Protection of Groundwater Resources: Worldwide Regulations and Scientific Approaches

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Abstract The increasing role of groundwater in municipal water networks in many countries of the world makes the protection of groundwater resources an essential practice for safeguarding drinking water supplies. Several scientific-technical approaches are adopted worldwide to face this issue. In addition, some countries mainly depend on groundwater also for non-domestic use, making this topic even more critical. This chapter provides an overview of the main directives and their related technical aspects, concerning the protection zones of groundwater sources for human consumption. The main results of a multidisciplinary study are also presented, highlighting how the knowledge of physical and chemical aspects of groundwater bodies is a fundamental tool for protecting this vital resource and assuring its availability for the future generations.

Keywords Groundwater protection directives, Multidisciplinary approach, Protection areas

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Contents

1 Introduction

Most of the available freshwater on Earth is stored in the underground [1]; consequently groundwater represents the main resource in terms of available quantities for water supply. Worldwide, more than two billion people depend on groundwater for their daily water use [2].

In many areas of the world, groundwater bodies represent the most important and safest source of drinking water [3, 4]. In the European countries, for example, the groundwater exploitation provides water for human consumption for 70% of the population on average [5].

According to the World Business Council for Sustainable Development, groundwater withdrawals supply 40% of industrial water [6] and groundwater use for irrigation is also significant and increasing. Siebert et al. [7] estimated that, globally, 38% of the areas with irrigation infrastructures are irrigated by groundwater.

Moreover, the exploitation of groundwater bodies will likely increase in order to face the climate change and the significant increasing of the global water demand, which has been predicted as a consequence of the economic expansion, population growth, and urbanization [8].

The general human pressure on groundwater becomes stronger if we consider those areas in which urban, industrial, and agricultural settlements are particularly developed, such as the alluvial and coastal plains. Globally, more than 150 million of people live below the altitude of 1 m a.s.l. and 250 million live below the altitude of 5 m a.s.l. [9]. Also, the touristic attitude that often characterizes the coastal areas causes a significant seasonal increase of the population. As a consequence, these areas are frequently interested by the deterioration of the environmental system and in particular of their water resources. Pollution phenomena as well as the overexploitation of groundwater cause a progressive qualitative and quantitative worsening of the stored water. One of the most recurring effects is the variation of the natural equilibrium between fresh and sea waters, with consequent advancing of the seawater intrusion in the coastal aquifers [10].

In this framework, the protection of groundwater is a must. Looking ahead, optimal management and preservation of this vital resource are required in order to assure its availability for the future generations. Taking into account the existent water directives, a correct and strategic planning of the groundwater management should be based on specific studies aimed at characterizing the groundwater bodies in terms of quality and quantity, defining the thresholds values of pollutants in water, and delimiting the protection areas for drinkable water sources. These issues are often faced once a specific critical situation occurs and consequently for aquifer systems already intensely exploited and sometimes polluted, e.g., plain and coastal aquifers. Nevertheless, since groundwater is difficult and expensive to restore once polluted and/or overexploited, such kinds of studies and preventive actions are strongly recommended also on aquifers moderately exploited hitherto (e.g., fractured and karst aquifers), in order to protect their strategic groundwater resources.

In this chapter we focus on the issue of the protection areas of groundwater resources for human consumption, firstly performing an overview on the scientific-technical approaches and the directive tools adopted by different countries worldwide and then introducing the main results achieved in recent studies.

2 Protection Areas of Groundwater Sources for Human Consumption

2.1 Directives and Technical Aspects

In the most developed countries, specific directives have been elaborated and adopted in order to drive actions aimed at protecting water bodies exploited for drinking water supply. Pioneering actions on this matter were performed by the USA and Germany, whose guidelines [11–13] are fundamental references to face the protection of groundwater abstractions. Even though different approaches are adopted by each country, as a general outline we observe a delineation of zones surrounding the sources of drinking water, in which several activities are prohibited or restricted.

Some countries are in an initial stage in terms of protection areas of groundwater sources or they have not yet started these practices because more stringent problems, such as the scarcity of water resources, take the priority.

The next sections provide a brief overview of the approaches that have been introduced worldwide, described on a regional basis.

2.1.1 Europe

With the Directive 2000/60/EC, the European Parliament and the Council [14] established a framework for a community action in the field of water policy, in which water protection is a primary objective. According to this directive, protected areas have to be defined for water bodies having particular interest (Annex IV of the Directive), including those exploited for drinking water supply (Drinking Water

Protected Areas – DWPAs). For the latter, member states shall ensure the necessary protection and may provide to establish safeguard zones (SGZs). Guidance documents were also produced [15] in order to clarify the relationship between DWPAs and SGZs.

Member states have approached this issue by domestic legislation, in which, although with some technical differences, three main zones are mentioned [5, 16], in order to define the SGZs (or source protection zones – SPZs):

Z1 An inner zone, which is the area immediately surrounding the abstraction point and is geometrically defined by a specific distance from the exploitation point
Z2 An intermediate zone, which corresponds to the area surrounding the previous one and is generally delineated on the base of a reference travel time
Z3 An outer zone, which is the area around a source, within which all groundwater recharge is presumed to be discharged by such source (catchment zone)

In some cases a subdivision of these main zones can be provided. In Germany, the Z3 can be optionally subdivided into two zones if its longitudinal extent exceeds 2 km [3], whereas in Belgium [17] and Italy (D. Lgs. 152/2006; Italian State-Regions agreement signed on 12th of December 2002), the Z2 can be further subdivided into two zones, whose boundaries are representative of different travel times. On the other hand, in some countries, e.g., France and the United Kingdom [16], a fourth zone can also be added in agreement with specific hydrogeological features or vulnerability conditions. Figure 1 shows a general scheme of the SGZs subdivision.

2.1.2 USA

The federal law "Safe Drinking Water Act" (SDWA) requires many actions in order to protect drinking water and its sources. Accordingly, each state shall provide to determine the Wellhead Protection Areas (WHPAs), which is defined as "the surface and subsurface area surrounding a water well or a field of water wells, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or well-field." After the Amendments of 1986 to the SDWA, the US Environmental Protection Agency faced hydrogeological aspects of groundwater protection, providing a "Guideline for Delineation of Wellhead Protection Areas (WHPAs)" [11]. Hypothetical situations in different hydrogeological settings are described, as well as a basis for several delineation methods, highlighting subzones (Fig. 2) of WHPA named ZOI (area overlying the cone of depression), ZOC (the whole catchment), and ZOT (zone of transport for specific travel times). Criteria on which WPHA delineation may be based include distance, drawdown, travel time, flow system boundaries, and the capacity of the aquifer to assimilate contaminants. Such document describes criteria and methods that can be adopted for WHPAs delineation; however states

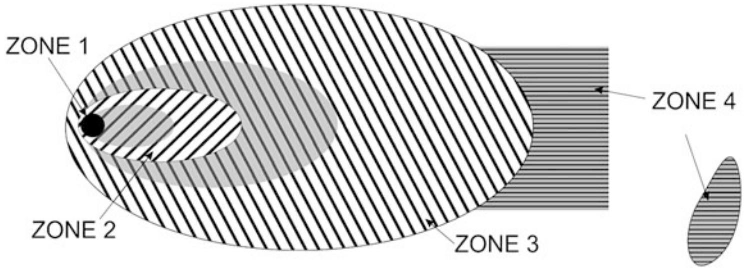

Fig. 1 General scheme of SGZs subdivision in European countries. In *gray*, optional subzones (see text)

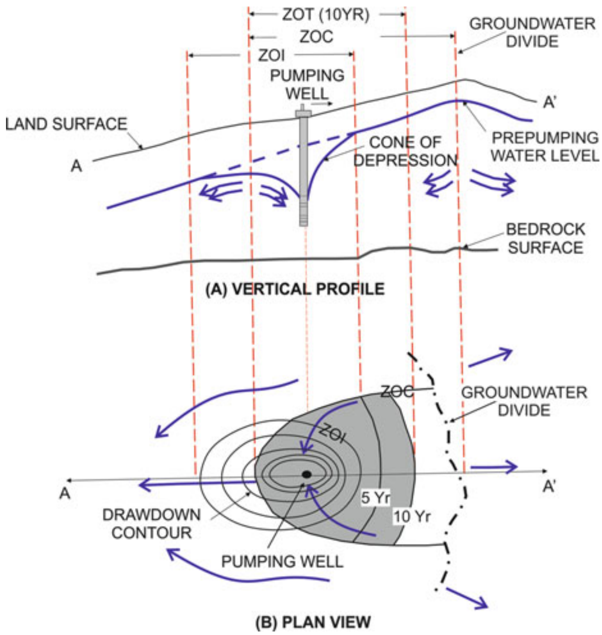

Fig. 2 Example of subzones of the WHPA according US EPA (after [11])

have flexibility in developing their WHPA programs as a function of their specific hydrogeological and environmental contexts.

2.1.3 Australia

The Australian National Water Quality Management Strategy is a joint national approach for improving water quality in Australia and New Zealand. In this framework national documents specifically covering groundwater protection have been produced, such as the ones by the Agriculture and Resources Management

Council of Australia and New Zealand [18, 19], in which wellhead protection plans are considered as one of the main tools for the protection of groundwater resources. Before the release of these documents, a small number of protection plans had been developed. One of these examples is described by ARMCANZ [18], in which a simplified approach based on concentric protection zones around the wellhead defines three zones with different prohibitions or restrictions in terms of land use and human activities. The nearest zone (Zone I) consists of a circular shape of radius 50 m and encompasses the water authority compound around the wellhead, including adjacent private areas where necessary. The second zone (Zone II) is arbitrarily delineated basing on a travel time of 10 years, and the third zone (Zone III) corresponds with the catchment area where greater than 10 years residence time is available.

More recently, explicit planning has been developed, by providing actions of protection within specific catchments, termed Public Drinking Water Source Areas (PDWSAs). The policy for the protection of PDWSAs includes three priority classification areas (P1, P2, P3) based on the management of risk and two types of protection zones distinguished in wellhead protection zones (WHPZs) and reservoir protection zones (RPZs) [20]. P1 and P2 areas are managed to ensure that there are no risk and no increased risk of water source pollution, respectively. Most land uses produce some risk to the quality of water and are therefore defined as “incompatible” in P1 areas, whereas some activity is allowed within P2 areas for land uses that are defined as either “compatible with conditions” or “acceptable.” P3 areas are defined to manage the risk of pollution to the water source from catchment activities and are declared over areas where water supply sources coexist with other land uses such as residential, commercial, and light industrial development. WHPZs encompass the drinking water sources and are generally circular with a radius of 500 m or 300 m, for sources that are in P1 or P2 areas. RPZs consist of a statutory 2 km wide buffer area around the top water level of storage reservoirs.

2.1.4 China

China is the world’s most populous country, with a consequent high request of water for human consumption. On the other hand, the distribution of water resources in China is highly diverse, thus negatively affecting social and economic growth in some regions [21]. Estimations by the Ministry of Water Resources [22] highlighted as in 2005 about 300 million people in China were unable to access safe drinking water, both in terms of quality and quantity. In spite of that, and although the law tools invite to establish a protection system for zones of drinking water sources [23–25], delineation of protection zones for groundwater sources is still at the initial stage [4], and in the locations where it has been performed, there is a lack of practical protective measures [26].

According to legislation [27], drinking water source reserves are classified into Grade I and Grade II. It is moreover possible to delimit a certain area at the periphery of a drinking water source reserve as a quasi-reserve. In the Grade-I

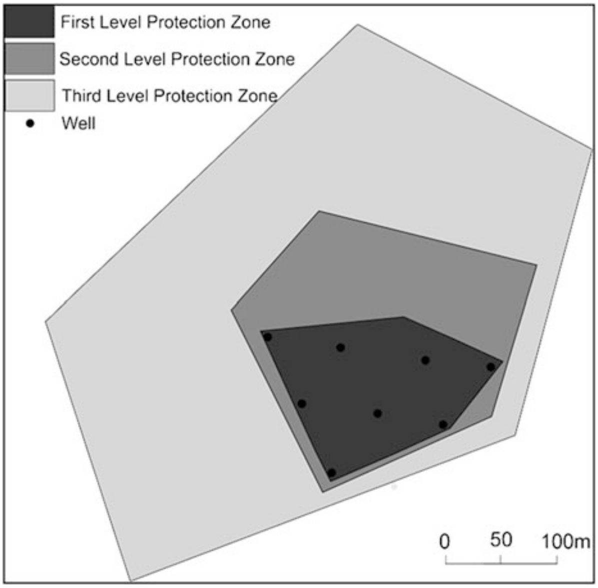

Fig. 3 Polygonal partitioning of protection zones for the well field in Dawukou District of Shizuishan City, China (after Wenjuan et al. [28]).

zone, any buildings or activities are not permitted, excluding those linked to water supply facilities and their management and protection. Within the Grade-II and quasi-reserve zones, it is prohibited to build, renovate, or enlarge any construction project discharging pollutants and seriously polluting waters. No technical criteria are given by the regulation. In fact, different case studies dealing with groundwater sources for human consumption in China report different ways to define the boundaries of the three zones. For the Grade-I and Grade-II zones, a benchmark travel time is generally taken into account. Wenjuan et al. [28] and Baoxiang and Fanhai [4] refer to 100 days and 60 days for the Grade-I protection and to 1,000 days and 10 years for the Grade-II protection, respectively. The quasi-reserve zone is chiefly referred to the whole catchment; nevertheless a residence time of groundwater is sometimes considered (e.g., 25 years in Baoxiang and Fanhai [4]). The shapes of the protection zones can be circular, elliptical, irregular, and even polygonal (Fig. 3) as a function of delineation methodologies (e.g., analytical rather than empirical) and of the source arrangement (e.g., single source rather than multipoint sources).

2.1.5 Africa

Many African countries have problems both with water scarcity and with pollution. For what regards the MENA region (Middle-East North Africa), large territories are characterized by arid and semiarid conditions where groundwater constitutes the main source of water supply, thus making the protection of this resource indispensable [29]. In this context, there is some degree of cooperation between the involved countries and foreign states having a significant experience about the protection of groundwater resources, on the basis of cooperation agreements.

In Sub-Saharan Africa, US EPA promotes the development and implementation of Water Safety Plans (WSPs) to improve the capacity of urban providers to deliver safe drinking water in a sustainable way [30]. WSPs consist in a "catchment to consumer" approach, which uses a health-based risk assessment methodology for identifying the greatest vulnerabilities to contamination within a drinking water supply system.

In North Africa, projects have been developed by means of the cooperation among Arab countries and Germany [31, 32], facing the issue of the management, protection, and sustainable use of groundwater. A proposal of guideline for the delineation of groundwater protection zones was also produced [32], in which a typical scheme with three zones of protection (reflecting different levels of risk) surrounding the abstraction point is presented. Different criteria for the delimitation of zones are suggested as a function of two main aquifer system types, based on a near homogeneous (e.g., unconsolidated aquifer) or heterogeneous (e.g., karst aquifer) distribution of groundwater flow velocities, respectively. The travel time is the most prominent factor for the delineation of groundwater protection zones for the first category of aquifers, whereas an approach based on the vulnerability is preferred for the second category of aquifers.

2.2 *Scientific-Technical Approaches*

As previously described, the protection of drinking water sources is generally approached by means of the delineation of zones surrounding the abstraction points (hereafter safeguard zones, SGZs) and by defining prohibitions and restrictions within such areas in term of land use and activities. Within a SGZ three or more subzones are generally distinguished as a consequence of the different degree of protection that is needed. Several methods for delineating such zones have been developed worldwide and are described in guideline documents or proposed in scientific papers. In general, the choice of the methodology is linked with the availability and the kind of hydrogeological data available, in addition to the aquifer typology. In the following subsections, the main approaches that are used worldwide are listed and briefly described.

2.2.1 Geometric Methods

These methods consist in drawing a shape (Fig. 4), which is either determined by purely geometric criteria or by considering both geometric aspects and hydrodynamic features. The geometric approach is generally used where other and more sophisticated methods cannot be applied. The simplest method consists in drawing a circle of an arbitrary fixed radius around each abstraction (Fig. 4a). The radius can

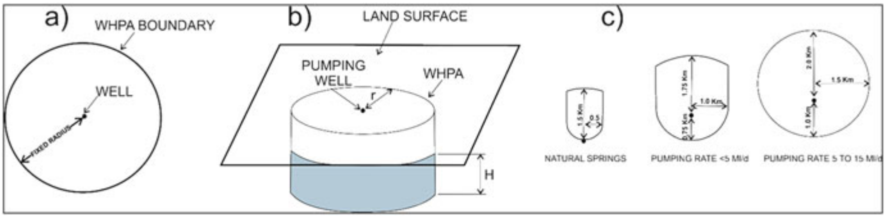

Fig. 4 Geometric methods for delineating SGZs. (**a**) Arbitrary fixed radius. (**b**) Calculated radius: the radius (r) determines a volume of water that is pumped from the well in a specified time period. (**c**) Simplified variable shapes: various standardized forms are generated by analytical equations and provided to calculate the upgradient extent on the base of times of travel (after US [11])

also be defined by taking into account the average distance corresponding to a given time of travel, averaged as a function of the different hydrogeological contexts insisting in the studied region. A similar method provides circular or semicircular protection areas using radii that are calculated by using volumetric equations. These latter consider hydrogeological parameters (e.g., porosity) and the volume of water drawn in a specified time interval from the well (Fig. 4b; Eqs. 1 and 2).

$$r = \sqrt{\frac{Q\,t}{\pi\,n\,H}}, \tag{1}$$

$$r = \sqrt{\frac{2\,Q\,t}{\pi\,n\,H}}\ , \tag{2}$$

where Q is the pumping rate (m^3/s), n is the aquifer porosity, H is the length of well screen (m), and t is the travel time (s).

Equation (2) refers to the half-circle method, which takes into account the flow direction by replacing the circular shape used for the simplest SGZ with a half circle having the same area. Such new asymmetrical shape is oriented to the upgradient direction [33], to encompass the effect of the flow. The travel time used as a reference is chosen in order to allow the occurrence of processes that adequately decrease the concentration of contaminants before they reach the well (i.e., dilution, dispersion, cleanup).

Another approach is the generation of various standardized and representative shapes (Fig. 4c) by using analytical equations (Sect. 2.2.2). Standardized shapes are calculated for different sets of hydrogeological conditions (essentially different values of T and hydraulic gradient) and well-pumping rates; then the more appropriate shape is applied to the wellhead zone and oriented according to the flow patterns. The down-gradient and lateral limits of the standardized shapes are defined by the uniform flow equation (Fig. 5) [34, 35], whereas the upgradient extent is estimated by considering a specific time of travel. By applying different times of travel, it is possible to identify several subzones forming the entire SGZ.

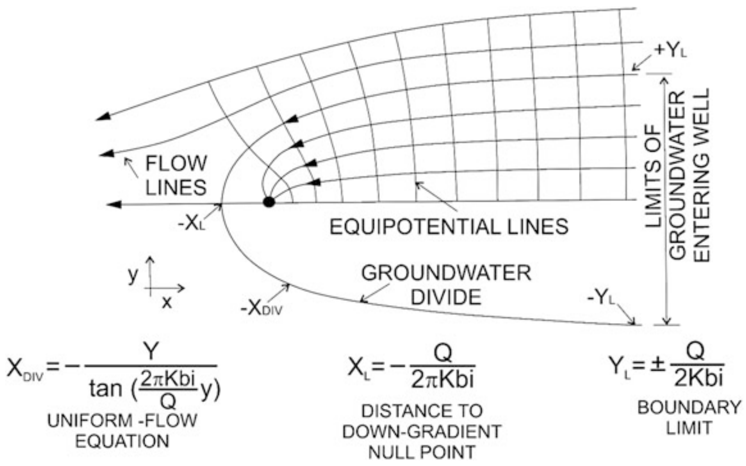

Fig. 5 SGZs delineation using the analytical method for a confined aquifer. *Q* well pumping rate, *K* hydraulic conductivity, *b* saturated thickness, *i* hydraulic gradient, π: 3.1416 (modified, after [34])

2.2.2 Analytical Methods

According to this class of methods, the delineation of SGZs is based on a set of equations, which assume two-dimensional horizontal flow and are applied to each abstraction or group of abstractions, accordingly to site-specific hydrogeological parameters. The latter can include hydraulic gradient, hydraulic conductivity, transmissivity, porosity, and saturated thickness of the aquifer. The assumption of uniform flow (and its relating equations) is often used for the definition of the downgradient and of the lateral limits (Fig. 5). The extent of the upgradient can then be evaluated basing either on specific travel times or on hydrogeological boundaries.

Analytical approaches were used by several authors for the definition of the capture zones of wells, considering both aquifers of infinite extent (e.g., [36]) and in the presence of boundaries (e.g., [37, 38]).

It must finally be noted that there are literature examples and relating software showing how this type of delineation can be automated by using analytical element models running on a computer, e.g., WhAEM and GFLOW [33].

2.2.3 Hydrogeological Mapping

This methodology provides the delineation of the protection areas by summarizing within hydrogeological maps the information derived from geological, geophysical, hydrogeological, and hydro-geochemical surveys. Starting from geological observations, changes of lithology corresponding to contrasts of permeability can be individuated and correlated with the boundaries of the protection areas. Surface geophysical data coupled with the geological interpretation may provide the spatial arrangement of buried structures, thus indicating possible groundwater divides linked to structural conditions. Hydrogeological mapping may also encompass groundwater-level contour lines, which can contribute to the identification of groundwater divides. Moreover, results of dye tracing tests can be included, as a tool to verify the recharge area and the flow systems. Also the vulnerability-based methodology (e.g., [39–41]) can be classified as a hydrogeological mapping approach, given the overlapped and integrated elaboration among several thematic layers (e.g., topography, permeability, fractures' density, etc.).

2.2.4 Numerical Models

Flow and transport numerical modeling represents a good practice for SGZs accomplishment (e.g., [17, 42–45]), as it's also discussed in the chapter by El Mansouri et al. inside this book. A wide variety of software (calculation modules, user interfaces, and complete suites for flow and transport models) are available to perform numerical modeling (e.g., Groundwater Vistas, Visual Modflow, GMS, Feflow, etc.). The input data consist of hydrodynamic and hydrodispersive parameters, aquifer geometries, recharge rates, and the location of some boundaries in which flow conditions and solute concentrations have to be defined. This approach is particularly useful for delineating SGZs where the hydrogeological framework is complex. Nevertheless, a large amount of data is required in order to develop a proper numerical model.

One critical aspect is that the predictions generated by these models are often considered as the portrait of exact scenarios by public policy decision-makers. Hence, and because "more than one model construction can produce the same output" [46], it is not sufficient to calibrate the models by using experimental data, but it is also mandatory to perform a background work, which consists in building a reliable conceptual framework that takes into account the modeling hypothesis and their associated uncertainties.

2.3 Case of Study: A Hydrogeological Approach Tested on Groundwater Sources of Tuscany (Italy)

This section refers to a particular case study, in which the hydrogeological approach was used.

According to the Italian law (D.Lgs. 152/2006; Italian State-Regions agreement signed on 12 of December 2002), the three subzones of a SGZ are named *absolute safety zone*, *respect zone* and *protection zone*, respectively. The first zone is simply defined by geometric criteria (minimum radius 10 m); the second one is delimited on the base of a travel time (60, 180, or 365 days), when the available data and the hydrodynamic context are favorable, otherwise by means of the so-defined "hydrogeological approach," which should encompass geological, hydrogeological, and geochemical data. The assessment of the protection zone (the third subzone of the SGZ) always follows the hydrogeological approach.

Due to their major importance in terms of safeguard, the respect zones in Italy have been delimited for several abstractions according to the said guidelines. Instead, for the delineation of protection zones (PZs), there are no official documents nor a significant number of case studies.

In the framework of a project funded by the administration of the Tuscany region, several studies were carried out in the areas surrounding several abstraction points of drinking water located in different parts of the regional territory. Fifteen PZs were delimited [47] by means of an integrated multidisciplinary approach thanks to cooperation between CNR-IGG, the Water Authorities (WAs), and the Integrated Urban Water Management Companies (IUWM-Cs). In the following of this section, the general approach adopted for delineating PZs is briefly discussed and some main results of its application are presented.

After a preliminary examination and elaboration of the existing/available data, a survey program was developed in collaboration with the WAs and the IUWM-Cs. The new surveys covered the following activities: (1) hydrogeological measurements (water head, flow rates) and hydraulic tests, (2) on-site measurements of chemical-physical parameters of the water and collection of water samples for the laboratory analyses of chemical and isotopic parameters, and (3) geological surveys and/or drilling of new boreholes to acquire new stratigraphic information.

A general scheme describing the integrated approach and the data used for its elaboration is reported in Fig. 6. The diagram shows how the geochemical, hydrodynamic, structural, and meteorological information converge into the process for the assessment of a protection zone.

The example discussed in this work regards a well field located next to the southern border of the Apuan Alps (NW Tuscany-Italy; Fig. 7). The well field is situated in the "Camaiore Basin" and it is made up by 32 wells; it drains about 300 L/s from an alluvial aquifer (gravel/pebbles, unconfined or semi-confined) whose substratum consists of permeable carbonate rocks, which widely outcrops on the nearby reliefs (Fig. 7).

Based on the scheme of Fig. 6, the study aimed at individuating the catchment basin for the well field and the main results achieved can be summarized as follows:

– The analysis of geological structures pointed out that in the area a general North-South groundwater flow is favored by a combination of bedding and/or foliation attitude and fold axis plunges. The main fault system leads to the partitioning of groundwater flow into different sub-basins. In addition, the study of the hydrostructures highlighted some possible hydrogeological divides and a presumable loss of groundwater from the "Camaiore Basin" toward the catchment at SE:
– A piezometric map was achieved for the alluvial aquifer that is exploited by the well field. The contours of the hydraulic head show a feeding from the carbonate complexes, which outcrop in the surrounding area. Three major streamlines exist

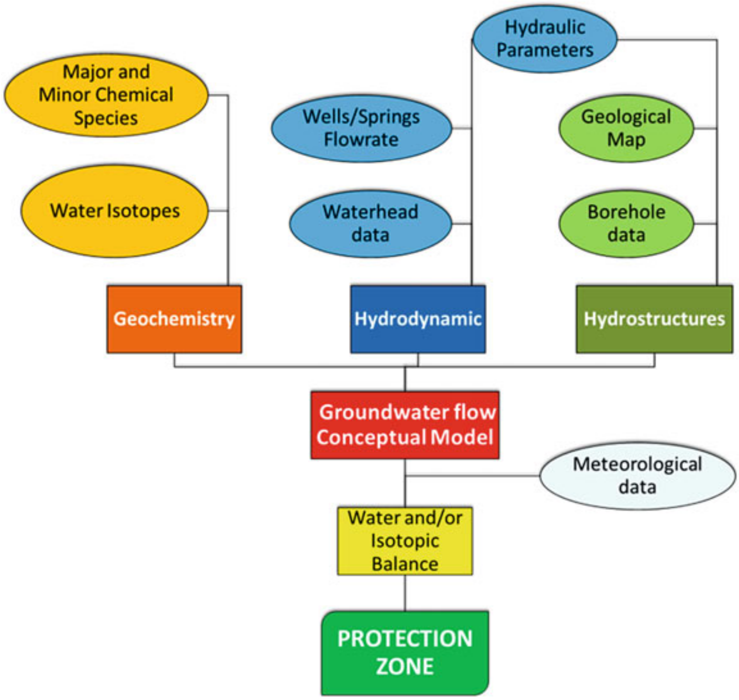

Fig. 6 Schematic diagram describing the integrated approach. Data provided as input are shown in *elliptical boxes*

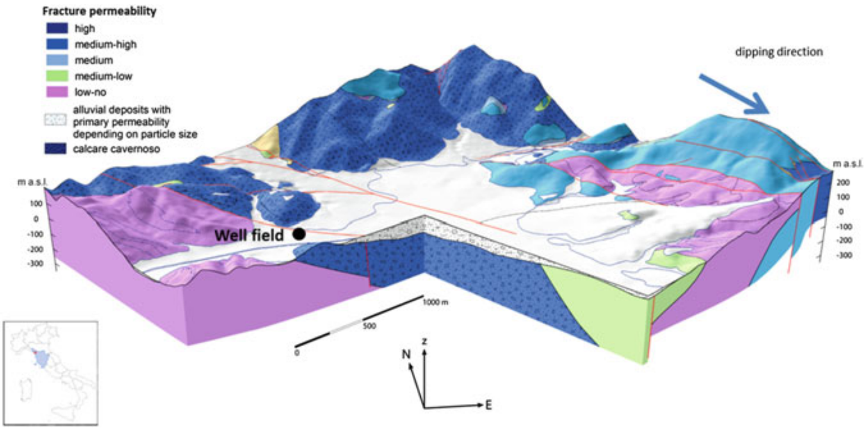

Fig. 7 3D representation of the hydrogeological structures (after [47]). The fractured hydrogeological units with permeability medium to high are made up by carbonate lithologies

and they converge toward the well field. After dividing the piezometric map into stream tubes, Darcy and Kamenskij equations were applied using the transmissivity values estimated by means of several pumping tests. In this way major and minor inputs at the system were identified:

– Chemical and water-isotope analyses have been performed twice, both for the abstractions under study and for a number of water points (about 15 springs, wells, and stream waters) in their surroundings. Among these, six springs were opportunely selected in order to assess the relationship "altitude/δ^{18}O‰," which is useful to achieve the average altitudes of the recharge of water abstractions [48, 49]. By combination of chemical and isotopic data, the presence of some inputs and of their mixing products was verified. Chemical features suggested what kind of lithology is involved in the water-rock interaction processes (e.g., Calcare Cavernoso for the SO_4 values or sandstone for the SiO_2 values), whereas isotopes indicated the average altitudes of infiltration for the different inputs. Taking into account these aspects and the mixing processes, it's been possible to achieve indications both on the areas involved in feeding the abstractions and on their importance in terms of quantity.

Based on all the above mentioned information, the catchment area was delineated for the well field. This polygon was additionally validated by means of the water and isotopic budget: for each zone in which the same hydrogeological complex outcrops, both infiltration rate (http://www.sir.toscana.it/, for meteorological data; [50] for the infiltration coefficients) and the average values of δ^{18}O‰ (comparing the average altitudes and the relationship "altitude/δ^{18}O‰") were estimated. Furthermore, these isotopic signatures were weighted by using the infiltration rates, thus obtaining the weighted mean of δ^{18}O‰ concerning the entire feeding area. The evaluated value (−6.41‰) resulted congruent with analyses' results for the water samples collected at the well field (−6.48‰).

After this validation, the final PZ was delimited, also allowing the distinction of two subzones, A and B, which, respectively, correspond to the chief zone and the secondary zone in terms of feeding (Fig. 8).

3 Conclusions

Groundwater bodies represent the safest source for satisfying water demand. Moreover, based on the expected scenarios of global climate change and degradation of surface water bodies, it is predictable that the claim for this resource will increase in the future. In this framework, the protection of groundwater is unavoidable, in order to guarantee safe water supplying for the next generations.

Hence, the appropriate knowledge of physical and chemical aspects of the aquifer systems becomes more and more a necessary prerequisite in order to face the several issues involved with the protection of groundwater, implying the necessity to develop robust conceptual hydrogeological models. Despite the

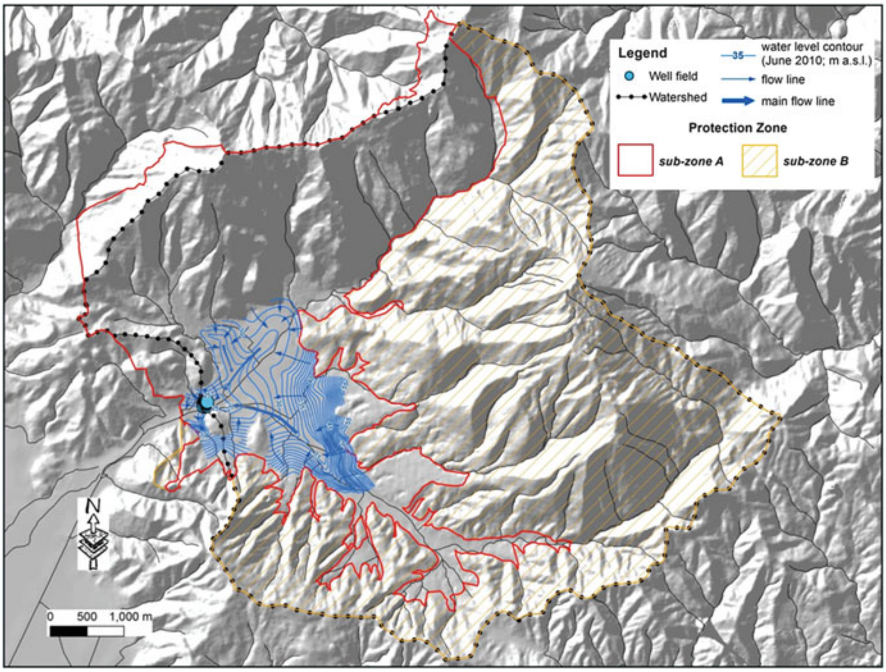

Fig. 8 Well-field protection zone. Water-level contour lines refer to the unconfined aquifer system that exists in the plain surrounding the well field and it is made up by alluvial sediments in the shallower part and mainly by carbonate rocks at depth. Subzone A is the main feeding area of the groundwater system exploited by the well field. Subzone B is the area from which a minor feeding occurs

relevant investment of resources necessary for the production and interpretation of multidisciplinary experimental data, a well-grounded conceptual framework should not be overcome with the direct use of specific and more straightforward tools (e.g., numerical modeling without sufficient experimental data, empirical methods based on few parameters and/or limited datasets, etc.). In particular, a comprehensive approach, following the guidelines and the examples discussed in this chapter, gives the perspective of an improved planning of the groundwater management, with a high chance of long-term benefits.

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