively young and characterized by medium-fast circuits. The ionic ratio indexes were managed with a multilayer approach in order to build up the IDX_SOST map (Fig. 20).

Surface Index – IDX_SUP

This is a qualitative index resulting from the sum of scores assigned on the basis of the nature of soils (permeability, IDX_LITO) (database: Lombardy Region Authority, 2016) and their use (IDX_USO) (database: DUSAF, 2010) and the presence of potential risk areas (in progress).

The risk increases with particle size, from clayey soils to gravelly ones. As far as land use is concerned, the risk increases from the urbanized areas, through the cultivation, pasture and woody areas to those with no vegetation. IDX_SUP (Fig. 21c) comes from overlaying IDX_LITO (Fig. 21a) and IDX_USO (Fig. 21b). Furthermore by combining this index, including the presence of potential risk areas (e.g. landfill sites, high-risk industrial factories, sewers, etc.), with the quality index (IDX_QUAL), an overview of the groundwater state of health can be achieved.

Climatic Index – IDX_CLIMA

IDX_CLIMA represents a quantitative index. It relies on the impact analysis of two climatic factors affecting the water balance (precipitation, evapotranspiration).

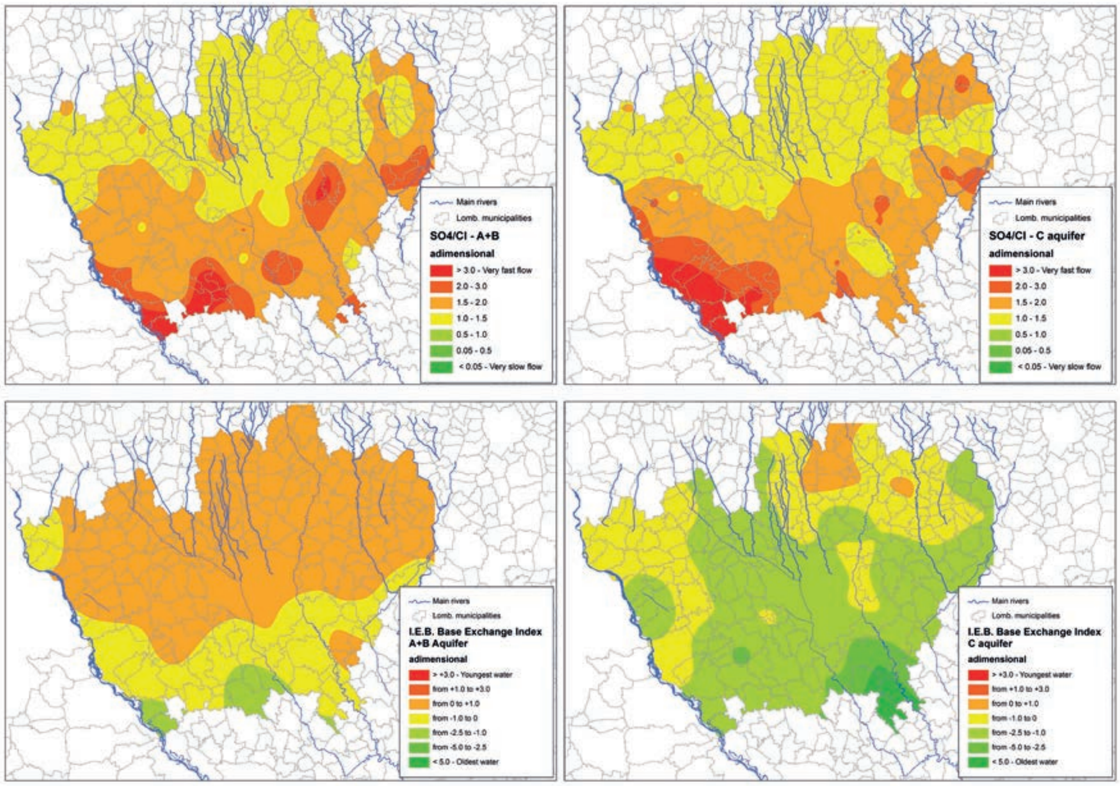


Fig. 19 - Main ionic ratios used to develop the sustainability index (IDX_SOST) (2010-2015).

Fig. 19 -Principali rapporti ionici usati per lo sviluppo dell'indice di sostenibilità (IDX_SOST) (2010-2015).

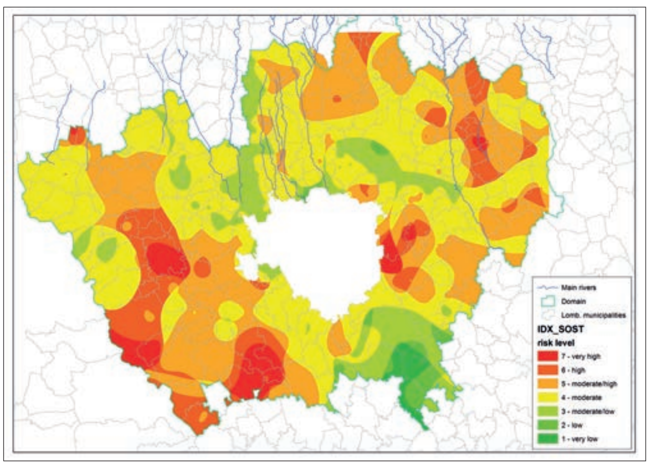


Fig. 20 - Sustainability index synoptic map (IDX_SOST).

Fig. 20 - Carta sinottica dell'indice di sostenibilità (IDX_SOST).

The monthly mean temperature and precipitation (provided by Epson Meteo - 2001-2015 period) were evaluated and the potential evapotranspiration according to the empirical equation of Turc (1954) was calculated. The outcome of these maps in a raster format made it possible, using map algebra, to define a summary index taking into account the two factors weighted according to post-hoc multivariate analysis. The IDX_CLIMA (Fig. 22c) index results from overlaying the IDX_PREC (Fig. 22b) (precipitation) and IDX_ETR (evapotranspiration) (Fig. 22a).

Demographic index – IDX_DEMO

IDX_DEMO represents the percentage of yearly mean variation of population within the investigated area (2001-2015) (Fig. 23).

Discussion

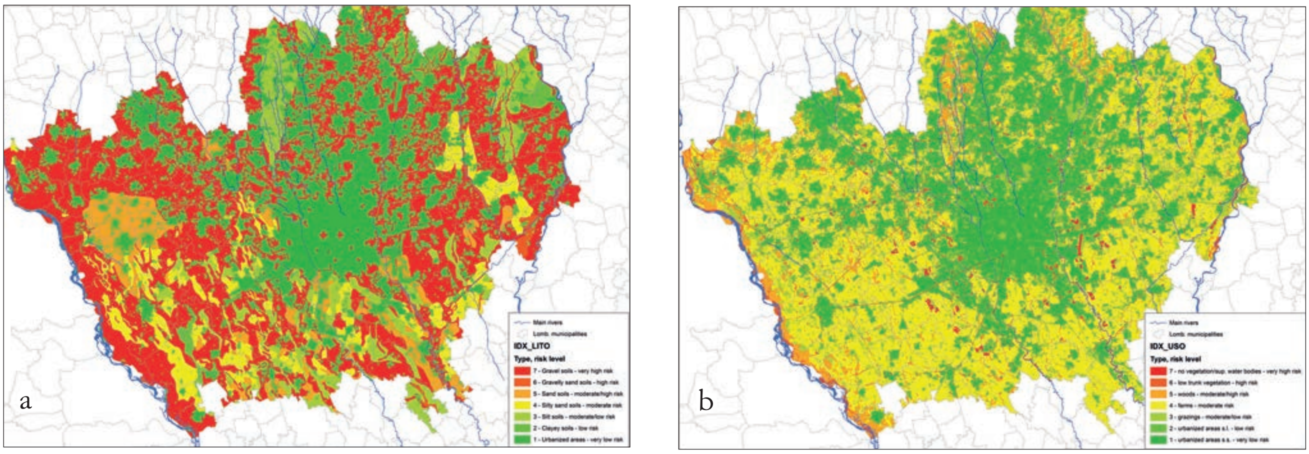
The multilayer analysis undertaken on a basin scale provided several indications useful for a sustainable management of the abstracted groundwater resources.

With regard to quantitative and discharge conditions, the most relevant criticality occurs where the aquifer is close to ground level, especially in the central and Southern part of the investigated area.

From a qualitative point of view, the laboratory analysis revealed the presence of widespread pollution in raw groundwater samples but, with respect to the recent past, it seems to lie just above the drinking water threshold values (Italian and European legislation).

With regard to the sustainability indexes, despite the prevalent meteoric nature of groundwater circulating at basin scale, some relevant differences associated with the type of circuit followed (shallow or deep) were recognized: groundwater is young and characterized by medium-rapid circuits which increases its vulnerability and requires a careful monitoring.

The soil end use and climate indexes confirmed the conditions described above. In particular, the areas that require most attention are located near the principal streams



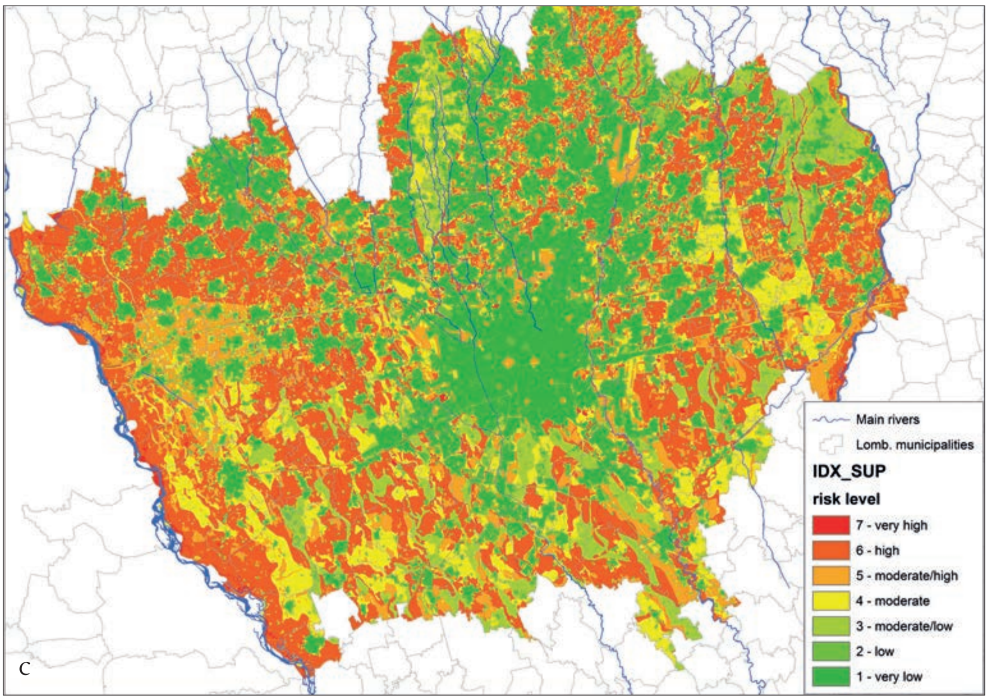


Fig. 21a, b, c - c) Surface index synoptic map (IDX_SUP) that takes into account lithology (IDX_LITO) (a) and use (IDX_USO) of the soils (b).

Fig. 21a, b, c - c) Carta sinottica dell'indice di superficie (IDX_SUP), che tiene conto della litologia (IDX_LITO) (a) e dell'uso (IDX_USO) dei suoli (b)

(above all the rivers Ticino and Adda) and have the most adverse climatic conditions (high evapotranspiration, low precipitation and infiltration).

The following figure (Fig. 24) shows an example of the final output of the multilayer analysis process.

This analysis refers to the current state of play. The input and output of the M.L.A. will be periodically updated and revalidated. An annual revision and update of the analysis could be appropriate.

Conclusions

This paper describes the preliminary steps concerning the design of a prototype D.S.S. aiming at the management of groundwater resources on a basin scale in the area between Ticino and Adda rivers in which CAP manages the integrated water cycle.

The building of a solid conceptual model of the area based on an in-depth hydrogeological, geochemical and isotopic characterization enabled the critical environmental problems to be identified, the origin of the water to be determined and the future evolution of the system to be predicted.

The use of criticality indexes for the hydrogeological, geochemical, climatic, soil use and demographic features, examined through a multilayer analysis, allowed all the available information to be combined in order to get a prototype D.S.S. for the assessment of present status of the water resources system, the investigation of unsatisfying conditions, the definition of alternative strategic measures and for an efficient water resources management at basin scale.

The main outcomes are the following:

- the most relevant hydraulic criticality occurs in the central and Southern part of the investigated area where the aquifer is close to ground level;
- a widespread pollution in raw groundwater was highlighted, even if lying just above the drinking water threshold values (Italian and European legislation);

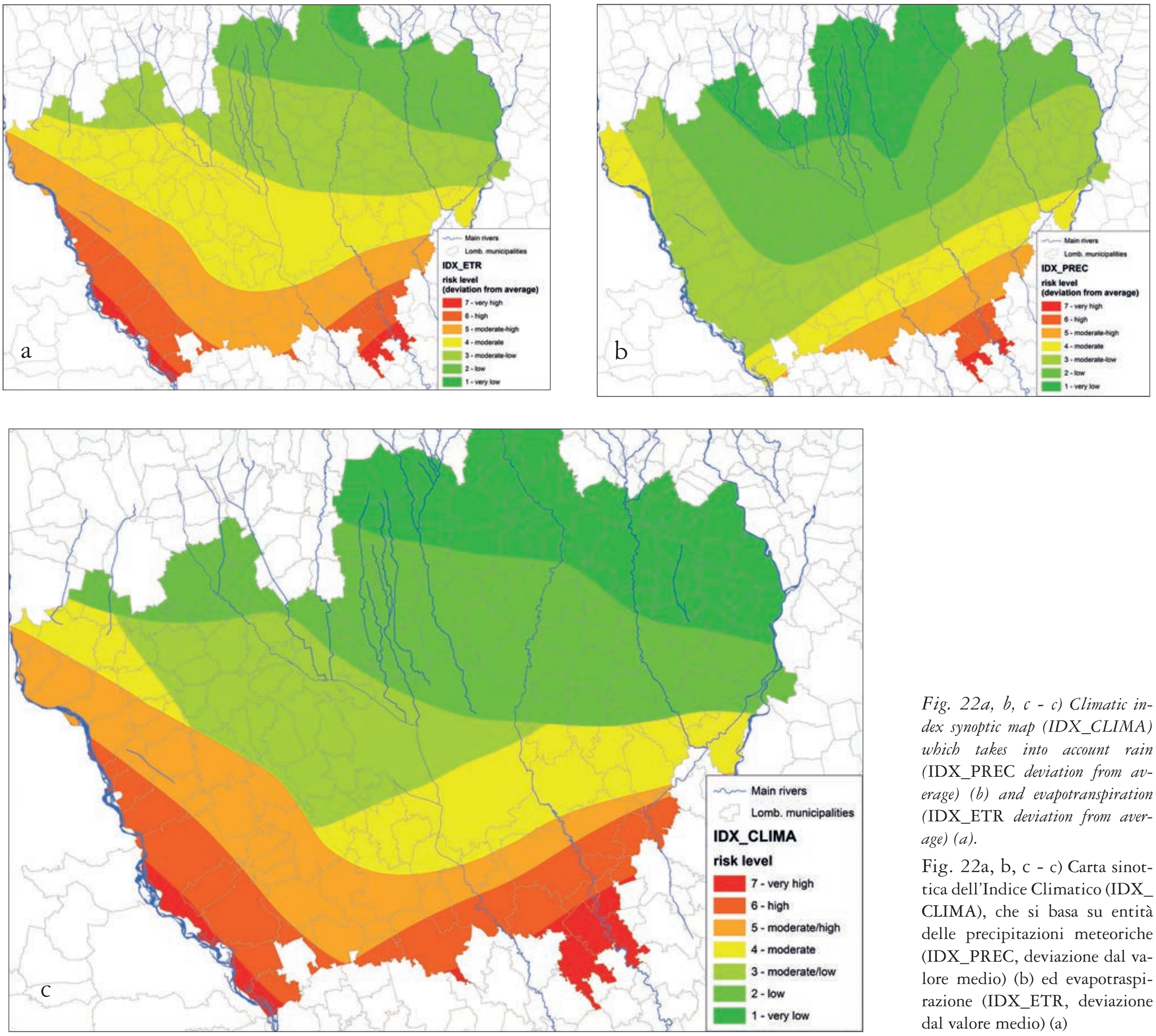


*Fig. 22a, b, c - c) Climatic index synoptic map (IDX_CLIMA) which takes into account rain (*IDX_PREC *deviation from average) (b) and evapotranspiration (*IDX_ETR *deviation from average) (a).*

Fig. 22a, b, c - c) Carta sinottica dell'Indice Climatico (IDX_CLIMA), che si basa su entità delle precipitazioni meteoriche (IDX_PREC, deviazione dal valore medio) (b) ed evapotraspirazione (IDX_ETR, deviazione dal valore medio) (a)

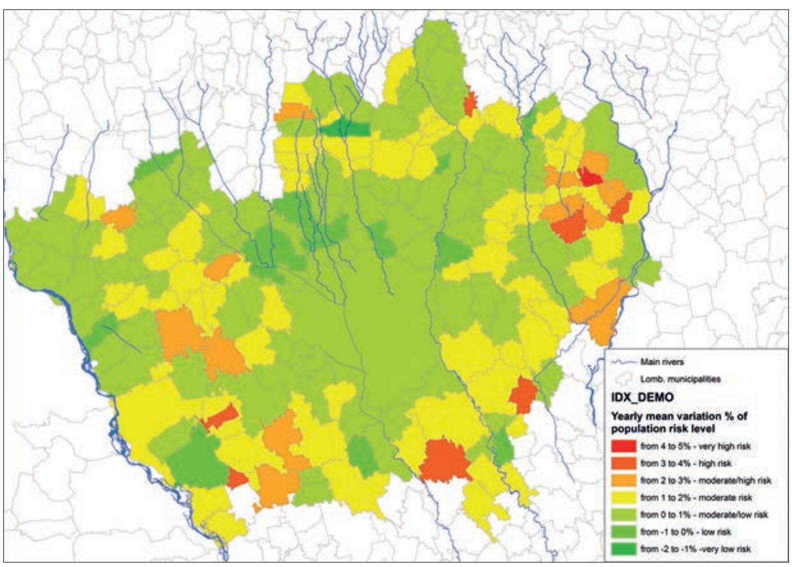


Fig. 23 - Demographic index synoptic map (IDX_DEMO).

Fig. 23 - Carta sinottica dell'indice demografico (IDX_DEMO).

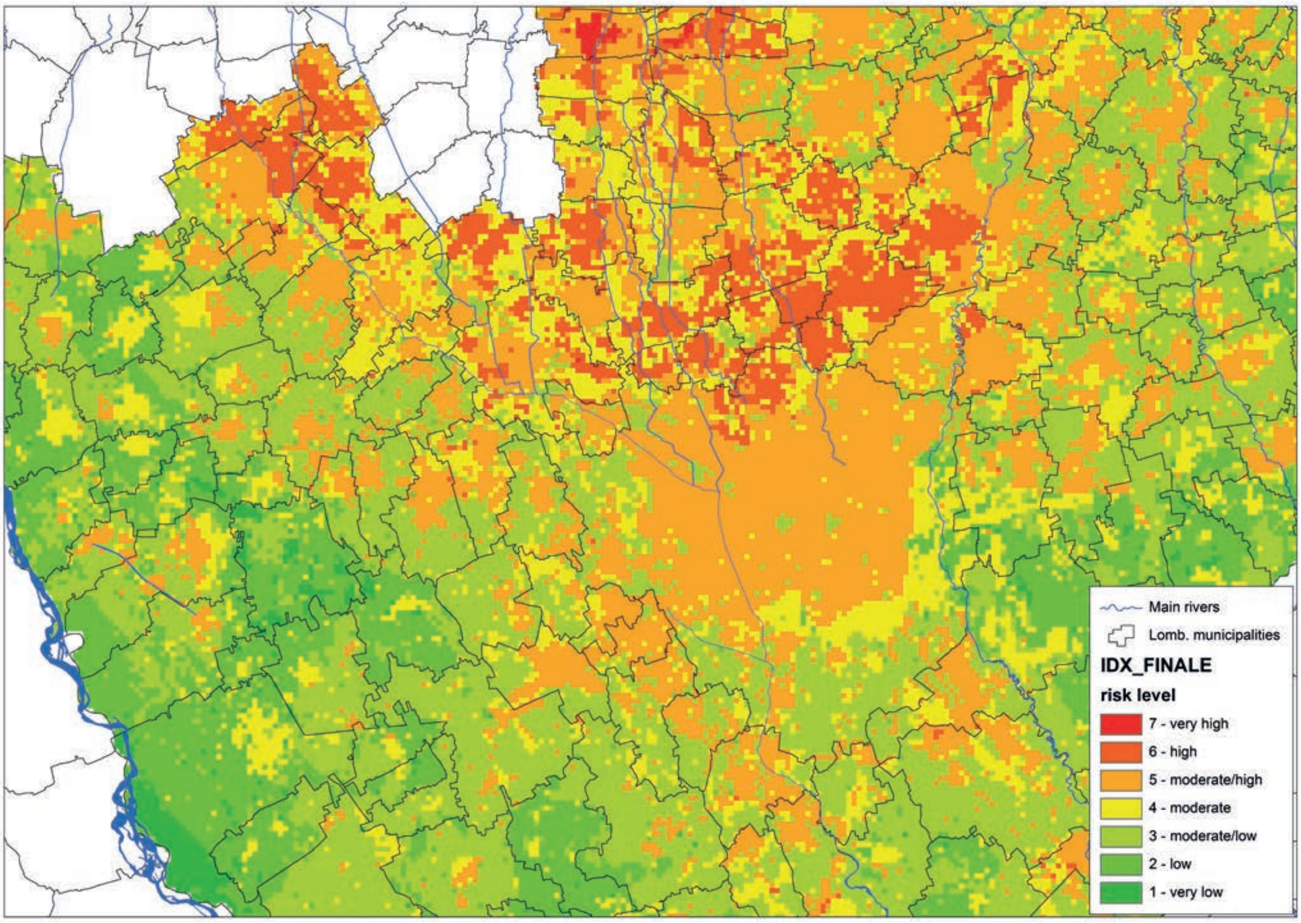


Fig. 24 - Indexes' overlay of the prototype Decision Support System.

Fig. 24 - Overlay degli indici considerati nel prototipo di Decision Support System.

- the prevalent meteoric nature of groundwater circulating at basin scale;
- a relative young groundwater age and medium-rapid flow circuits;
- the areas need for more attention are located near the principal streams and undergo the most adverse climatic conditions (high evapotranspiration, low precipitation and infiltration).

The prototype D.S.S. will be further enhanced with:

- a basin-scale groundwater flow model, currently under construction. The numerical model, implemented by using the finite-element code FEFLOW® 7.0 (DHI-WASY GmbH) (Diersch, 2013), will simulate groundwater flow on a basin scale for the three main aquifer systems identified (A, B and C). This tool will provide a valuable decision support to quantify hydrogeological water balance.
- the contouring of the wellhead protection areas for drinking water wells (FEFLOW® groundwater age module).
- a space-temporal analysis of the main pollutant plumes, following the implementation of numerical transport models.
- the implementation of a remote control system (early warning system) collecting data on potentiometric levels, chemico-physical parameters and flow rates withdrawn from the drinking water wells managed by CAP.

Future developments of the project will be focused on the design of a more complete decision support system (D.S.S.) being able to gather GIS tools, numerical groundwater and water distribution modelling, and remote data acquisition.

Acknowledgments: We would like to thank the colleagues of Brianzacque for their cooperation and for the valuable data sharing..

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