

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, protection areas, multidisciplinary approach

1. Introduction

Most of the available freshwater on Earth is stored in the underground (Shiklomanov, 1998), consequently groundwater represents the main resource in terms of available quantities for water supply. Worldwide, more than 2 billion people depend on groundwater for their daily water use (Hiscock, 2011).

In many areas of the world groundwater bodies represent the most important and safest source of drinking water (Zhu and Balke, 2008; Baoxiang and Fanhai, 2011). In the European countries, for example, the groundwater exploitation provides water for human consumption for 70% of the population on average (Martínez et al., 2008).

According to the World Business Council for Sustainable Development, groundwater withdrawals supply 40% of industrial water (WBCSD, 2006) and groundwater use for irrigation is also significant and increasing. Siebert et al., 2010 estimated that, globally, 38% of the areas with irrigation infrastructures are irrigated by groundwater.

35 Moreover, the exploitation of groundwater bodies will likely increase in order to face the cli-
36 mate change and the significant increasing of the global water demand, which has been predicted as
37 a consequence of the economic expansion, population growth, and urbanization (Rosegrant et al.,
38 2002).

39 The general human pressure on groundwater becomes stronger if we consider those areas in
40 which urban, industrial and agricultural settlements are particularly developed, as such the alluvial
41 and coastal plains. Globally, more than 150 million of people live below the altitude of 1 m a.s.l.
42 and 250 million live below the altitude of 5 m a.s.l. (UNESCO, 2007). Also, the touristic attitude
43 that often characterizes the coastal areas causes a significant seasonal increase of the population. As
44 a consequence, these areas are frequently interested by the deterioration of the environmental sys-
45 tem, and in particular of their water resources. Pollution phenomena as well as the overexploitation
46 of groundwater cause a progressive qualitative and quantitative worsening of the stored water. One
47 of the most recurring effects is the variation of the natural equilibrium between fresh and sea wa-
48 ters, with consequent advancing of the seawater intrusion in the coastal aquifers (Custodio, 2002).

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

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

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65 **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 US and Germany, whose guidelines (U.S. EPA, 1987; DVGW, 1995; USGS, 1998) 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 (European Communities, 2000) 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 (European Communities, 2007) 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 (García-García and Martínez Navarrete, 2005; Martínez Navarrete et al., 2008), in order to define the SGZs (or Source Protection Zones - SPZs):

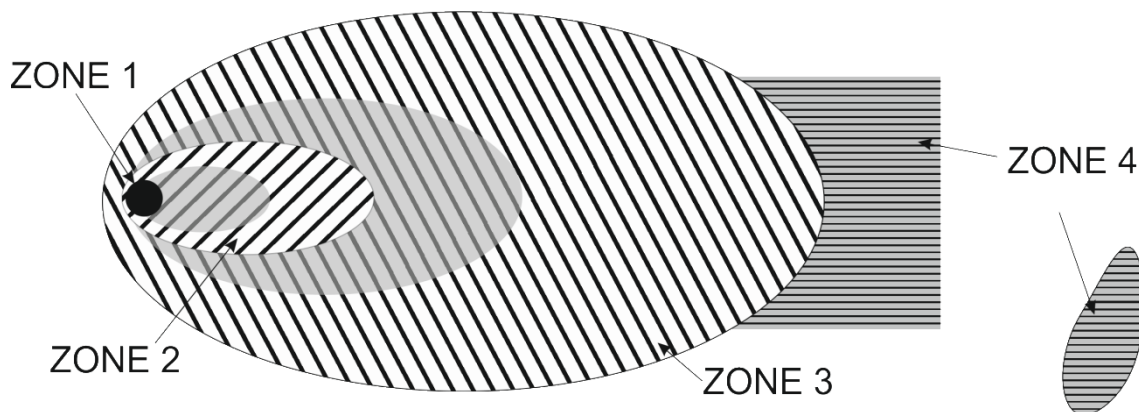
Z1 - an inner zone, which is the area immediately surrounding the abstraction point and is geometrically defined by a specific distance from the exploitation point;

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;

97 Z3 - an outer zone, which is the area around a source, within which all groundwater recharge is
 98 presumed to be discharged by such source (catchment zone).

99 In some cases a subdivision of these main zones can be provided. In Germany, the Z3 can be op-
 100 tionally subdivided into two zones if its longitudinal extent exceeds 2 km (Zhu and Balke, 2008),
 101 whereas in Belgium (Derouane and Dassargues, 1998) and Italy (D. Lgs. 152/2006; Italian State-
 102 Regions agreement signed on 12th December 2002) the Z2 can be further subdivided into two
 103 zones, whose boundaries are representative of different travel times. On the other hand, in some
 104 countries, e.g. France and United Kingdom (García-García and Martínez Navarrete, 2005), a fourth
 105 zone can also be added in agreement with specific hydrogeological features or vulnerability condi-
 106 tions. Fig. 1 shows a general scheme of the SGZs subdivision.

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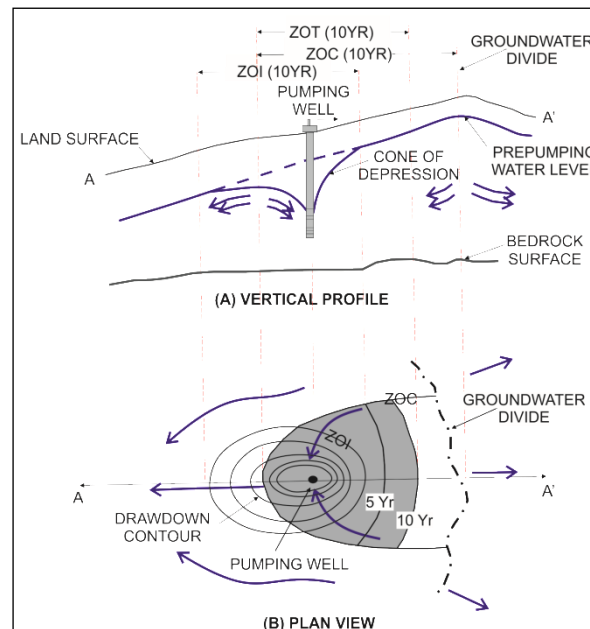
109 Fig. 1 - General scheme of SGZs subdivision in European countries. In gray, optional sub-zones
 110 (see text).

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112 2.1.2 U.S.A.

113 The federal law “Safe Drinking Water Act” (SDWA) requires many actions in order to protect
 114 drinking water and its sources. Accordingly, each State shall provide to determine the Wellhead
 115 Protection Areas (WHPAs), which is defined as “the surface and subsurface area surrounding a wa-
 116 ter well or a field of water wells, supplying a public water system, through which contaminants are
 117 reasonably likely to move toward and reach such water well or well-field”. After the Amendments
 118 of 1986 to the SDWA, the United States Environmental Protection Agency faced hydrogeological
 119 aspects of groundwater protection, providing a “Guideline for Delineation of Wellhead Protection
 120 Areas (WHPAs)” (U.S. EPA, 1987). Hypothetical situations in different hydrogeological settings
 121 are described, as well as a basis for several delineation methods, highlighting subzones (Fig. 2) of

122 WHPA named ZOI (area overlying the cone of depression), ZOC (the whole catchment), ZOT
 123 (zone of transport for specific travel times). Criteria on which WHPA delineation may be based in-
 124 clude distance, drawdown, travel time, flow system boundaries, and the capacity of the aquifer to
 125 assimilate contaminants. Such document describes criteria and methods that can be adopted for
 126 WHPAs delineation, however States have flexibility in developing their WHPAs programs as a
 127 function of their specific hydrogeological and environmental contexts.
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Fig. 2 Example of subzones of the WHPA according U.S. EPA (after U.S. EPA, 1987)

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133 2.1.3 Australia

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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 (ARMCANZ, 1995 and 1996), 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 (1995), 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

143 (Zone I) consists of a circular shape of radius 50 m and encompasses the water authority compound
144 around the wellhead, including adjacent private areas where necessary. The second zone (Zone II) is
145 arbitrarily delineated basing on a travel time of 10 years, and the third zone (Zone III) corresponds
146 with the catchment area where greater than 10 years residence time is available.

147 More recently, explicit planning has been developed, by providing actions of protection within
148 specific catchments, termed Public Drinking Water Source Areas (PDWSAs). The policy for the
149 protection of PDWSAs includes three priority classification areas (P1, P2, P3), based on the man-
150 agement of risk and two types of protection zones distinguished in wellhead protection zones-
151 WHPZs and reservoir protection zones-RPZs (DoE, 2004). P1 and P2 areas are managed to ensure
152 that there is no risk and no increased risk of water source pollution, respectively. Most land uses
153 produce some risk to the quality of water and are therefore defined as “Incompatible” in P1 areas,
154 whereas some activity is allowed within P2 areas for land uses that are defined as either “Compati-
155 ble with conditions” or “Acceptable”. P3 areas are defined to manage the risk of pollution to the
156 water source from catchment activities and are declared over areas where water supply sources co-
157 exist with other land uses such as residential, commercial and light industrial development. WHPZs
158 encompass the drinking water sources and are generally circular with a radius of 500 m or 300 m,
159 for sources that are in P1 or P2 areas. RPZs consist of a statutory 2 km wide buffer area around the
160 top water level of storage reservoirs.

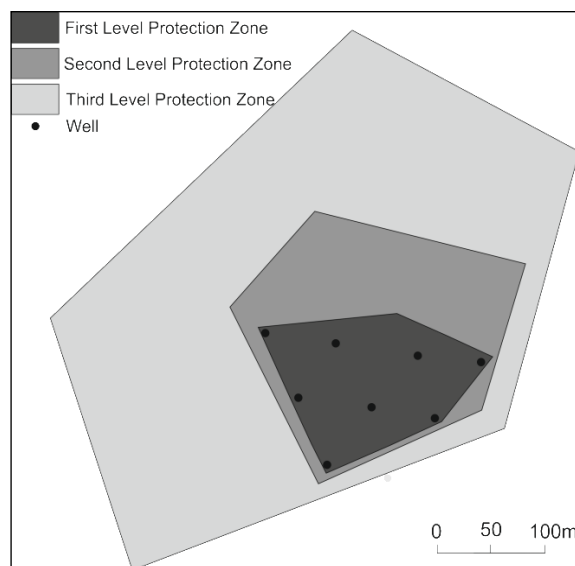
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162 *2.1.4 China*

163 China is the world's most populous country, with a consequent high request of water for human
164 consumption. On the other hand, the distribution of water resources in China is highly diverse, thus
165 negatively affecting social and economic growth in some regions (Nitikin et al., 2012). Estimations
166 by the Ministry of Water Resources (MWRC, 2014) highlighted as in 2005 about 300 million peo-
167 ple in China were unable to access safe drinking water, both in terms of quality and quantity. In
168 spite of that, and although the law tools invite to establish a protection system for zones of drinking
169 water sources (L1984/11/01; D74/2002; L2008/06/01), delineation of protection zones for ground-
170 water sources is still at the initial stage (Baixiang and Fanhai, 2011), and in the locations where it
171 has been performed there is a lack of practical protective measures (Wang and Yu, 2014).

172 According to L2008/06/01, drinking water source reserves are classified into Grade-I and Grade-
173 II. It is moreover possible to delimit a certain area at the periphery of a drinking water source re-

174 serve as a quasi-reserve. In the Grade-I zone any buildings or activities are not permitted, excluding
 175 those linked to water supply facilities and their management and protection. Within the Grade-II
 176 and quasi-reserve zones it is prohibited to build, renovate or enlarge, any construction project dis-
 177 charging pollutants and seriously polluting waters. No technical criteria are given by the regulation.
 178 In fact, different case studies dealing with groundwater sources for human consumption in China
 179 report different ways to define the boundaries of the three zones. For the Grade-I and Grade-II
 180 zones a benchmark travel time is generally taken into account. Wenjuan et al. (2011) and Baoxiang
 181 and Fanai (2011) refer to 100 days and 60 days for the Grade-I protection, and to 1000 days and 10
 182 years for the Grade-II protection, respectively. The quasi-reserve zone is chiefly referred to the
 183 whole catchment, nevertheless a residence time of groundwater is sometimes considered (e.g. 25
 184 years in Baoxiang and Fanai, 2011). The shapes of the protection zones can be circular, elliptical, ir-
 185 regular and even polygonal (Fig. 3) as a function of delineation methodologies (e.g. analytical ra-
 186 ther than empirical) and of the source arrangement (e.g. single source rather than multi-point
 187 sources).



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 189 Fig. 3 Polygonal partitioning of protection zones for the wells-field in Dawukou District of Shi-
 190 zuishan City, China (after Wenjuan et al., 2011).

191 192 2.1.5 Africa

193 Many African countries have problems both with water scarcity and with pollution. For what re-
 194 gards the MENA region (Middle-East North Africa), large territories are characterized by arid and
 195 semi-arid conditions where groundwater constitutes the main source of water supply, thus making

196 the protection of this resource indispensable (Scozzari & El Mansouri, 2011). In this context, there
197 is some degree of cooperation between the involved countries and foreign states having a significant
198 experience about the protection of groundwater resources, on the basis of cooperation agreements.

199 In Sub-Saharan Africa, U.S. EPA promotes the development and implementation of Water Safety
200 Plans (WSPs) to improve the capacity of urban providers to deliver safe drinking water in a sustain-
201 able way (U.S. EPA, 2014). WSPs consist in a “catchment to consumer” approach, which uses a
202 health-based risk assessment methodology for identifying the greatest vulnerabilities to contamina-
203 tion within a drinking water supply system.

204 In North Africa, projects have been developed by means of the cooperation among Arab coun-
205 tries and Germany (Schelkes et al. 2004; Margane, 2003), facing the issue of the management, pro-
206 tection and sustainable use of groundwater. A proposal of guideline for the delineation of ground-
207 water protection zones was also produced (Margane, 2003), in which a typical scheme with three
208 zones of protection (reflecting different levels of risk) surrounding the abstraction point is present-
209 ed. Different criteria for the delimitation of zones are suggested as a function of two main aquifer
210 system types, based on a near homogeneous (e.g. unconsolidated aquifer) or heterogeneous (e.g.
211 karst aquifer) distribution of groundwater flow velocities, respectively. The travel time is the most
212 prominent factor for the delineation of groundwater protection zones for the first category of aqi-
213 fers, whereas an approach based on the vulnerability is preferred for the second category of aqi-
214 fers.

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216 **2.2. Scientific-technical approaches**

217 As previously described, the protection of drinking water sources is generally approached by
218 means of the delineation of zones surrounding the abstraction points (hereafter Safeguard Zones,
219 SGZs) and by defining prohibitions and restrictions within such areas in term of land use and activi-
220 ties. Within a SGZ three or more sub-zones are generally distinguished as a consequence of the dif-
221 ferent degree of protection that is needed. Several methods for delineating such zones have been
222 developed worldwide, and are described in guideline documents or proposed in scientific papers. In
223 general, the choice of the methodology is linked with the availability and the kind of hydrogeologi-
224 cal data available, in addition to the aquifer typology. In the following sub-sections the main ap-
225 proaches that are used worldwide are listed and briefly described.

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227 *2.2.1 Geometrical Methods*

228 These methods consist in drawing a shape (Fig. 4), which is either determined by purely geomet-
 229 ric criteria or by considering both geometric aspects and hydrodynamic features. The geometric ap-
 230 proach is generally used where other and more sophisticated method cannot be applied. The sim-
 231 plest method consists in drawing a circle of an arbitrary fixed radius around each abstraction (Fig.
 232 4a). The radius can also be defined by taking into account the average distance corresponding to a
 233 given time of travel, averaged as a function of the different hydrogeological contexts insisting in the
 234 studied region. A similar method provides circular or semi-circular protection areas using radii that
 235 are calculated by using volumetric equations. These latter consider hydrogeological parameters (e.g.
 236 porosity) and the volume of water drawn in a specified time interval from the well (Fig. 4b; Eq. 1
 237 and 2).

$$238 \quad r = \sqrt{\frac{Q t}{\pi n H}} \quad (1)$$

$$239 \quad r = \sqrt{\frac{2 Q t}{\pi n H}} \quad (2)$$

240
 241 Where:

242 Q = pumping rate (m³/s)

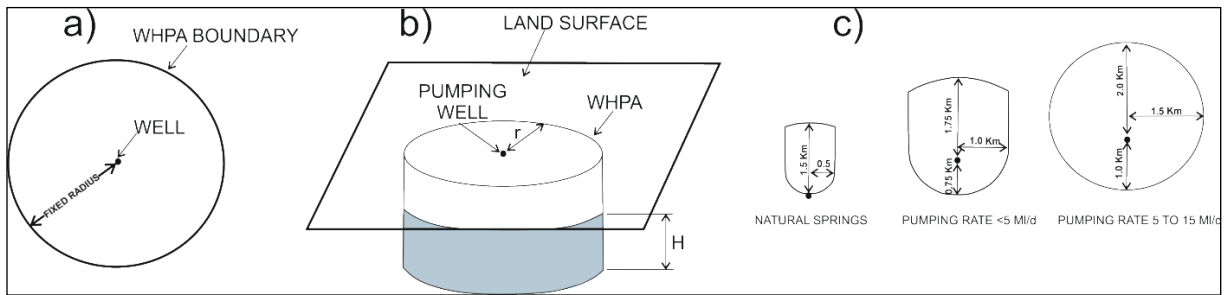
243 n = aquifer porosity

244 H = length of well screen (m)

245 t = travel time (s)

246
 247 Eq. 2 refers to the half-circle method, which takes into account the flow direction by replacing
 248 the circular shape used for the simplest SGZ with a half circle having the same area. Such new
 249 asymmetrical shape is oriented to the up-gradient direction (OhioEPA, 2009), to encompass the ef-
 250 fect of the flow. The travel time used as a reference is chosen in order to allow the occurrence of
 251 processes that adequately decrease the concentration of contaminants before they reach the well (i.e.
 252 dilution, dispersion, clean-up).

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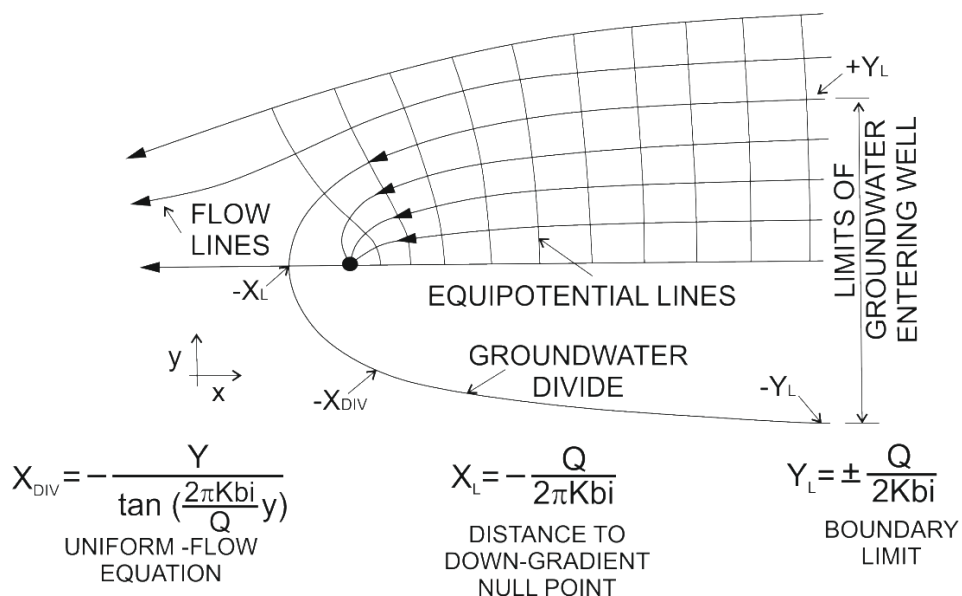
255 Fig. 4 Geometric methods for delineating SGZs. a) Arbitrary fixed radius; b) Calculated radius:
 256 the radius (r) determines a volume of water that is pumped from the well in a specified time period;
 257 c) Simplified variable shapes: various standardized forms are generated by analytical equations and
 258 provided to calculate the up-gradient extent on the base of times of travel. (after U.S. EPA, 1987).

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260 Another approach is the generation of various standardized and representative shapes (Fig. 4c) by
 261 using analytical equations. Standardized shapes are calculated for different sets of hydrogeological
 262 conditions (essentially different values of T and hydraulic gradient) and well-pumping rates, then
 263 the more appropriate shape is applied to the wellhead zone and oriented according to the flow pat-
 264 terns. The down-gradient and lateral limits of the standardized shapes are defined by the uniform
 265 flow equation (Fig. 5) (Todd, 1980; Grubb, 1993), whereas the upgradient extent is estimated by
 266 considering a specific time of travel. By applying different times of travel it is possible to identify
 267 several sub-zones forming the entire SGZ.

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271 Fig. 5 SGZs delineation using the analytic method for a confined aquifer. Q: well pumping rate;
272 K: hydraulic conductivity; b: saturated thickness; i: hydraulic gradient; π : 3.1416 (modified, after
273 Todd, 1980).

274

275 2.2.2 Analytical Methods

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

283 Analytical approaches were used by several authors for the definition of the capture zones of
284 wells, considering both aquifers of infinite extent (e.g. Shan, 1999) and in the presence of bounda-
285 ries (e.g. Intaraprasong and Zhan, 2007; Samani and Zarei-Doudeji, 2012).

286 It must finally be noted that there are literature examples and relating software showing how this
287 type of delineation can be automated by using analytical element models running on a computer,
288 e.g., WhAEM, GFLOW (OhioEPA, 2009).

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291 2.2.3 Hydrogeological Mapping

292 This methodology provides the delineation of the protection areas by summarizing within hydro-
293 geological maps the information derived from geological, geophysical, hydrogeological and hydro-
294 geochemical surveys. Starting from geological observations, changes of lithology corresponding to
295 contrasts of permeability can be individuated and correlated with the boundaries of the protection
296 areas. Surface geophysical data coupled with the geological interpretation may provide the spatial
297 arrangement of buried structures, thus indicating possible groundwater divides linked to structural
298 conditions. Hydrogeological mapping may also encompass groundwater level contour lines, which
299 can contribute to the identification of groundwater divides. Moreover, results of dye tracing tests
300 can be included, as a tool to verify the recharge area and the flow systems. Also the vulnerability-
301 based methodology (e.g. Pochon et al., 2008; Elewa et al., 2012; Lo Russo and Taddia, 2012) can

302 be classified as a hydrogeological mapping approach, given the overlapped and integrated elaboration among several thematic layers (e.g., topography, permeability, fractures' density, etc.).

304

305 2.2.4 Numerical Models

306 Flow and transport numerical modelling represents a good practice for SGZs accomplishment (e.g. Kinzelbach, 1986; Derouane and Dassargues, 1998; Rayne et al., 2001; Rock and Kupfersberger, 2002; Saravanan et al., 2011), 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) is available to perform numerical modelling (e.g. GroundwaterVistas, 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.

316 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" (Oreskes et al., 1994), 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.

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323 2.3. Case of Study: a hydrogeological approach tested on groundwater sources of Tuscany (Italy)

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

326 According to the Italian law (D.Lgs. 152/2006; Italian State-regions agreement signed on 12 December 2002) the three sub-zones 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

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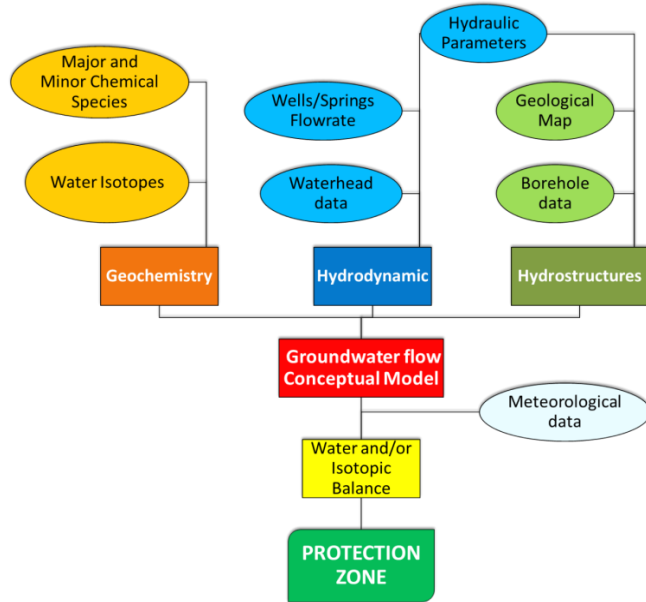
332 data. The assessment of the protection zone (the third sub-zone of the SGZ) always follows the hy-
333 drogeological approach.

334 Due to their major importance in terms of safeguard, the respect zones in Italy have been delim-
335 ited for several abstractions according to the said guidelines. Instead, for the delineation of protec-
336 tion zones (PZs) there are no official documents, neither a significant number of case studies.

337 In the framework of a project funded by the Administration of the Tuscany Region, several stud-
338 ies were carried out in the areas surrounding several abstraction points of drinking water located in
339 different parts of the regional territory. Fifteen PZs were delimited (Menichini et al., 2015) by
340 means of an integrated multi-disciplinary approach thanks to cooperation between CNR-IGG, the
341 Water Authorities (WAs) and the Integrated Urban Water Management Companies (IUWM-Cs). In
342 the following of this section the general approach adopted for delineating PZs is briefly discussed
343 and some main results of its application are presented.

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

350 A general scheme describing the integrated approach and the data used for its elaboration is re-
351 ported in Fig. 6. The diagram shows how the geochemical, hydrodynamic, structural and meteoro-
352 logical information converge into the process for the assessment of a protection zone.



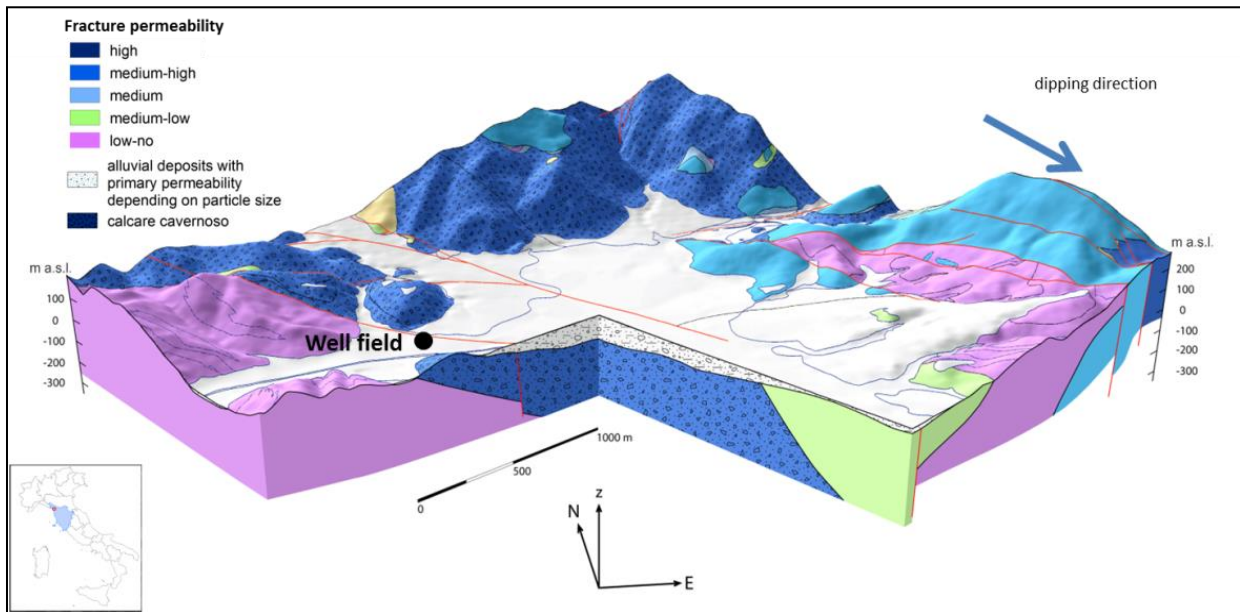
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354 Fig. 6 – Schematic diagram describing the integrated approach. Data provided as input are shown
 355 in elliptical boxes.

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

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Fig. 7 – 3D representation of the hydrogeological structures (after Menichini et al., 2015). The fractured hydrogeological units with permeability medium to high are made up by carbonate lithologies.

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 summarised as follows:

- the analysis of geological structures pointed out that in the area a general North-South groundwater flow is favoured 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 hydro-structures highlighted some possible hydrogeological divides and a presumable loss of groundwater from the “Camaiole Basin” towards 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 and they converge towards the wells 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;

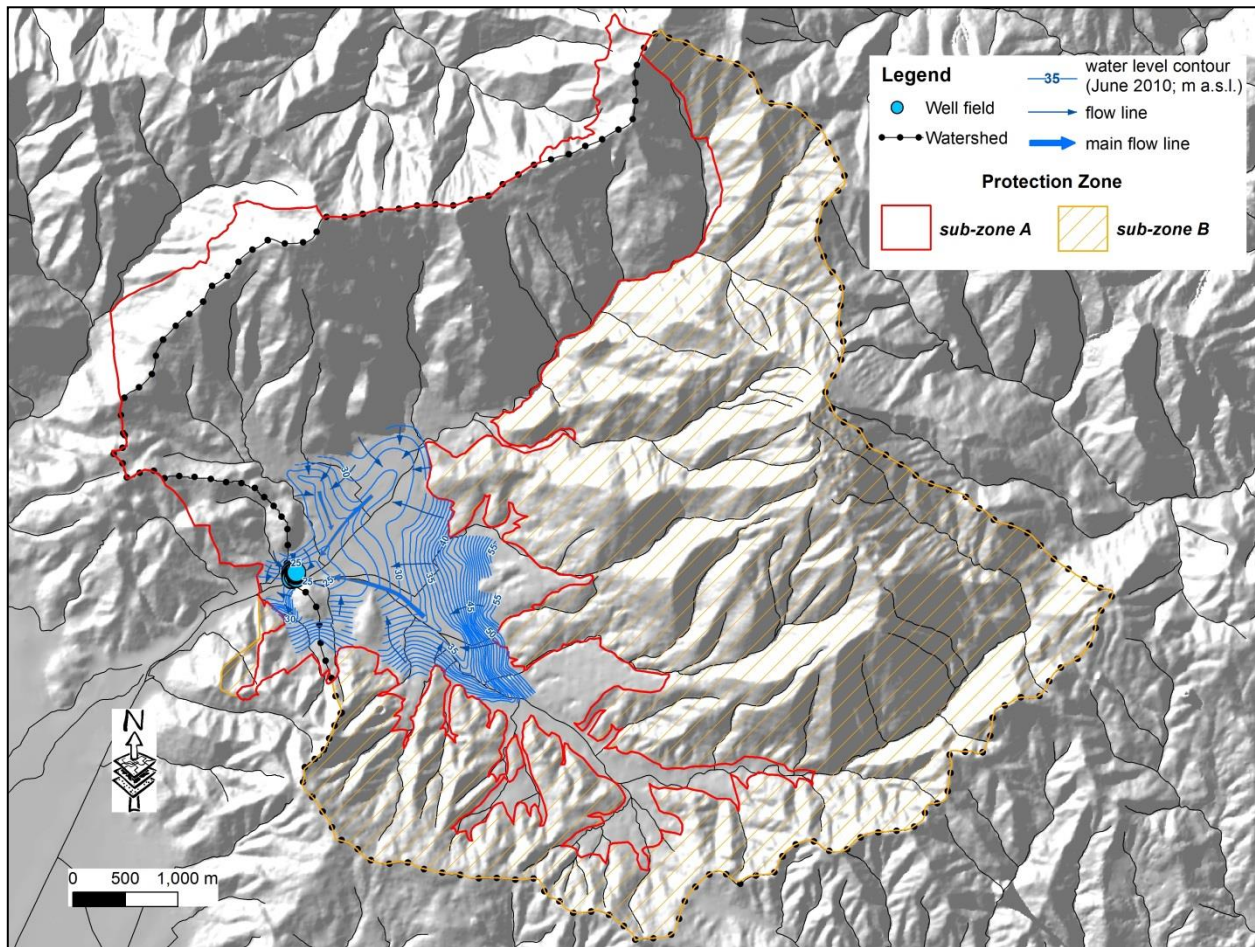
- chemical and water-isotopes analyses have been performed twice, both for the abstractions under study and for a number of water points (about 15 springs, wells and stream waters) in their

384 surroundings. Among these, six springs were opportunely selected in order to assess the relationship
385 “altitude/ $\delta^{18}\text{O}\text{‰}$ ”, which is useful to achieve the average altitudes of the recharge of water abstrac-
386 tions (Doveri and Mussi, 2014; Doveri et al., 2013). By combination of chemical and isotopic data,
387 the presence of some inputs and of their mixing products was verified. Chemical features suggested
388 what kind of lithology is involved in the water-rock interaction processes (e.g., Calcare Cavernoso
389 for the SO_4 values, or Sandstone for the SiO_2 values), whereas isotopes indicated the average alti-
390 tudes of infiltration for the different inputs. Taking into account these aspects and the mixing pro-
391 cesses, it’s been possible to achieve indications both on the areas involved in feeding the abstrac-
392 tions and on their importance in terms of quantity.

393 Based on all the above mentioned information, the catchment area was delineated for the well
394 field. This polygon was additionally validated by means of the water and isotopic budget: for each
395 zone in which the same hydrogeological complex outcrops, both infiltration rate
396 (<http://www.sir.toscana.it/>, for meteorological data; Piccini et al., 1999, for the infiltration coeffi-
397 cients) and the average values of $\delta^{18}\text{O}\text{‰}$ (comparing the average altitudes and the relationship “alti-
398 tude/ $\delta^{18}\text{O}\text{‰}$ ”) were estimated. Furthermore, these isotopic signatures were weighted by using the
399 infiltration rates, thus obtaining the weighted means of $\delta^{18}\text{O}\text{‰}$ concerning the entire feeding area.
400 The evaluated value (-6.41‰) resulted congruent with analyses’ results for the water samples col-
401 lected at the well field (-6.48‰).

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

405



406

407 Fig. 8 – Well field Protection Zone. Water level contour lines refer to the unconfined aquifer sys-
 408 tem that exists in the plain surrounding the well field and it is made up by alluvial sediments in the
 409 shallower part and mainly by carbonate rocks at depth. Sub-zone A is the main feeding area of the
 410 groundwater system exploited by the well field. Sub-zone B is the area from which a minor feeding
 411 occurs.

412

413 3. Conclusions

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

418 Hence, the appropriate knowledge of physical and chemical aspects of the aquifer systems be-
 419 comes more and more a necessary prerequisite in order to face the several issues involved with the
 420 protection of groundwater, implying the necessity to develop robust conceptual hydrogeological

421 models. Despite the relevant investment of resources necessary for the production and interpretation
422 of multidisciplinary experimental data, a well-grounded conceptual framework should not be over-
423 come with the direct use of specific and more straightforward tools (e.g. numerical modeling with-
424 out sufficient experimental data, empirical methods based on few parameters and/or limited datasets
425 etc.). In particular, a comprehensive approach, following the guidelines and the examples discussed
426 in this chapter, gives the perspective of an improved planning of the groundwater management, with
427 a high chance of long-term benefits.

428

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