

An integrated methodology to define Protection Zones for groundwater-based drinking water sources: an example from the Tuscany Region, Italy

Un approccio integrato per la definizione della Zona di Protezione per captazioni idropotabili: applicazione su captazioni della Toscana, Italia

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Riassunto: La percezione che l'acqua sia un bene economico e sociale, oltre che una risorsa finita e vulnerabile, è stata tradotta nelle normative europea e nazionale (2000/60/EC e D.Lgs. 152/2006) ed ha portato alla consapevolezza del ruolo di questa risorsa e della sua importanza nei differenti sistemi socio-economici, culturali e politici. In questo contesto la definizione delle Aree di Salvaguardia delle captazioni idropotabili che sopperiscono al fabbisogno idrico acquisisce un ruolo fondamentale. Nella normativa vigente non esiste un protocollo tecnico-scientifico che descriva una metodologia di indagine per la delimitazione della Zona di Protezione, che insieme a quella di Tutela Assoluta e di Rispetto vanno a costituire l'Area di Salvaguardia. L'obiettivo di questo contributo è quello di descrivere una metodologia integrata da poter essere utilizzata come riferimento per la delimitazione delle Zone di Protezione di captazioni idropotabili. Il lavoro si inserisce in un progetto dell'Istituto di Geoscienze e Georisorse del CNR (IGG-CNR), finanziato dalla Regione Toscana attra-

verso il Consorzio Lamma e finalizzato alla individuazione delle zone di protezione di alcuni principali campi pozzi o sorgenti idropotabili distribuiti sul territorio regionale. Nello specifico la metodologia utilizzata consiste in uno studio integrato che vede coinvolte discipline geologiche, idrogeologiche, geochemiche ed isotopiche per la definizione di un modello concettuale volto alla conoscenza dei sistemi acquiferi in esame. Lo studio svolto ha permesso di delineare l'assetto idrostrutturale 3D dei sistemi acquiferi in esame, stimare i volumi idrici in gioco, individuare e caratterizzare le varie componenti di alimentazione nonché i rapporti esistenti fra quest'ultime. Mediante questo approccio sono state individuate quindici Zone di Protezione, generalmente, suddivise in due macro aree che concorrono con diversi quantitativi e con meccanismi differenti ad alimentare il sistema acquifero in esame. Le suddette aree sono state ulteriormente validate per mezzo di bilanci idrogeologici e bilanci di massa.

Parole chiave: zone di protezione, acque potabili, gestione delle acque sotterranee, modello idrogeologico concettuale.

Keywords: protection zones, water for human consumption, groundwater management, conceptual hydrogeological model.

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Abstract: *Water is an essential economic and social resource. It is also finite and vulnerable. For Europe, this generally accepted understanding has been translated into the European and National Directive (2000/60/EC, D.Lgs. 152/2006). This law has led to an increased awareness of the role of the resource and its importance in the socio-economic, cultural, and political realms. To protect this resource, safeguard zones for drinking water sources must be delineated. In Italy, a drinking water source such as a well or spring is to be protected by means of a three-level safeguard zone: an absolute safety zone close to the source, a respect zone depending on groundwater travel time, and a Protection Zone. The aim of this paper is to describe an integrated methodology used to define the Protection Zone. The work, developed within the framework of a project of the Institute of Geosciences and Earth Resources (IGG-CNR) and funded by the Tuscany Region Administration through "Consorzio Lamma", focused on the delineation of the Protection Zones for several abstraction points located throughout the regional territory. The proposed methodology for protecting drinking water sources described in this paper integrates geological, hydrogeological, and hydrogeochemical methodologies. The approach includes a definition of the hydrostratigraphy of the aquifer systems, estimates of the water volume, and the quantification of inflows and outflows, as well their interrelationships. By means of this integrated methodology, fifteen Protection Zones were defined; each of these zones was divided in two areas according to their relative importance to supplying a drinking water source. The Protection Zones were further validated by means of hydrogeological and isotopic budget calculations.*

Introduction

Worldwide, more than 2 billion people depend on groundwater for their daily water use (Hiscock, 2011); furthermore in many areas groundwater bodies are the most important and safest sources of drinking water (Zhu and Balke, 2008; Baoxiang and Fanhai, 2011). In the countries of the European Union, groundwater provides nearly 70% of the piped water supply and 80 % of the drinking water (Zhu and Balke, 2008). The use of groundwater has significantly increased in recent decades due to its wide-spread occurrence, good quality, high reliability during droughts, and modest development costs. Industry and agriculture widely depend on groundwater. However, pollution as well as overexploitation can cause a progressive qualitative and quantitative degradation of the groundwater resources. Optimal management and preservation of this vital resource are required in order to assure its availability for future generations. With the Water Framework Directive (European Union, 2000) coming into effect, water protection has turned into one of the priority environmental targets of European policies. A correct and strategic planning of groundwater management should be based on specific studies aimed to characterize groundwater bodies in terms of quality and quantity, and defining the threshold values of pollutants in water. In order to protect this essential resource the delineation of safeguard areas for drinking water is a very important task. Pioneering actions on this matter were performed by US and Germany, whose guidelines (EPA, 1987; USGS, 1998; DVGW, 1995) are fundamental references for defining technical elements for groundwater protection such as wellhead protection areas and well capture zones.

Following Directive 2000/60/EC, European Member States approached this issue by domestic legislation, in which, although with some technical differences, three main zones are mentioned:

- an inner zone, that is the area immediately surrounding the abstraction point;
- an intermediate zone, which corresponds to the area surrounding the previous one and is generally delineated on the base of a reference travel time;
- an outer zone, that is the area around a source within which all groundwater recharge is presumed to be discharged at such source.

Italian law (D. Lgs. 152/2006; 12 December 2002 agreement) states that the above-mentioned zones are named “absolute safety zone”, “respect zone” and “protection zone”, respectively. The first zone is simply an area of at least 10 m radius immediately surrounding the abstraction zone; the second one is the surrounding territory delimited by a travel time of 60 and 180 or 365 days depending on vulnerability and hazard condition; and “the protection zone”, which is identified within the groundwater recharge area and defined by means of the approach named “hydrogeological approach”. Furthermore, Italian law states that Regions (Italian administrative units) must identify these safeguard zones in order to protect and improve the quality of groundwater resources intended for human consumption. Due to their major impor-

tance in terms of safeguard, in Italy the “respect zone” has been delimited for several abstractions according to existing guidelines. On the other hand, documentation for the delineation of “protection zones” is scarce, with neither official documents nor a significant number of study cases in existence. Some case studies relating to this issue have been published both for alluvial aquifers (e.g., Derouane and Dassargues 1998; Beretta et al. 2002; Frind et al. 2002; Zhu and Balke 2008; Elewa et al. 2012; Meyer et al. 2014), and fractured/karst aquifers (e.g., Hao et al. 2006; Pochon et al. 2008; Zhu and Balke 2008; Civita 2008). However, despite the fact that Environmental Agencies and Authorities often consult the scientific community, it is very difficult in many practical cases to determine a rigorous and scientific methodology for all types of aquifer systems.

This paper summarizes a general approach for delineating protection zones (hereafter PZs) for drinking water sources. In particular, we describe the integrated approach developed within the framework of a project funded by the Tuscany Region Administration and applied to fifteen groups of sources throughout the regional territory, in cooperation with the Water Authorities (hereafter WAs) and the Integrated Urban Water Management Companies (hereafter IUWM-Cs).

Methodology

The proposed method is an interdisciplinary approach, based on the synergy and comparison of geological, hydrogeological and hydrogeochemical aspects.

Firstly, existing/available data were collected and a preliminary assessment was performed in order to develop some new sampling surveys, with the cooperation of the WAs and the IUWM-Cs. Especially, where available data were inadequate, the new surveys covered: 1) hydrogeological measurements (water head, discharge) and hydraulic tests; 2) on site measurements of water chemical-physical parameters and collection of water samples for the laboratory analyses on chemical and isotopic parameters; and, 3) geological surveys and/or drilling of new boreholes to acquire new stratigraphic information. These activities were planned taking into account the specific hydrogeological context for each aquifer system and basing on the knowledge acquired in the first phase of the study.

Subsequently, in order to define the conceptual model of the aquifer system, the new acquired geological, hydrogeological, and geochemical data were processed together with existing data and all data provided by WAs and IUWM-Cs (such as withdrawal values, discharge of springs, borehole data, well completion, etc). Figure 1 shows a scheme of the integrated and multidisciplinary approach used to delineate the conceptual hydrogeological model, useful to define the PZ of the abstraction point of interest.

Geology and hydrostratigraphy

The geological data processing and the hydrogeological interpretation of the results allowed the identification of the hydrostructures likely involved in the groundwater flow systems

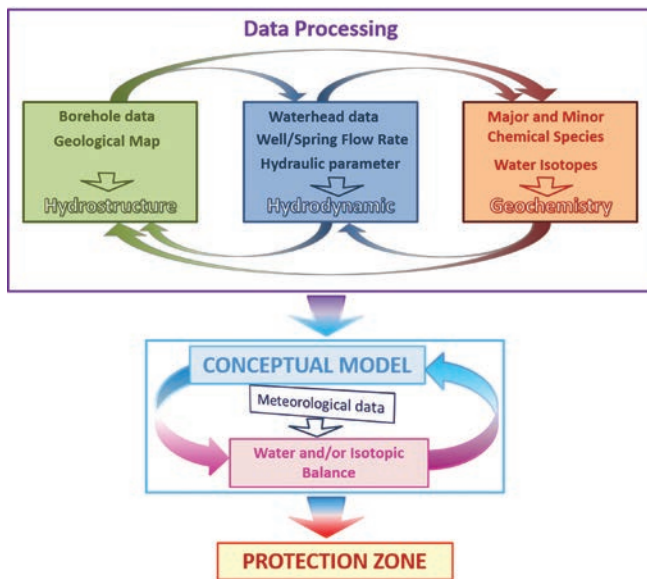


Fig. 1 - Integration of different data types into conceptual model for delineation of protection zone.

Fig. 1 - Approccio multidisciplinare volto alla definizione di una modello concettuale per la delimitazione delle Zone di Protezione.

that feed the abstraction points under examination. The main structural elements that affect the groundwater flow were also identified (e.g. groundwater divides). Figure 2, for example, shows the 3D reconstruction obtained considering the geology together with the permeability properties of the rocks within a catchment in NW-Tuscany, where an important well field is located. By this reconstruction it was possible to define not only the geometry and the volume of the aquifers, but also the relationship among the several hydrogeological units. Especially, the hydrostructural framework suggests that a

significant contribution to the alluvial system in the well discharge area can originate in the "Calcare cavernoso" unit, outcropping in the vicinity of the well. On the other hand, only minor contribution are expected from the medium/medium-high permeability rock units outcropping in the eastern part of the catchment, because of the general southwards dip of the structures and of the presence of an aquiclude that promotes an exit of groundwater towards SE.

In addition to the structural geology study, in some cases a sedimentological and micropaleontological analysis of continuously cored boreholes were performed for alluvial aquifers obtaining a reconstruction of the stratigraphic sequence.

Hydrogeology and hydrodynamic features

For alluvial systems, the hydrogeological data assessment led to the characterization of the aquifer from a hydraulic and hydrodynamic point of view. Fundamental parameters such as hydraulic conductivity, transmissivity, specific storage were obtained and potentiometric maps were drawn up, thus obtaining hydraulic gradients, hydrogeological divides, and flow paths. Groundwater flowrates were then estimated, also helping to identify priority areas for supplying the drinking water source. Figure 3 shows an example of a water table contour map that, in the specific case, refers to an unconfined aquifer system made up by alluvial sediments in the shallower part and mainly by carbonate rocks at depth. The hydraulic heads were considered as the equilibrium values affected by groundwater flows that develop within both the alluvial and carbonate-rock aquifer. The main flow lines were identified and approximate stream tubes were plotted on the basis of the water table contours. For estimating the groundwater flowrate for each stream tube, Darcy and Kamenskij equations (Kamenskij, 1943; Celico, 1986) were applied, thus obtaining, as

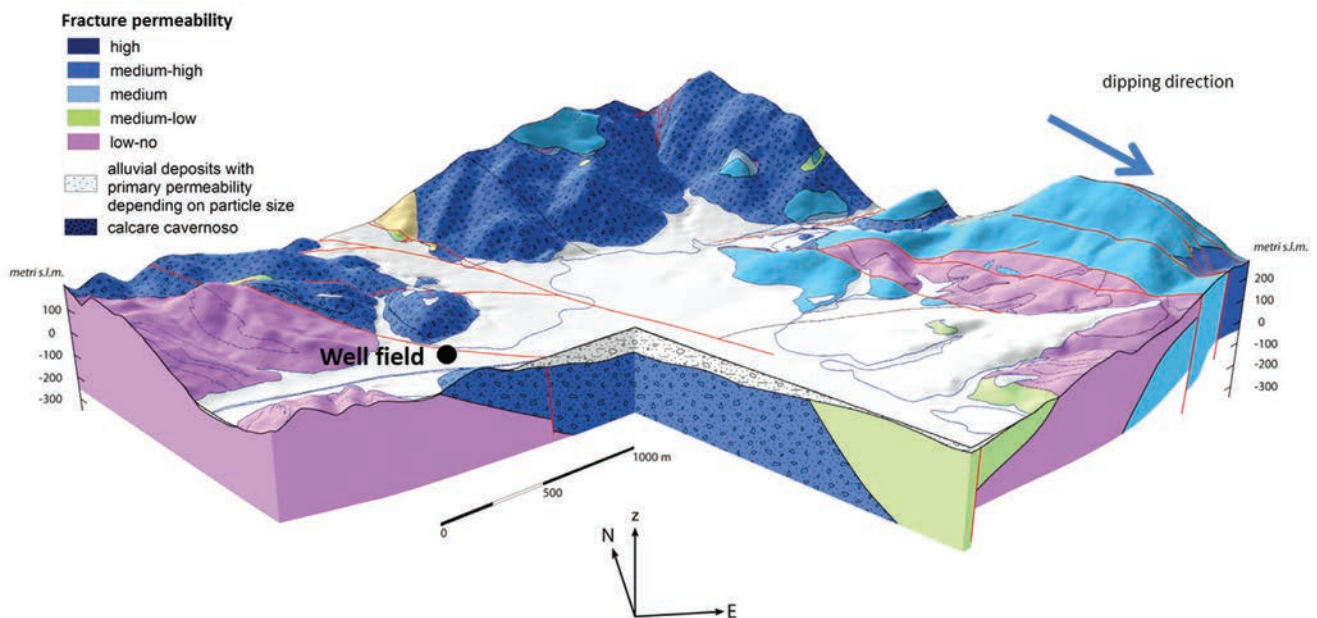


Fig. 2 - 3D reconstruction of hydrostructure.

Fig. 2 - Ricostruzione in 3D delle idrostrutture.

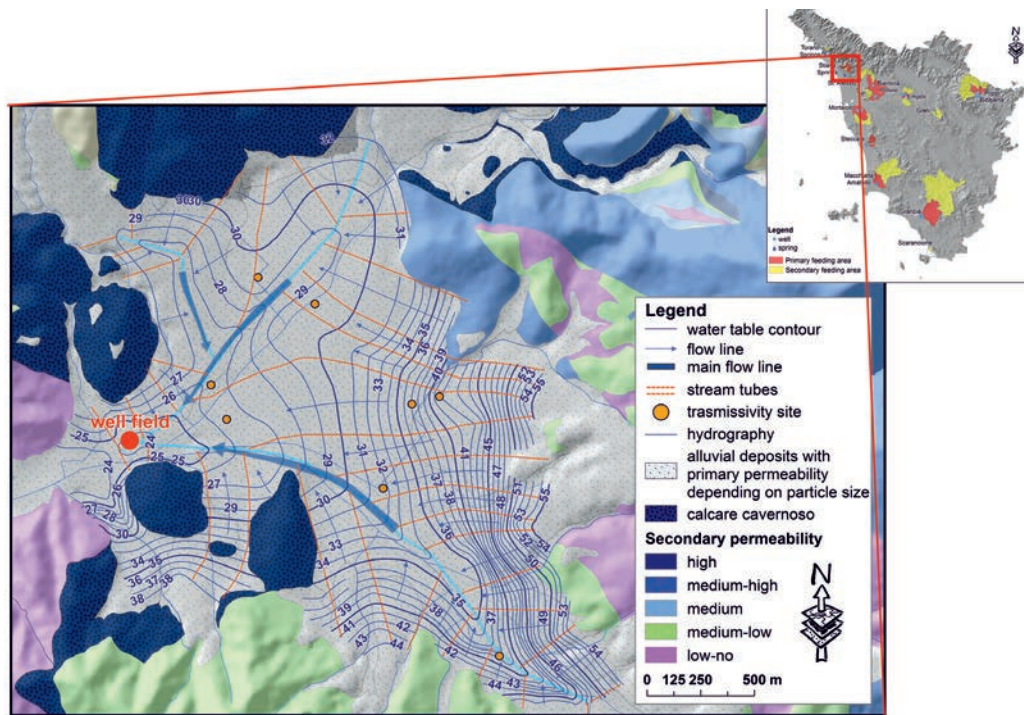


Fig. 3 - Hydrogeological map and water table contours (m a.s.l. – June 2012). Water level data were collected after a period without significant rainfall.

Fig. 3 - Mappa idrogeologica e piezometrica (m s.l.m.- Giugno 2012). I livelli piezometrici sono stati misurati dopo un periodo non influenzato da precipitazioni.

a first approximation, the flux for the main flow lines. Several very important assumptions are implied by adopting this approach (e.g. two dimensional horizontal flow, negligible rainfall infiltration). Nevertheless, by using stream tubes reliable information about the values of flow rate can be achieved (Hunt & Wilson, 1974; Bouwer, 1978), especially if such values are considered for evaluating the relative contribution of different sectors involved in the groundwater flow occurrence. In the presented case the calculated values showed that 85% of groundwater flux in the abstraction zone comes from the central and northern part of the plain.

In the case of springs draining fractured aquifers, when discharge value and meteorological data were available, the study of hydrographs and recession curves was performed to obtain information about the hydrodynamic behavior of the aquifers and the storage capacity of catchment areas (Tallaksen, 1995).

Water geochemistry and isotope signature

The hydrogeochemical data processing gives information about the main units involved in water-rock interaction and about the main chemical processes occurring in the aquifer, such as marine ingression, ionic exchange, and mixing among different components. Furthermore, by analyzing water isotopes it is possible to highlight the existence of different flow systems within the same groundwater body, even if the waters have the same chemical features. Isotopic data are also useful to achieve important information on groundwater flow, such as the average altitude of recharge areas and the hydrodynamic conditions within the aquifer (Doveri et al., 2013 and references therein).

During the project carried out for delineating PZs in the Tuscany region both chemical and water isotope analyses were performed, obtaining helpful indications in terms of groundwater flowpaths. Figure 4 gives an example of a SiO_2 vs SO_4 scatterplot that is significant for discriminating three different components involved in a piedmont alluvial aquifer: a “Sandstone Component”, with water characterized by major

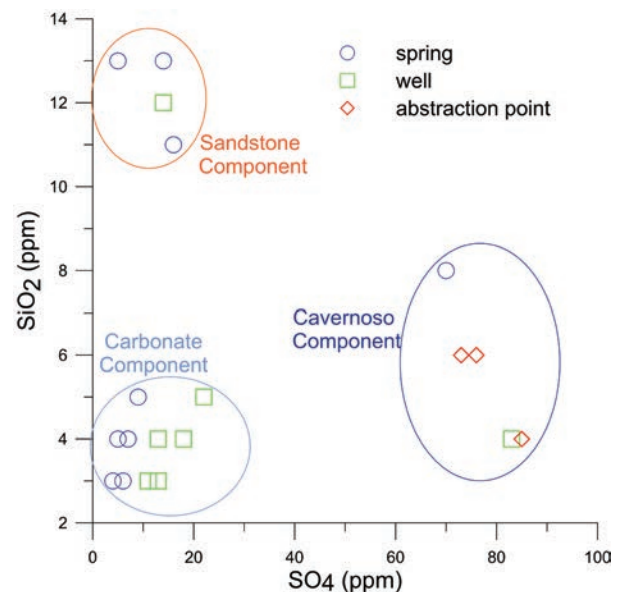


Fig. 4 - Binary diagrams of geochemical data (SO_4 vs SiO_2).

Fig. 4 - Diagramma di correlazione di dati geochimici (SO_4 vs SiO_2).

value of SiO₂ and minor value of SO₄; a “Cavernoso Component”, with high concentration of SO₄; and a “Carbonate component” with low value for both SiO₂ and SO₄.

In order to define the average altitude of the hydrogeological basins, several relationships between δ¹⁸O ‰ (or δ²H ‰) and altitudes of water infiltration were defined in different catchments. These relationships were obtained collecting some samples in small springs (low flow rate) with recharge area of limited extension (Doveri and Mussi, 2014; Doveri et al., 2013). Figure 5 shows an example of this kind of relationship and its application for evaluating the recharge average altitude of the hydrogeological domain for some drinking water abstraction points.

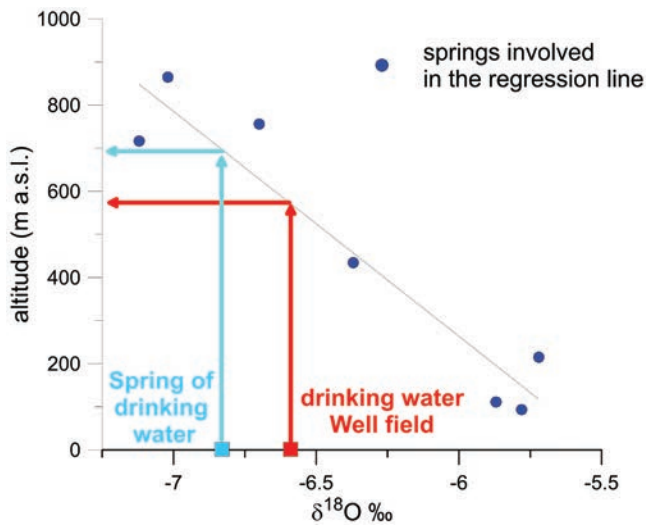


Fig. 5 - Relationship between altitude and δ¹⁸O‰ used to provide average recharge elevation of abstraction points.

Fig. 5 - Relazione fra quota e δ¹⁸O‰ utilizzato per determinare la quota media della zona di ricarica delle captazioni idropotabili.

Conceptual model and hydrogeological-geochemical budget

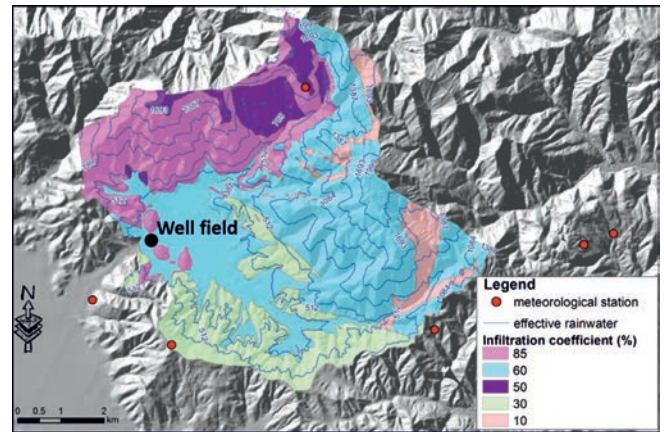
By combining geological, hydrogeological, geochemical, and isotopic data, the conceptual hydrogeological model was developed for each aquifer under examination. The comparison among hydrostratigraphy, hydrodynamic data, isotope and geochemical data allowed the identification of the areas that feed the abstraction points. In particular, the elaboration of geochemical and isotope data provides information about the lithology involved in water-rock interaction and the average altitude of infiltration. These data, taking also into account the hydrostratigraphy and the hydrogeological data processing, facilitated the identification of the main areas that feed the abstraction points. Within such areas it was moreover possible to rank the relative importance of sub-sectors in terms of their contributions to the well.

In general, the defined PZ were additionally validated by means of hydrogeological and isotopic budgets. In particular,

for each zone of the groundwater basin in which a type of hydrogeological unit outcrops, the infiltration rate was estimated. Infiltration rates were calculated starting from meteorological data (<http://www.sir.toscana.it/>), evaluating the evapotranspiration and applying ratio coefficients between infiltration and runoff available in the literature (e.g. Piccini et al., 1999). The water budget was calculated adding infiltration and runoff rates, coming from different zones of the catchment area where various units outcrop, thus obtaining the total dynamic resources (Fig. 6). This value was compared to the flowrate in the abstraction zone (table in Fig. 6). The isotopic budget was calculated from the weighted means of δ¹⁸O‰ signatures concerning the zones covered by different hydrogeological units. Firstly the δ¹⁸O‰ value for each hydrogeological unit was obtained by comparing the average altitude with the relationship “altitude/δ¹⁸O‰”; such values were then weighted by using the infiltration rates. An example of an isotopic budget with comparison between calculated and measured values is reported in the table of figure 6. If the calculated values of the dynamic water resource or isotope signature weren't in agreement with the measured ones, the conceptual model was adjusted.

This procedure also allowed dividing the PZs into subzones that differently participate to feed the abstraction points. Criteria for subdivision consist of: i) firstly on the amount of the contribution; ii) and secondarily on the distance from the abstraction points. Finally, for each PZ a primary and a secondary area were defined.

The areas that feed the abstraction points, even if validated by means of water and isotopic budgets, were delineated by means of conceptual models, which are affected by uncertainty due to many different factors. Infiltration rate, evapotranspiration and a scarcity of flowrate measurements are major sources of uncertainty.



		Total feeding area			
Area (Km ²)	42	Flowrate (l/s)		δ ¹⁸ O‰	
P-E (mm)	6008	measured	evaluated	measured	evaluated
Dynamic hydric resources (l/s)	865	970	865	-6.48	-6.41

Fig. 6 - Water and mass balance.

Fig. 6 - Bilancio idrogeologico e di massa.

Delineation of Protection Zones

The methodology discussed above was used to delineate the PZ for 15 abstraction groups of drinking water throughout the Tuscany Region (Fig. 7). The contexts in which the study was carried out encompasses porous, fractured, karst and mixed aquifers.

The PZs were divided into two subzones, generally corresponding to the primary and secondary feeding area in term of quantity. In some cases, the land use and the human activities affected the criteria of subdivision, as well as the presence of particular processes in the aquifer, such as seawater intrusion phenomena.

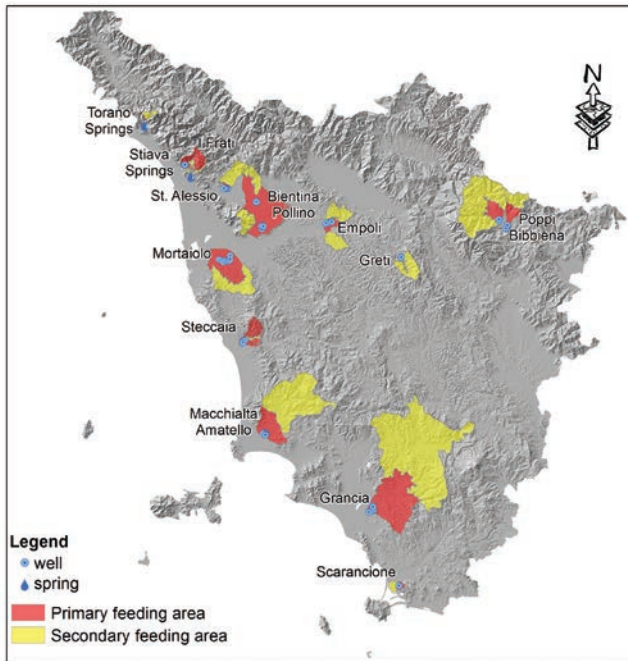


Fig. 7 - Delineated Protection Zones in Tuscany Region.

Fig. 7 - Delimitazione delle Zone di Protezione in Regione Toscana.

Conclusions

The approach described in this paper represents a practical proposal for delineating the PZs of drinking water abstraction points, in accordance with Italian law (D.Lgs. 152/2006; 12 December 2002 agreement). As regards the PZs, the law states that they have to be identified within the groundwater recharge areas, using a generic "hydrogeological approach". The method proposed uses an integrated approach involving geological, hydrogeological, geochemical, and isotopic surveys, allowing a comparison among all types of data in order to define a robust conceptual model of the hydrogeological system under examination.

The conceptual model, indeed, represents the fundamental basis not only for delineating recharge areas of abstraction points, but also for ranking the relative importance of different contributing areas. In this way it is possible to prioritize different objectives involved in drinking water protection, also taking into account possible contamination sources.

While PZs serve the purpose of protecting water resources by means of restrictions imposed on land use activities within these areas, but it is important to keep in mind that the delineations are subject to uncertainty due to many different factors (Sousa et al., 2013; Oreskes et al., 1994).

This paper summarized the final result for the 15 groups of drinking water sources studied in the Tuscany Region and for which PZs were delineated also discriminating sub-zones that require a priority protection, as compared to sub-zones for which a lighter degree of protection can be allowed. This information is fundamental for reaching the correct equilibrium between human activities and the safeguarding of water resources.

REFERENCES

- Baoxiang Z, Fanhai M (2011). Delineation methods and application of groundwater source protection zone. *Water Resource and Environmental Protection (ISWREP)*, 2011 International Symposium on Volume: 1 DOI: 10.1109/ISWREP.2011.5892945 (IEEE Conference Publications): 66 - 69.
- Beretta G.P., Farina M., Zavatti A. (2002). Aree di salvaguardia delle captazioni idriche: linee guida "Safeguard zones of water abstraction points: guidelines". I manuali di Arpa ed. Tipografia Moderna, 52 pp.
- Bouwer H. (1978). *Groundwater hydrology*. McGraw-Hill, New York, NY, 480 pp.
- Celico P. (1986). *Prospezioni idrogeologiche "Hydrogeological surveys"*. Liguori Editore, Napoli, vol. 1, 735 pp.
- Civita M. (2008). An improved method for delineating sources protection zones for karst springs based on analysis of recession curve data. *Hydrogeology Journal*, 16: 855-869.
- Derouane J., Dassargues A. (1998). Delineation of groundwater protection zones based on tracer tests and transport modeling in alluvial sediments. *Env. Geol.* 36 (1-2): 27-36.
- Doveri M., Menichini M., Cerrina Feroni A. (2013). Stable water isotopes as fundamental tool in karst aquifer studies: some results from isotopic application in the Apuan Alps carbonatic complexes (NW Tuscany). *Italian Journal of Engineering Geology and Environment*, 1: 25-42.
- Doveri M., Mussi M. (2014). Water isotopes as environmental tracers for conceptual understanding of groundwater flow: An application for fractured aquifer systems in the "Scansano-Magliano in Toscana" area (Southern Tuscany, Italy). *Water*, 6: 2255 - 2277.
- DVGW (1995). *Guidelines on drinking water protection areas - Part 1: Groundwater protection areas. Code of practice W 101*, 23pp. [in German]
- Elewa H. H., Shohaib R. E., Qaddah A. A., Nouisir A. M. (2012). Determining groundwater protection zones for the Quaternary aquifer of northeastern Nile Delta using GIS-based vulnerability mapping. *Environ. Earth Sci.* 68: 313-331.
- EPA (1987). *Guidelines for delineation of wellhead protection areas*. Office of Groundwater Protection, EPA-Washington, Reprinted in 1993 as EPA 440/5-93-001: 212 pp.
- Frind, E.O., Muhammad, D.S., Molson J.W. (2002). Delineation of three-dimensional capture zones in complex multi-aquifer systems. *Ground Water*, 40(6): 586-589.

- Hao Y., Yeh T., Hu C., Wang Y., Li X (2006). Karst groundwater management by defining protection zones based on regional geological structures and groundwater flow fields. *Environmental Geology* 50: 415-422.
- Hunt B. W. and Wilson D.D. (1974). Graphical calculation of aquifer transmissivities in northern Canterbury, New Zealand. *J. Hydrol.* 13(2): 66-80.
- Hiscock K M (2011). Groundwater in the 21st Century – Meeting the Challenges. In: *Sustaining Groundwater Resources: A Critical Element in the Global Water Crisis*, J. Anthony A. Jones (eds) in *International Year of Planet Earth* (2011), 207-225.
- Kamenskij G. N. (1943). *Elements de dynamique des eaux souterraines* "Elements of groundwater dynamic". O.N.T.I., Gosgeolizdat, Moscou (in French).
- Meyer P A, Brouwers M, Martin P J (2014). A three-dimensional groundwater flow model of the Waterloo Moraine for water resource management. *Canadian Water Resources Journal* 39 (2): 167-180.
- Oreskes N., Shrader-Fechette K., Belitz K. (1994). Verification, validation, and confirmation of numerical models in the earth sciences. *Science, New Series* 263 (5147): 641-646.
- Piccini L, Pranzini G, Tedici L, Forti P (1999). Le risorse idriche degli acquiferi carbonatici del comprensorio apuo-versiliese "Water resources of the carbonate aquifer in the apuo-versilian region". *Quad. Geol. Appl.*, 6 (I): 61-78 (in Italian).
- Pochon A, Tripet JP, Kozel R, Meylan B, Sinreich M, Zwahlen F (2008). Groundwater protection in fractured media: a vulnerability-based approach for delineating protection zones in Switzerland. *Hydr. J.* 16: 1267-1281.
- Sousa M.R., Frind E.O. Rudolph D.L. (2013). An integrated approach for addressing uncertainty in the delineation of groundwater management areas. *Journal of Contaminant Hydrology*, 148: 12-24.
- Tallaksen L M (1995). A review of baseflow recession analysis. *Journal of Hydrology* 165: 349-370.
- US Geological Survey (1998). Estimating areas contributing recharge to wells. *US Geological Survey Circular* 1174, 14pp.
- Zhu Y and Balke KD (2008). Groundwater protection: What can we learn from Germany?. *Journal of Zhejiang University SCIENCE B* 9(3): 227-231.