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Aquifer Vulnerability Assessment and Wellhead Protection Areas to Prevent Groundwater Contamination in Agricultural Areas: An Integrated Approach

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ABSTRACT

To implement successful policies for the protection of groundwater and curtail the possibility of water supply contamination, an early evaluation of aquifer vulnerability is needed. Rather than implementing broad restrictions to land use and effluent discharge, it is more cost-effective and economically favourable to approach protection in a stepwise manner by first assessing the intrinsic vulnerability of the aquifer when defining the level of land use control that is needed to protect groundwater quality. Following aquifer vulnerability evaluation, specific land uses and restrictions should be defined locally for each water supply within the wellhead protection areas (WHPAs), which are identified by means of the groundwater time of travel (TOT). The WHPA should be established for each individual situation, considering the level of vulnerability of the exploited aquifer. We applied our findings to a specific test site in the Piemonte region of NW Italy, following the current local procedure for individuating the WHPAs. Using data gathered from this site-specific exercise, we identified that the procedure allows methods that consider only aquifer parameters to evaluate vulnerability and discourages the use of techniques that already compartmentalize soil parameters in the vulnerability assessment.

Keywords: Groundwater Protection Zones; WHPA; Vulnerability; FEFLOW; Piemonte; Italy

1. Introduction

Groundwater quality in many parts of the world has experienced significant degradation due to agricultural, industrial and/or commercial activities. Historically, damage to groundwater supplies has often occurred when contaminants reach aquifers via the vertical pathway introduced by surface wells. Because of the importance of groundwater, and the difficulty and expense in remediating groundwater supplies, steps are now often taken to prevent initial pollution. Those steps can include protecting the whole aquifer, as well as the area surrounding the surface wellhead, from inadvertent contamination [1-6].

Use of the term "aquifer pollution vulnerability" began in the 1970s in France [7] and more widely in the 1980s [8-10], when it became increasingly clear through research that many aquifers were suffering from significant anthropogenic contamination resulting in degradation which compromised usability of the resource. Several studies have targeted the development of vulnerability mapping techniques; results of these investigations have led to new definitions applicable to groundwater protecttion issues [11-20]. "Vulnerability" is generally defined as the (intrinsic) sensitivity of an aquifer to being adversely affected by a contaminant; "groundwater pollution hazard" relates to the probability that groundwater in an aquifer will be contaminated at concentrations that pose a risk to human health or the environment that is hydraulically connected to the groundwater [4]. An absolute (numeric) index of aquifer pollution vulnerability is far more useful than relative indicators for all practical applications in land-use planning and effluent discharge control. With this goal in mind, several methods proposed in the literature are focused on vulnerability assessment. They vary by the parameters and mathematical expressions considered. GOD [10] and modified GOD [4], DRASTIC [9], EPIK for karst settings [21] and SINTACS [22] are acronimous of the most widely utilized processes. Each method can provide a numerical index which is generally correlated to a vulnerability class definition that is qualitatively described at the end of the evaluation process (usually high, moderate, low and negligible). The selection of the appropriate methodology depends on the hydrogeological setting and

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available data. It is quite possible to have high vulnerability but no pollution hazard because of the absence of significant subsurface contaminant load, or vice versa [4]. Following this approach, an inventory of potential subsurface contaminant load is necessary to design adequate safeguards for specific situations.

In order to protect the groundwater intercepted by a production well, it is essential to develop a thorough understanding of the groundwater flow system and to delineate the area surrounding the well where potential contamination could occur [23]. The proximity of the land-use activity to a groundwater supply (well or spring) is a critical factor in determining the potential for contamination [24,25]. More specifically, the pollution threat depends on 1) whether the activity is located within the (subsurface) capture area of the supply and 2) the horizontal groundwater flow time in the saturated aquifer. In order to completely eliminate the risk of unacceptable pollution of a supply source, all potential activities that might lead to contamination in the recharge zone would have to be prohibited. This will often be unsustainable or economically impractical, especially in developed areas with pre-existing land-use constraints [26]. It may be more practical to segregate the recharge zone, so that the most stringent land use restrictions will only be applied in areas closer to the source [27].

To achieve the necessary segregation, a series of generically concentric surface zones around the groundwater source can be defined through knowledge of local hydrogeological conditions and the characteristics of the groundwater supply source itself [28]. Once delineated, the protection areas may be managed to prevent contamination and for clean-up if contamination occurs. The supply protection areas must protect the source against persistent contaminants as well as those that degrade over time [29]. Both are necessary for comprehensive protection. Such an area is referred to as the wellhead protection area (WHPA). The US EPA [30] early defined a WHPA as "the surface and subsurface area surrounding a water well or well field, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or well field". Several WHPA delineation methods exist, differing in their degree of complexity and precision. Naturally, the integration of more geological and hydrogeological characteristics of the study area increases the accuracy of any given method. These methods include [1]:

- Arbitrary fixed radius
- Calculated fixed radius
- Simplified variable shapes
- Flow system mapping with uniform flow equation
- Analytical flow/particle-tracking tools
- Numerical flow/transport models

Since the early 1990s, many WHPA studies have been completed, some of which have stressed the necessity of integrating various hydrogeological characteristics into the delineation methods. A comparative review of WHPA delineation methods is provided in Paradis *et al*. [31]. From a practical perspective, the most appropriate method for WHPA delineation should be one that simplifies the flow system as much as possible while preserving its geologic and hydrologic characteristics [32,33].

The WHPA can be referred to as the zone of contribution, *i.e.*, the two-dimensional (2D) projection to the land surface of the aquifer volume containing all the groundwater that may flow toward a pumping well over an infinite time period. The zone of travel is defined within the zone of contribution and can be described as an isochrone indicating the transfer time—time of travel (TOT)—necessary for water or a conservative contaminant to reach the well from that location. The TOT will depend on the pumping rates and the aquifer characteristics such as transmissivity, hydraulic gradient, porosity and aquifer thickness. The level of aquifer vulnerability should address the selection of TOT for identification of WHPAs. In fact, water wells exploiting low-vulnerability aquifers can be protected by limited WHPAs (low TOT values) without compromising the level of the protection. Conversely, wells tapping vulnerable aquifers require extended WHPAs (high TOT) to ensure adequate safeguards are in place. The proper evaluation of aquifer vulnerability and the selection of a suitable TOT for WHPAs is thus very important to avoid over- or underestimating the level of land protection that is required. This selection is especially significant in agricultural areas where fertilizers, agrochemicals and pesticides are intensively utilized [34]. Therefore an effective comprehensive protection strategy for groundwater quality should integrate the assessment of the aquifer vulnerability with the WHPAs in a suitable way.

As early as 1980 the European Union developed a directive concerning the preservation of water quality for human consumption [35]. In concordance with that directive, the Italian Government, in the 1980s, developed a national regulatory framework for the protection of groundwater resources, including the need for WHPA delineation for water supplies (wells, springs and surface water acquisition points) [36]. Subsequent European directives designed to protect the subsurface environment from unacceptable contamination [37-40] were progressively incorporated into the Italian national legislative framework [41-43]. These new legislative directives introduced novel procedures and scientific aspects to groundwater protection policies. Based on these newly-defined perspectives, some Italian regional governments implemented specific groundwater resources programs to safeguard water supplies within their territory. Through

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specific regulations [44] the Piemonte region environmental authority (NW Italy) tried to ensure proper alignment between aquifer vulnerability and the WHPAs delineation.

Actions taken to preserve and protect groundwater resources within a WHPA, particularly those encompassing limitations on certain agriculture practices, must be approached in a collaborative fashion with local agriculture stakeholders, and must take into account available best practices and supporting scientific data.

In this paper we tested 1) the current comprehensive technical framework for individual WHPAs in the Piemonte region on a representative case study. We highlighted some critical and 2) we proposed a limited review of the adopted methodology.

2. Methods

2.1. Identifying WHPAs in the Piemonte Region (NW Italy): Techniques and Regulations

As implemented in the Piemonte region [44], a WHPA consists of three different decreasing protection levels situated at increasing distances, respectively, from the well (**Table 1**).

The WHPA has to be defined through a procedure based on existing information and specific surveys. The regulations procedure individuating the WHPA requires an initial geological and hydrogeological general investtigation of the area. It is followed by evaluation of aquifer vulnerability, assessment of the aquifer hydrodynamic parameters by means of appropriate pumping tests, calculation of the isochrones through analytical or numerical models and, finally, an inventory of activities that have the potential for causing contamination within the WHPAs. These data allow for delineation of the WHPA and definition of the land use management plan within the area. Once defined, land use restrictions are controlled by the water supply company managing the well in cooperation with the regional environmental authority.

The WHPA is usually divided into two sub-areas, namely the inner protection zone (IPZ) and the outer protection zone (OPZ). The IPZ is always individuated by the 60-d isochrone, while the TOT that identifies the OPZ depends on the vulnerability of the exploited aquifer. There are four generally accepted vulnerability categories: Very High, High, Medium and Low. For low aquifer vulnerability the OPZ must be calculated using the 180-d isochrone; the remaining vulnerability categories are determined by utilizing the 365-d isochrone. It should be noted that regulations do not provide any specifications about the methodology for assessing aquifer vulnerability. The suitable method must be decided on a case by case basis. For WHPAs overlaying agricultural areas, a specific fertilizer and phytosanitary management plan must be developed which integrates the general land use management plan. It should ensure the safe application of fertilizers, agrochemicals and pesticides, taking into account the attenuation capacity of the soil cover with respect to groundwater pollution. Determination of this protection capacity must consider at least the following soil parameters: texture, skeleton, soil depth and cracks. These soil data are generally available for the general region. Soil protection capacity has been evaluated by IPLA [45] and is currently available digitally via the internet. In areas for which historical data are not available, a specific site evaluation should be developed (minimum 1 soil profile/2 ha of WHPA). Four soil protection capacity categories have been established: very high, high, medium and low. By combining the aquifer vulnerability and the soil protection capacity within the WHPA in a suitable manner (**Table 2**), four levels of land use restrictions are identified and the corresponding agricultural land use limitations have been specifically defined (**Table 3**).

2.2. Test Site: The Castagnole Well

The procedure for developing a specific WHPA, as described in Section 2.1, was tested on a water well supplying the Castagnole municipality, located 20 km south of the Turin urban area (see **Figure 1**), which is the capital of the Piemonte region (well geographical coordinates are 45°54'01.93"N, 7°33'23.55"E). The elevation of the site is 244 m asl. The tested well is 88 m deep. The di-

Table 1. WHPA differentiation and permitted land uses according to the Italian water regulations (modified after [42]).

WHPA zone	Individuating criteria	Land uses
Total protection zone (TPZ)	Fixed radius (10 m minimum)	None. This zone should be fully preserved, impermeabilized, enclosed, and with limited access for authorized personnel only.
Inner protection zone (IPZ)	Time of Travel (60-d isochrone)	Strongly limited. No excavation and subsurface work is allowed. Hazardous activities should be re-located if they are present. New buildings construction is prohibited.
Outer protection zone (OPZ)	Time of Travel (180-d and 365-d isochrones for low vulnerability aquifers or medium, high and very high vulnerability aquifers, respectively)	Limited. Only minor anthropogenic activities are allowed, and safeguard measures against groundwater pollution are necessary for existing and new buildings.

Table 2. Identification of the land use protection levels required within the WHPA in the agricultural areas by the association of aquifer vulnerability and soil protection capacity. See Table 3 for details concerning authorized land uses and agricultural practices (modified after [44]).

	Soil protection capacity (related to groundwater pollution)	
	Very high and high	Medium and low
Low aquifer vulnerability	Level 4 (minimum protection)	Level 3
Medium aquifer vulnerability	Level 3	Level 2
High and very high aquifer vulnerability	Level 2	Level 1 (maximum protection)

Table 3. Authorized land uses and agricultural practices within the WHPAs as indicated by the protection levels derived by the association of aquifer vulnerability and soil protection capacity (see Table 2) (simplified and modified after [44]).

Water supply protection level	In the inner protection zone (60 d isochrone)	In the outer protection zone (180 d or 365 d isochrone)
Level 1 (Maximum Protection)	Pasture, fertilizers and phytosanitary products are fully prohibited	Fertilizer balance plan is mandatory. Nitrogen effluent discharges are limited below yearly 170 Kg/ha maximum value. Phytosanitary products are authorized under European regulations for organic farming [46]
Level 2	Fertilizer balance plan is mandatory. Nitrogen effluent discharges must be less than the maximum annual value of 170 Kg/ha. Phytosanitary products are authorized under European regulations for organic farming [46]	Same as the IPZ. A wider range of phytosanitary products and weed practices can be allowed on a case by case basis under specific conditions and regulations defined by the public surveillance authority.
Level 3	Fertilizer balance plan is mandatory. Nitrogen effluent discharges must be less than the maximum annual value of 170 Kg/ha. Phytosanitary products are authorized under European regulations for organic farming [46]. A wider range of phytosanitary products and weed practices can be allowed on a case by case under specific conditions and regulations defined by the public surveillance authority.	Same as the IPZ
Level 4 (minimum protection)	Fertilizers balance plan is mandatory. Nitrogen effluent discharges must be less than the maximum annual value of 170 Kg/ha. Phytosanitary products and weed practices are allowed on a case by case basis under specific conditions and regulations defined by the public surveillance authority.	Same as the IPZ

ameter of the casing is 650 mm. The well is cemented from the surface to a depth of 28 m. Three screened sections are located in producing sand-gravel layers between depths of 46 - 50 m, 67 - 69 m and 78 - 81 m. The undisturbed water level of the confined aquifer (without any pumping) is at 242 m asl on the well vertical (**Figure 2**). The withdrawn groundwater is analyzed by regional sanitary authorities twice a month to control the chemical and bacteriological parameters according with Italian regulation for water intended for human consumption [36, 38-40]. Since 1990 no organic or inorganic pollution was detected.

2.3. Geology Site Description

The Castagnole area is mainly developed on the outwash plain comprised of several glaciofluvial coalescing fans connected to the Pleistocene-Holocene expansion phases

east of the Alpine glaciers. The substrate of the outwash plain outcrop corresponds to the Torino Hill and consists of a Cenozoic terrigenous marine succession deposited in an episutural basin [47] (see Unit 3 in **Figure 1**). As a result of a complex Pliocene-Holocene evolution characterized by the deposition of continental sediments related to the dynamic evolution of the Plio-Pleistocene "Villafranchian" glaciolacustrine facies [48] and the Pleistocene-Holocene expansion phases of the main Alpine glaciers, the geological setting of the plain is characterized by a strong geographical anisotropy.

The hydrogeological setting can be described with a high degree of confidence due to the large number of wells drilled in the plains area [49]. Downhole log data in the study area indicate the presence of two lithologic zones with distinct hydraulic properties. On the well vertical it is possible to identify Units 1 and 2 (**Figure 2**), which are described in greater detail below.
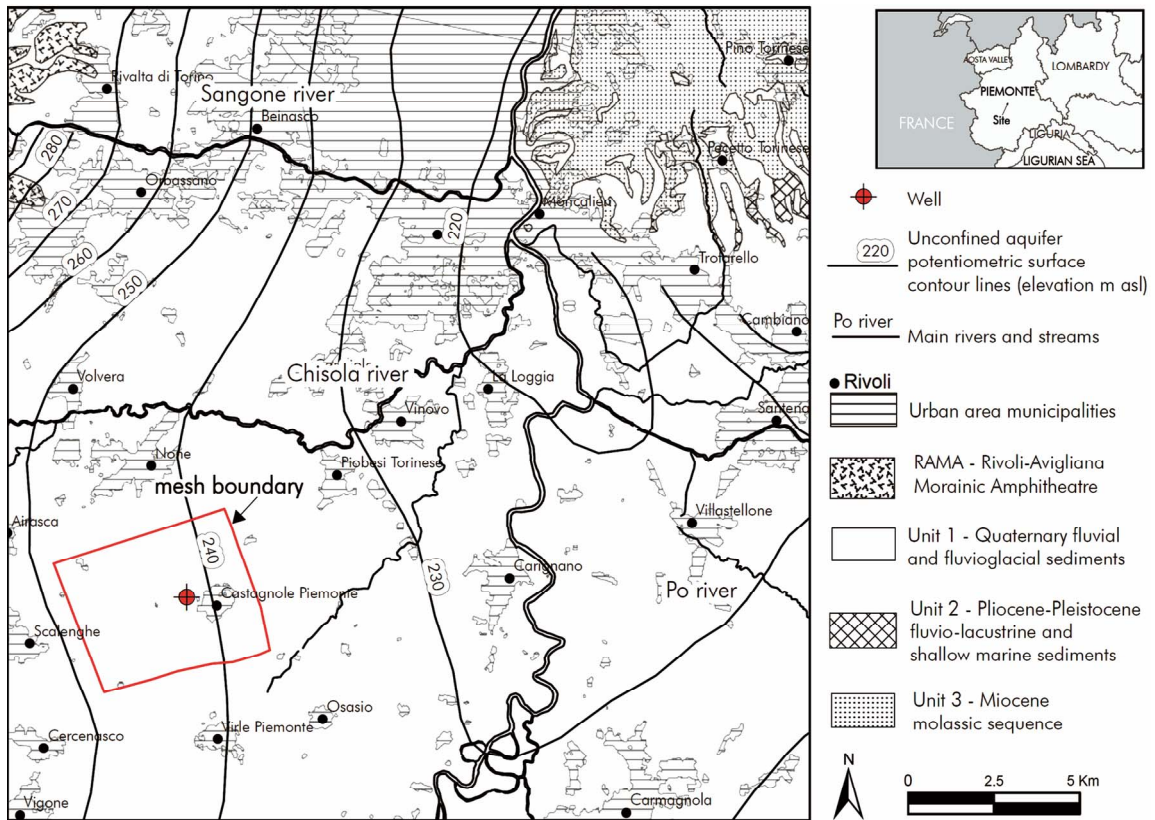
Figure 1. Hydrogeological map of the southern Turin area and location of the study site (modified after [50]).
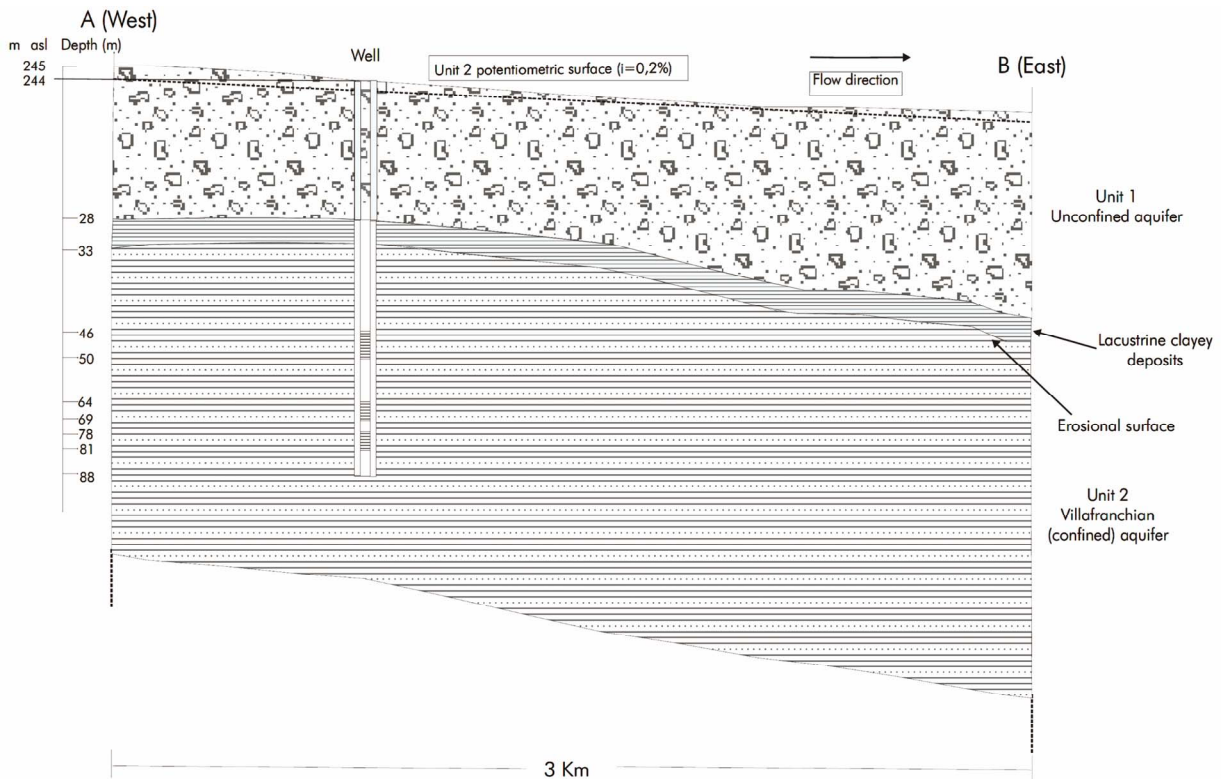

Figure 2. Schematic hydrogeological cross section of the study site (see Figure 3 for location). i: Gradient of confined aquifer potentiometric surface.

Unit 1—(Middle Pleistocene-Holocene; from the surface to a depth of 28 m). Continental alluvial cover is composed mainly of coarse gravel and sandy sediments (locally cemented) derived from alluvial fans aggraded by the Alpine rivers flowing downgradient to the east. At the base of the unit there are clayey lacustrine deposits (ca. 4 - 5 m thick) that extend over the entire area and act as a confining layer between Units 1 and 2. The base of Unit 1 (erosional surface) dips gently (0.5%) to the east and overlays Unit 2.

Unit 2—(Early Pliocene-Middle Pleistocene; from a depth of 33 m). Fluvio-lacustrine facies usually referred to as the "Villafranchian", consisting of fine-grained sediments (sand, silt and clay with interbedded gravel) divided into several sedimentary bodies. Other portions of the plain highlight the heteropic relationships with sediments originally deposited in a shallow marine environment and traditionally defined as Sabbie di Asti and/or Argille di Lugagnano. They are mainly composed of fossiliferous sand–clay layers with subordinate fine gravel and coarse, sandy marine layers, or by quartz-micaceous sands with no evidence of fossils. The top of Unit 2 has been eroded away and covered by the lacustrine facies and alluvial deposits of Unit 1.

2.4. Hydrodynamic Characterization of the Aquifers

In order to numerically model groundwater flow, an accurate characterization of the site's hydrogeological properties, groundwater flow direction and hydraulic gradient (the potentiometric surface), and the hydrodynamic properties (transmissivity, hydraulic conductivity, storage coefficient) is required. The unconfined aquifer that extends over the entire plain, including the study site location, is hydraulically connected to the main surface water drainage network (*i.e.* Chisola River and Po River). The potentiometric surface, 2 m below ground level, shows a W-to-E gradient of 0.2%. The saturated thickness of the unconfined aquifer at the site is about 26 m.

In order to characterize the hydrogeological properties of the aquifer in Unit 1, an appropriate step drawdown test was initially performed on a 30 m deep well located less than 1.5 km from the site. The test data yielded a transmissivity (T_1) of 7.3×10^{-3} m^2/s. The hydraulic conductivity ($K_1 = 3.65 \times 10^{-4}$ m/s) was calculated assuming an average saturated thickness of 20 m. On the basis of a constant-rate pumping test, the storativity (S_1) was assumed to be 0.20.

A confined aquifer system occurs in Unit 2. The available subsurface data indicate that the direction of groundwater flow and the potentiometric gradient (0.2%) in the Unit 2 aquifer system are similar to those in the unconfined aquifer of Unit 1. In the productive well the potentiometric surface of the confined aquifer stabilizes 31 m above the top of Unit 2, just 2 m below the ground's surface, which is roughly equivalent to the value measured in the overlaying Unit 1. The hydraulic transmissivity (T_2) of the Unit 2 aquifer system (7.52×10^{-3} m^2/s) was determined by means of a specific step-drawdown test in the studied well. The storativity (S_2) was calculated as 10.6×10^{-4}.

2.5. Modelling Study of the Aquifers

The modelling study was performed using the finite-element FEFLOW® package developed by Diersch [51]. A conceptual model with three layers was simulated using physical properties appropriate to the hydrogeology of the formation. Layer 1 represented the unconfined aquifer in Unit 1, Layer 2 corresponded to the 5 m thick impermeable clay layer at the base of this aquifer and Layer 3 represented the confined aquifer system of Unit 2. The distribution of the different layers in the model area was determined from topographic elevation data for the different geological units as listed in the regional authority database [49].

A plan view of the area covered by the computational grid (about 27.82 million m^2; 14,133 elements and 9800 nodes) is shown in **Figure 3**. The ground surface ranges from 253 m at the NW mesh vertex boundary to 240 m at the SE vertex. The horizontal dimensions of the model grid are 5238 m (SW-NE) and 4334 m (NW-SE). The average mesh spacing in the modelling domain is 70 m, which was refined to 8 m in the central area close to the well to provide enhanced estimation of potentiometric disturbed surface and the wellhead protection area isochrones. The north and south boundaries are set as no-flow boundaries. The east and west boundaries are constant-head boundaries (Dirichlet conditions). These levels were determined by initially calibrating the model against the steady-state groundwater heads obtained from a potentiometric surface map [50] and a specific survey of the area. An assumption of the model was that the system was closed to fluid flow at bottom (Layer 3 is set 200 m thick). The system has only recharge from rainfall and the ground surface is set as a prescribed flux boundary recharged by rainfall. An infiltration rate of 5.7×10^{-4} m/day is used in the model, which is equivalent to 25% [52] of the annual rainfall of 834 mm.

The simulations were run assuming steady-state conditions for groundwater flow. The withdrawal rate on the tested well (12 L/s) corresponds to the abstraction peak conditions. In reality, such conditions never actually occur because of variable (transient) water demand and the presence of a groundwater storage tank. Therefore, the actual impacts to the aquifer in terms of potentiometric surface changes due to well pumping will be less than
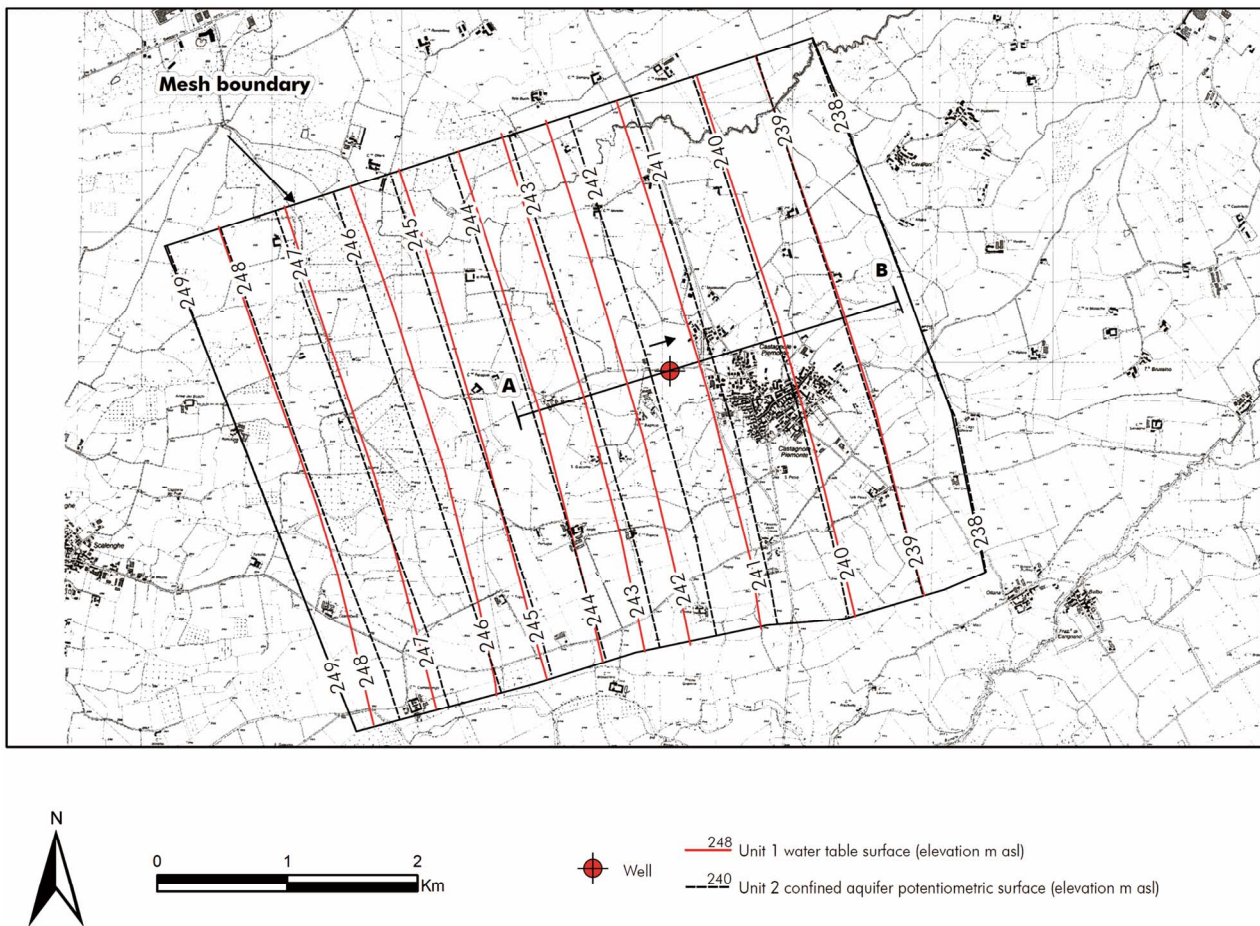
Figure 3. Plan view of the site and modelling domain overlain onto the topographical map. Potentiometric surface for the Unit 1 unconfined aquifer (continuous lines) and Unit 2 confined aquifer (dashed lines) under undisturbed conditions (in meters above mean sea level; m asl). Contour spacing: 1 m. Shown is the location of the cross section given in Figure 2.

those computed by the model. As a result, the WHPAs individuated by means of the calculated isochrones will be slightly overestimated and thus conservative relative to aquifer protection.

2.6. Aquifer Vulnerability and Soil Protection Capacity

Qualitatively, the unconfined aquifer accessed in Unit 1 is considered highly vulnerable to pollution because of its shallow depth and the direct connection with the surface water drainage network. The confined aquifer in Unit 2, on the other hand, is only moderately vulnerable to pollution, due both to depth (on average, the top of Unit 2 is situated at 30 - 35 m) and to several clay interlayers subdividing the formation. Only damaged or improperly constructed wells could introduce contaminants to this system of confined aquifers. To identify the suitable isochrone values delineating the WHPAs, aquifer vulnerability must be numerically defined. To achieve this, the modified GOD method [4] was selected as a

suitable method. In fact, more sophisticated vulnerability assessment methods such as DRASTIC or SINTACS are not suitable because they already include in the aquifer vulnerability assessment the soil parameters affecting the protection capacity. Therefore the required protection level identified by means of the procedure described in the **Table 2** could be erroneously evaluated. The GOD technique assigns numerical values between 0 and 1 to the Groundwater confinement level (*i.e.* G value), the lithological characteristics and the degree of consolidation of the vadose zone or confining layers (*i.e.* Overlying strata or O value) and depth to the groundwater table for unconfined aquifers, or to the strike for confined aquifers (*i.e.* Depth or D value). No soil parameter is considered. The resulting GOD value that identifies aquifer vulnerability is calculated by the multiplication of these three parameters. Due to the relative homogeneity of the aquifer over the entire modelling domain, the GOD value has been computed on the well vertical. At the test site, the Unit 2 aquifer has a G value of 0.2 (confined aquifer), an O value of 0.8 (alluvial and fluvio-glacial sands and

gravels) and a D value of 0.7 (depth of 20 - 50 m), resulting in a GOD value of 0.112, which indicates low vulnerability. Therefore, the OPZ can be identified by the 180-d isochrone.

The modelling domain overlays different soil units characterized by an appropriate level of protection against groundwater pollution. **Figure 4** and **Table 4** highlight the result of a GIS analysis of the soil units over the whole modelling domain.

3. Results and Discussion

The calculated WHPA for the test site is delineated in **Figure 5**. The 60-d isochrone (IPZ) covers about 4334
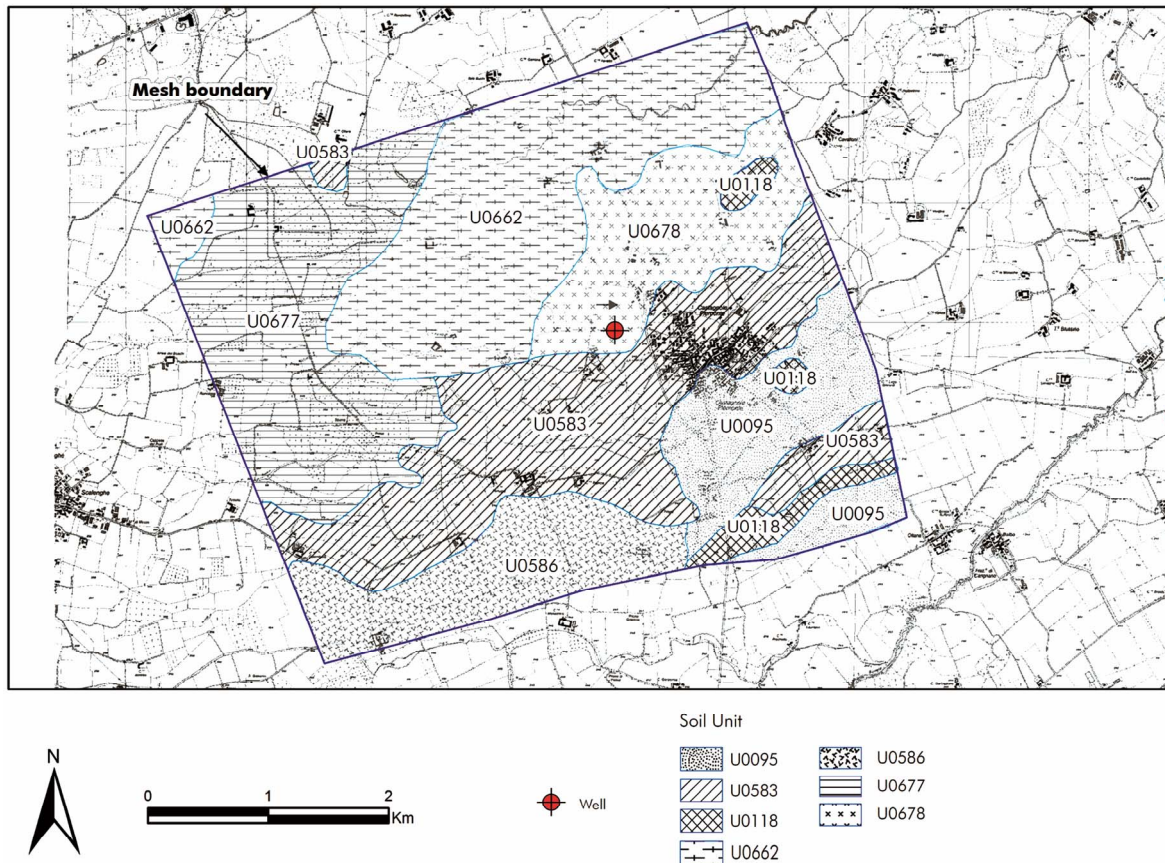
Figure 4. Soil units in the modelling domain (modified after [45]). See Table 4 for description.

Table 4. Soil units in the modelling domain and corresponding degree of soil protection capacity. (Simplified and modified after [45]).

| Soil unit	Soil classification	Area (m² and %) in the modelling domain	Soil protection capacity (related to groundwater pollution)
U0677	Typic endoaquept, coarse-loamy, mixed, nonacid, mesic	4,248,990 (15.3%)	Low
U0095	Dystric fluventic eutrudept, coarse-loamy, mixed, nonacid, mesic	8,439,617 (30.3%)	Very high
U0118	Psammentic haplustalf, coarse-loamy, mixed, nonacid, mesic	580,037 (2.1%)	Very high
U0583	Typic endoaquept, coarse-loamy, mixed, nonacid, mesic (70% UTS—Unit territorial surface) Aquic dystric eutrudept, coarse-loamy, mixed, nonacid, mesic (30%UTS)	5,149,067 (18.5%)	Medium
U0586	Dystric eutrudept, coarse-loamy, mixed, nonacid, mesic (60%UTS) Aquic dystric eutrudept, coarse-loamy, mixed, nonacid, mesic (40%UTS)	2,139,180 (7.7%)	Very high
U0662	Typic endoaquept, coarse-loamy, mixed, nonacid, mesic (70%UTS) Aeric endoaquept, coarse-loamy, mixed, nonacid, mesic (30%UTS)	4,996,325 (18.0%)	Medium
U0678	Fluventic dystrudept, coarse-loamy, mixed, acid, mesic	2,269,850 (8.2%)	Medium

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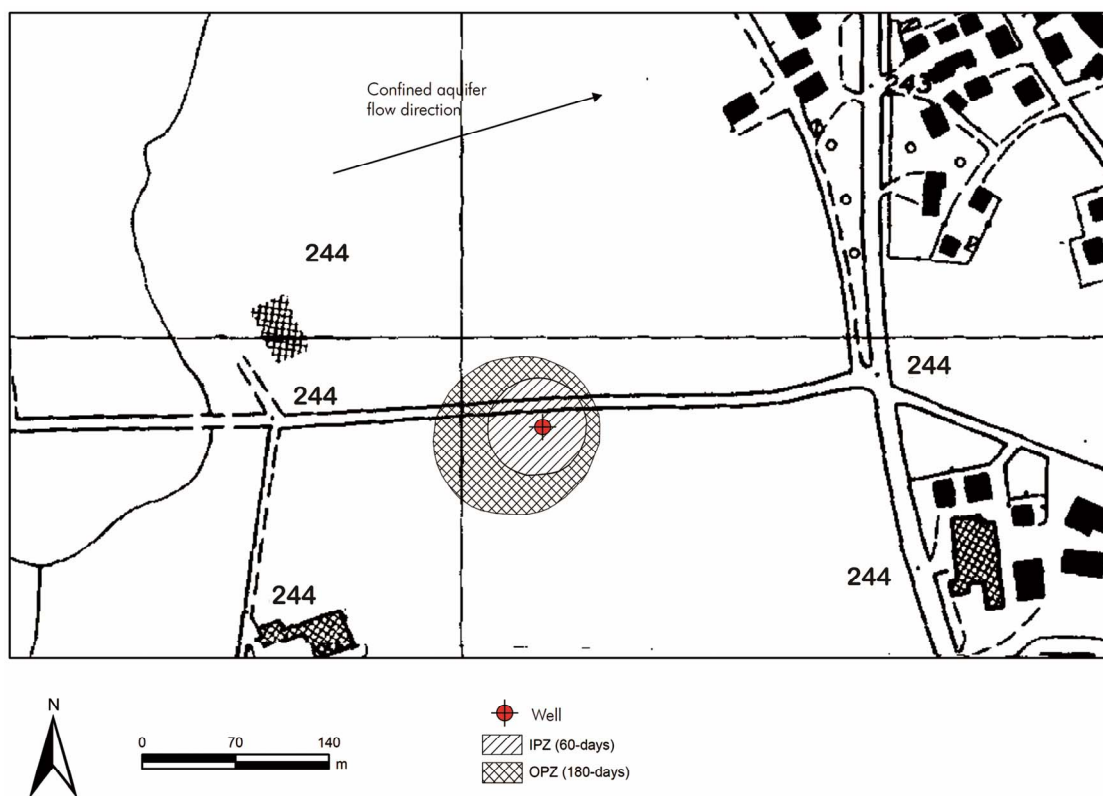
Figure 5. Wellhead protection areas identified by means of isochrones.

m^2, while the 180-d isochrone (OPZ) covers 11,734 m^2. Considering both the aquifer vulnerability (low) and the medium soil protection capacity of the soil unit overlaid by the WHPA (U0678), the corresponding level of protection was calculated as Level 3 (**Table 2**). Given this level of protection, certain restrictions on agricultural practices must be observed (**Table 3**). The calculated WHPA includes a minor road and therefore additional precautionary measures should be developed in order to prevent contaminant migration from the surface due both to accidental spills and infiltration of dust and water running off the road surface that might carry contaminants (e.g., petroleum hydrocarbons, metals). Safety measures applied along the motorway would include:

a) Using catchments and channelling to collect rain water that contacts the road surface, or any other fluid that is accidentally released;

b) Transport of collected fluids to monitoring basins and, after verifying the absence of contamination, sending those liquids for final disposal (water drains or streams). If contaminants are found to be present at concentrations exceeding established criteria, standards or benchmarks, the fluids will be sent to treatment plants;

c) The final destination of clean water should be outside, and downgradient, of the WHPA.

The specific measures that are instituted to safeguard the WHPA should be managed by the regional environ-mental authority in cooperation with the farmers, the water well managing company and the road maintenance company.

4. Conclusions

An effective and economically-sustainable land management strategy to protect subsurface water resources from anthropogenic pollution must combine general safe-guards applied to the whole aquifer recharge area with specific local land use restrictions in the proximity of the abstraction point (*i.e.* WHPAs). The first component, *i.e.* general protection strategies, can be derived through an extensive, broad-scale investigation, taking into account aquifer vulnerability, while data for the second component can be obtained using site-specific investigations within a narrowly-defined area proximal to the abstract-tion point. The importance of considering these two components in an integrated fashion cannot be under-stated. In particular, the selection of TOT for WHPA delineation is critically linked to the anticipated vulner-ability of the aquifer in question.

This study has highlighted a technical approach de-veloped in the Piemonte region, and designed to protect drinking water wells. An important aspect of this ap-proach was the integration of broad-scale aquifer vul-nerability assessment with localized WHPA delineation.

The method has been successfully tested on a community drinking water well and is both affordable and effective. However, for this method to be accepted for broad application, additional refinement is needed in certain areas. In particular, improved specifications should be provided to allow the user to more confidently select an appropriate aquifer vulnerability assessment method. The present version provides little guidance, leaving the selection to professional subjectivity and experience. However, current regulations combine the vulnerability level with soil protection capacity, thus discouraging the use of techniques that already compartmentalize soil parameters in the vulnerability assessment (e.g. DRASTIC and SINTACS). Given this constraint, only methods that consider aquifer parameters (*i.e.* GOD) seem suitable to evaluate vulnerability. Future iterations should simplify the procedure to individuate the necessary level of protection within the WHPA if soil protection capacity is directly included in the aquifer vulnerability assessment.

5. Acknowledgements

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