# Aquifer protection zones in urban areas (Rome, central Italy): from definition to monitoring

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**Abstract:** The expansion of large cities into the surrounding rural areas has changed the nature of land use within the catchment areas for groundwater sources (springs and wells). Such changes result in the protection areas for these sources now including many human activities that can cause serious groundwater pollution problems. In such circumstances adequate groundwater protection can be ensured by two methods:

- the transfer of these hazardous activities out of the protection zone;
- the monitoring of the groundwater quality and the implementation of an emergency plan in case of pollution.

It is frequently difficult to accomplish the first option and therefore the management of groundwater resources in urban and suburban areas depends on monitoring the sources threatened by human activities. In these cases, the protection zones are defined as "limited effectiveness". In multilayer aquifers (alluvial and volcanic deposits) the definition of these "limited effectiveness" protection zones is complicated by the hydrogeological setting and by the depths of the inflow sections in individual wells. The monitoring programme has to include both the extension of the protection area and the location and the depth of the piezometers, the time step of the monitoring (depending on flow velocity and distance from the source) and the determinands for analysis that are appropriate to the characteristics of the hazardous human activities included in the area. A case study of Grottaferrata, a suburb of Rome (Central Italy), is used to demonstrate these problems and suggests a methodology to guarantee groundwater quality over time.

**Résumé:** L'élargissement des grandes villes et de leur périphérie dans les dernières années, a déterminé l'inclusion de plusieurs sources et puits d'extraction de l'eau potable dans l'environnement urbain. Pour assurer une suffisante protection des eaux souterraines, l'existence de plusieurs activités humaines dans les surfaces de protection de sources, peut causer problèmes de pollution des eaux souterraines. Dans ce cas, il est possible d'assurer la bonne qualité des ressources en eau par l'use de deux différentes méthodes :

- le transfert des activités humaines dangereuses loin des zones de protection ;
- le monitorage de la qualité des eaux souterraines et la réalisation d'un plan d'émergence en cas de pollution.

Pourquoi la première possibilité n'est pas souvent possible d'adopter, le management des ressources souterrain dépend seulement du monitorage dans la zone de protection ; en ces conditions, la zone est dite « à efficace limitée ».

Dans les aquifères volcaniques et alluviales, la définition de ces zones de protection « à efficace limitée » est très difficile, par la situation hydrogéologique et la profondeur de puits.

Le model de monitorage doive établir non seulement la zone de protection, mais aussi la position et la profondeur des piézomètres, le temps du monitorage (dépendant de la vélocité de l'eau souterraine et de la distance de la source) et les analyses chimiques qui doivent être faites (dépendant des activités humaines dans la zone).

L'étude du cas de Grottaferrata, dans la zone métropolitaine de Rome (Italie Centrale), où ces problèmes ont été étudiés, a permis de proposer une méthodologie pour assurer la qualité des eaux potables dans le temps.

**Keywords:** environmental protection, groundwater contamination, hydrogeology, monitoring, regulations, water resources

## INTRODUCTION

Proper management of drinking water resources should respond to two basic requirements: maintaining good water quality and conserving groundwater resources (Foster *et al.* 2002, Ekmekci & Gunay 1997). The designation of groundwater protection areas across Italy has the purpose of defining the boundaries of the areas to be protected, imposing constraints on local water use and controlling local human activities, to ensuring long-term drinking water supply.

A key element in groundwater protection policies is the delineation of drinking water protection areas (Berg & Curry, 1999, Derouane & Dassargues 1998). The demarcation of "intermediate protection areas" is complicated by two factors: the option of or need for determining the extent of the intermediate area under different criteria (geometric, hydrogeological and temporal) and the presence of drinking water abstraction systems in urban areas.

 

It is worth stressing that, in the past few years, residential and industrial settlements in semi-urban areas surrounding megacities have grown at staggering rates (Foster *et al.* 1999), occupying previously green belts. As a result, many springs and wells used as "historical" drinking water sources have been totally incorporated into the urban fabric.

Land use constraints in intermediate areas do not automatically guarantee groundwater quality over time. It is necessary therefore to manage water abstraction systems by monitoring them spatially (siting of monitoring points), temporally (time interval of sampling and analysis) and, finally, analytically (physio-chemical and hydrogeochemical parameters to be analysed). Time-based criterion is the most suited to urban areas, since it is based on groundwater pathways and velocity. Under this criterion, the intermediate area is sized as a function of the time required for groundwater to flow over given distance (corresponding to the "safe travel time") so as to maximise the dilution of pollutants and undertake pollution control efforts.

The case study discussed in this paper concerns groundwater that has been exploited in the urbanized Grottaferrata Municipality near Rome, inside the Latium volcanic domain. In Rome's hinterland, which has become an integral part of the urbanised fabric, water availability depends on wells that were drilled some decades ago. At present, these water intake systems cannot be relocated because groundwater depletion and water use constraints prevent the drilling of new wells. The pollution hazards created by the urbanization of the catchment areas cannot be removed and therefore the only solution is to enhance the effectiveness of their intermediate protection areas.

These "limitedly effective" areas require the design and installation of on-line and/or off-line monitoring networks so that any anthropogenic alteration of groundwater quality can be detected before drinking water is delivered to users. This approach calls for in-depth analysis of the local hydrogeological setting, preparation of a physio-chemical monitoring protocol and, obviously, prediction of contingencies and cost-benefit analysis.

# GEOLOGICAL AND HYDROGEOLOGICAL SETTING

The Alban Hills District, southwest of Rome, is the southernmost of a range of alkaline-potassic volcanoes of Quaternary age, which extend along the Tyrrhenian coast of Latium. The evolution of volcanism in this area is related to extensional tectonic movements; in the Pleistocene, as a result of the opening of the Tyrrhenian basin, these movements affected the northern margin of the Apennine ridge (De Rita *et al.* 1995).

The activity of the Alban Hills started less than 600,000 years ago and ended about 20,000 years ago. This activity classified into three different stages (De Rita *et al.* 1988, De Rita *et al.* 1995). Over 90% of the total volume of volcanic products, mostly ignimbritic (> 280 km$^3$, De Rita *et al.* 1992), was erupted in the "Tuscolano-Artemisio" stage (0.6-0.3 Myr ago) that includes four eruptive cycles. Most of the activity took place in the central area, with subsequent collapse of its large caldera. From a hydrogeological viewpoint, the most interesting rock-types are the "Tufo Lionato" (cohesive ignimbrite) and the "Tufo di Villa Senni" (lithoid tuff), which have a very low permeability. At the end of the sequence, the central volcanic edifice collapsed, involving above all the central and eastern sectors of the old caldera.

After a short hiatus in volcanic activity, a new stage began. In this stage ("Faete" stage, 0.3-0.2 Myr ago), a new volcanic cone developed in the collapsed area, erupting a smaller volume of products (about 6 km$^3$) with a dominantly Strombolian style of eruption. Various lava effusions flowed out from the central sector of the volcanic edifice and some of them reached the suburbs of the present city of Rome. The end of the Faete activity caused the new volcanic cone to collapse, giving rise to the "Campi d'Annibale" caldera, which accommodated some debris fans (De Rita *et al.* 1995). The activity of the Alban Hills volcanic complex terminated with a series of phreatomagmatic explosions from eccentric craters in the western sector, with a total volume of erupted products of roughly 1 km$^3$ ("Hydromagmatic stage" 0.2-0.02 Myr ago).

The investigated area of the Grottaferrata Municipality (18.3 km$^2$) has outcrops area that may be ascribed to the closing stage of the Tuscolano-Artemisio volcanic complex, to the "Faete" stage and to the final hydromagmatic stage. Recent alluvia are sporadically encountered in the lowermost areas. Wells drilled into the subsoil of the extracalderic and pericalderic sector encountered the oldest strata from the "Tuscolano-Artemisio" stage.

At regional scale, the Alban Hills volcanic district is regarded as a hydrogeological system whose outer boundaries consist of terrains of lower relative permeability. Its morphological, structural and stratigraphic features favour the existence of a multi-layer aquifer, whose water mostly circulates at depth, in a radial direction from the extracalderic sector towards the boundaries of the volcanic edifice (Figure 1). The aquifer, supported at its base by terrigenous deposits of Neogene-Quaternary age, hosts the deep regional groundwater that feeds most of the perennial streams originating from the piedmont of the volcano (Boni *et al.* 1995). The calderic sector, where the thickest volcanic deposits are located, comprises a multi-layer aquifer with considerable potential discharge. In the past, these aquifer layers supplied intracalderic springs and Albano and Nemi lakes with an overall discharge of roughly 0.5 m$^3$/s (Boni *et al.*, 1995). Groundwater mining has depleted and in some causes exhausted this groundwater flow, bringing about the near-total disappearance of springs and significantly contributing to the lowering of lake water levels (Capelli *et al.*, 2005).

Hydrological balance studies (Boni *et al.* 1986, Boni *et al.* 1995, Capelli *et al.* 2000, Capelli *et al.* 2005) agree on the fact that the volcanic aquifer is only recharged via rainwater infiltration, confirming the no-flow boundaries of the system. As a result of its morphology, the intracalderic area is a high-seepage zone and thus the preferential recharge zone of the entire system.

The potential discharge of the Alban Hills hydrogeological system was assessed by directly measuring the overall discharge from all the springs that the system feeds and by estimating public withdrawals of groundwater. During the period 1978-1979, Boni *et al.* (1986) measured the flow as 15.9 m$^3$/s and during the particularly dry 1981-1982 period, recorded it as 10 $m^3$/s. Based on average yearly values of precipitation and temperature from 1921 to 1989, Boni *et al.* (1995) calculated an average net recharge of 285 mm/year, corresponding to an average potential discharge by the system of 13.6 $m^3$/s. More than one third of the total discharge feeds the streams running in the southern sector (Boni *et al.* 1995) with the highest in-stream inputs observed at the points of intersection between the streams and the ancient products of the "Tuscolano-Artemisio" stage (De Rita *et al.* 1992).

The drainage area of the Alban Hills hydrogeological unit consists of 26 basins, 17 of which are perennial and supplied by the regional basal aquifer (Capelli *et al.* 2005). The comparison of cumulated low-flow discharges measured in 1978-82 with those of 1998 shows a sharp drop (50%) in the basal flow of perennial streams (Capelli *et al.* 2000).

Various authors reconstructed the geometry of the Alban Hills regional aquifer, drawing up regional piezometric maps. Groundwater flow has a radial pattern in the extracalderic sector (Boni *et al.* 1986, Capelli *et al.* 2005). For the calderic sector, Capelli *et al.* (2000) hypothesised that Alban and Nemi lakes would be supplied by a perched aquifer with piezometric levels reaching 450 m in the central calderic sector. As the depth of Albano Lake is 175 m (corresponding to 120 m above sea level), the lake also intercepts the deep regional aquifer, whose piezometric level in the outer pericalderic area reaches 250-200 m. Capelli *et al.* (2005) confirmed the existence of an upper aquifer, sustained by the low-permeability sequence corresponding to the "Tufo lionato" and "Tufo di Villa Senni" deposits, and of a lower aquifer within the volcanic sequence.

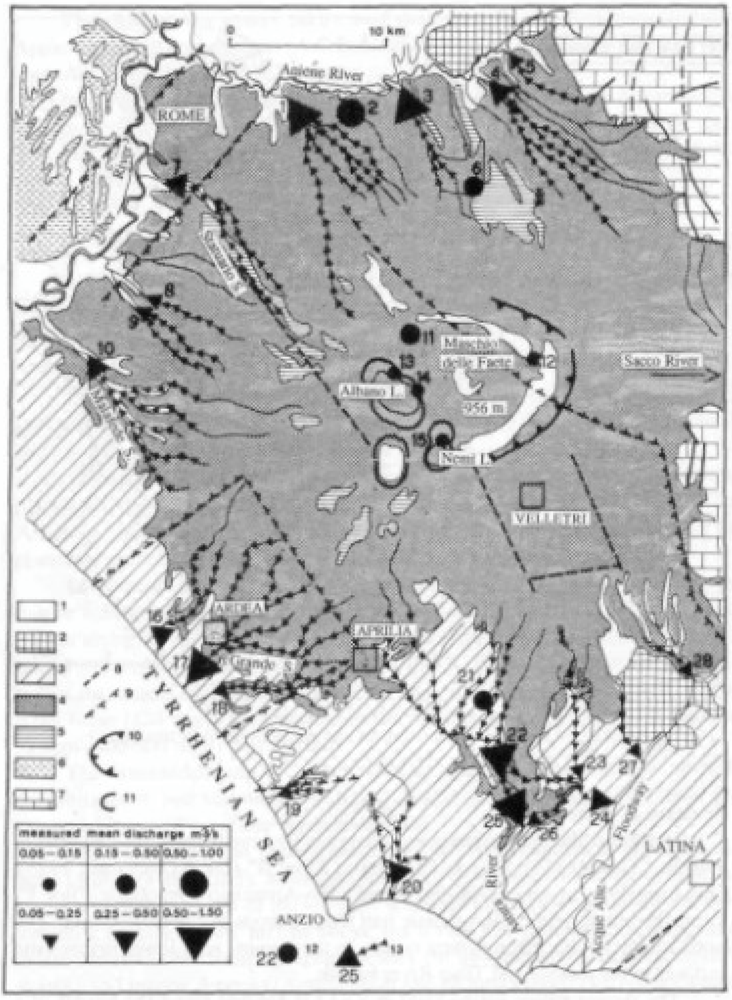


**Figure 1.** Hydrogeological map of the Alban Hills hydrogeological system (from Boni *et al.* 1995). Legend: 1- recent alluvial deposits; 2- travertines; 3- coastal deposits; 4- ignimbrites; 5- lavas deposits; 6- Northern Latium volcanic deposits; 7- carbonate deposits; 8- faults; 9- direct faults; 10- main old collapsed caldera; 11- minor calderas; 12- main springs; 13-main linear springs (directly discharge into stream).

# INVESTIGATIONS

Investigations were aimed at giving a hydrogeological interpretation of the local geological structural setting, using a 1:5,000 geological map and more than 60 logs for existing wells. An interpretation of the borehole logs using the hydrogeological characteristics of the deposits allowed the three-dimensional distribution of the different volcanic rocks to be completed. The identification of the "Tufo lionato" and "Tufo di Villa Senni" horizons was given priority as they separate deep groundwater circulation from shallow water circulation throughout the Alban Hills area (Capelli *et al.* 2005).

Hydrogeological surveys were focused on identification of the different aquifer layers. Out of the 250 wells in the investigated area, 86 wells (including those used for drinking water supply by the Grottaferrata Municipality) were surveyed, measuring their static water level, collecting water samples for chemical analysis and measuring physio-chemical parameters (pH, conductivity and temperature).

Eighteen chemical analyses were carried out on samples collected from wells, where also the main physio-chemical parameters of waters (temperature, pH and conductivity) were on-site measured. During December 2002, samples from nine wells, of which six are connected to the municipal aqueduct, were collected and analysed. The second sampling survey (June 2004) involved a further (private) nine wells. Water samples were analysed in the geochemical laboratory of the Earth Science Department of "La Sapienza" University of Rome, in order to determine the concentrations of the main cations ($Ca^{++}$, $Mg^{++}$, $Na^{+}$, $K^{+}$, $NH_4^{+}$, $Li^{+}$) and anions ($Cl^{-}$, $SO_4^{=}$, $HCO_3^{-}$, $F^{-}$, $NO_2$, $NO_3$). Use was made of the liquid-phase ion chromatography method, except for $HCO_3^{-}$, where hydrochloric acid titration was employed.

Seasonal fluctuations were assessed by monitoring the hourly static and pumping water level in a well for one year (September 2003-August 2004). Measurements were recorded using a pressure transducer with built-in data logger, capable of storing the values measured over time and of operating unattended. The hydrodynamic parameters of aquifers were assessed on the basis of the results of four pumping tests that had been previously carried out by municipal authorities and owners of private wells.

## RESULTS

Three different aquifers were identified in the Municipal Territory from the interpreting of the data collected from the study as follows:

- lower regional aquifer;
- upper regional aquifer;
- perched local aquifer (Colle delle Ginestre – Poggio Tulliano).

The first two are regional-scale aquifers extending well beyond the administrative boundaries of the Municipality. The third is a more limited aquifer located in the most elevated urban area of Grottaferrata and with a low potential discharge is not being intensively exploited. Shallow aquifers of limited extent were also found in fluvio-lacustrine or alluvial deposits, but their productivity is extremely poor.

Figure 2 displays the piezometric surface of the two identified regional aquifers. The blue lines denote the piezometric curves of the lower regional aquifer, while the red ones correspond to the piezometric curves of the upper regional aquifer.

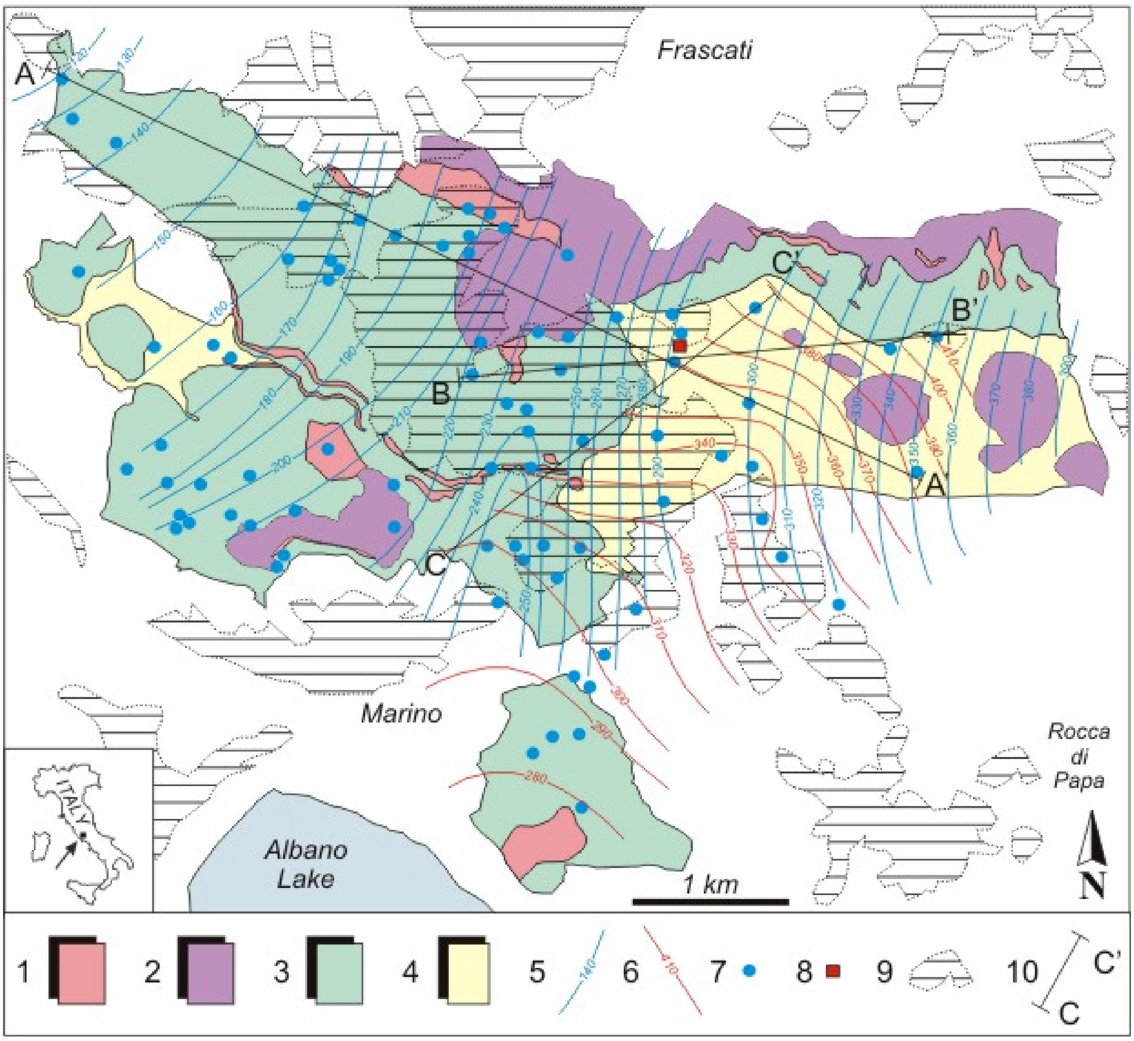


**Figure 2.** Hydrogeological map of Grottaferrata municipality area. 1- fissured leucititic lava and lithoid tuff (medium-high permeability); 2- scoria cones and welded scorias (medium-high permeability); 3- lapillistone and tuff (medium permeability); 4- cinerites, alluvium and swamp deposit (low permeability); 5- isopiezometric line of lower aquifer (m asl); 6- isopiezometric line of upper aquifer (m asl); 7- water well; 8- well used to establish the aquifer protection criteria (Bivio Tuscolo well); 9- urban area; 10- line of hydrogeological section (see Figures 3, 4 and 5).

Piezometric lines evidence two groundwater flows that remain independent in the investigated area. The shallower flow (red piezometric lines) has a dominant NE-SW direction towards Albano Lake. The reconstructed piezometric surface falls, with an average gradient of 3.1%, from about 410 m a.s.l. to a level of 280 m a.s.l. that corresponds with the water surface of Albano Lake. This flow from the upper regional aquifer feeds the lake that, in the investigated areas, is underlain by the "Faete" stage deposits.

The deeper groundwater circulation (blue piezometric curves) has an E-W direction in the eastern sector and a SE-NW direction to the west. In the eastern sector, the lower groundwater level falls from 390 m asl to 250 m a.s.l. (average gradient: 3.7%), always lying below the upper groundwater saturation level by at least 30 m. In the western sector, the reconstructed piezometric surface decreases from 250 m a.s.l. to 120 m a.s.l. with an average gradient of 3.2%.

In common with the overall Alban Hills hydrogeological system, the investigated area comprises a multi-layer aquifer. In multi-layer aquifers, groundwater vulnerability and possible water quality deterioration decreases with groundwater depth.

Consequently, in the investigated area, the following zones may be distinguished (Figure 2):

- the more elevated eastern zone, corresponding to the calderas and whose outcrops dominantly consist of the most recent volcanic rocks; this sector is marked by the coexistence of two groundwater flows, corresponding to two hydraulically separate aquifer layers;
- the topographically more depressed western zone, corresponding to the area outside the calderas and whose outcrops dominantly consist of the most ancient volcanic deposits (last "Tuscolano-Artemisio" stage). A single groundwater flow that is in hydraulic continuity with the deep groundwater flow in the eastern zone, was identified in this sector.

The piezometric surface of the local aquifer of Colle delle Ginestre – Poggio Tulliano could not be reconstructed owing to the limited extent of the aquifer although its groundwater levels are intermediate between the upper and lower regional groundwater systems.

To gain greater insight into the deep hydrogeological setting, three representative hydrogeological sections were reconstructed. Detailed stratigraphic data made it possible to identify the individual eruptive stages of the Alban Hills volcanic activity, as well as the aquiclude consisting of the "Tufo lionato" and "Tufo di Villa Senni" formations belonging to 4$^{th}$ "Tuscolano-Artemisio" stage. The aquiclude formed by these tuffs is only significant in the area outside the calderas. Inside the "Tuscolano-Artemisio" belt, the collapse of the caldera gave rise to extensional faults down-throwing the previous sequences of the "Fase delle Faete" stage in a step-wise fashion (De Rita *et al.* 1988, Capelli *et al.* 2005). The aquiclude lies at greater depth towards the centre of the caldera and is not generally reached by water wells.

Section A-A' (Figure 3) shows the differences between the caldera area and the area beyond. The western sector accommodates a single deep aquifer, underlying the aquiclude that sporadically outcrops. In eastern sector of the section (caldera area), two overlapping piezometric surfaces are clearly visible: the deeper one extends westwards, while the shallower one appears to be laterally limited by sudden rise in elevation of the aquiclude. Section B-B' (Figure 4) shows that the aquiclude represents the hydraulic lateral limit of the upper aquifer; the section also displays the perched aquifer of Colle delle Ginestre (wells with green dots). In section C-C' (Figure 5), the aquiclude is relatively deep.  As a result, the upper groundwater flows are unobstructed to the southwest and contribute to the recharge of Albano Lake.

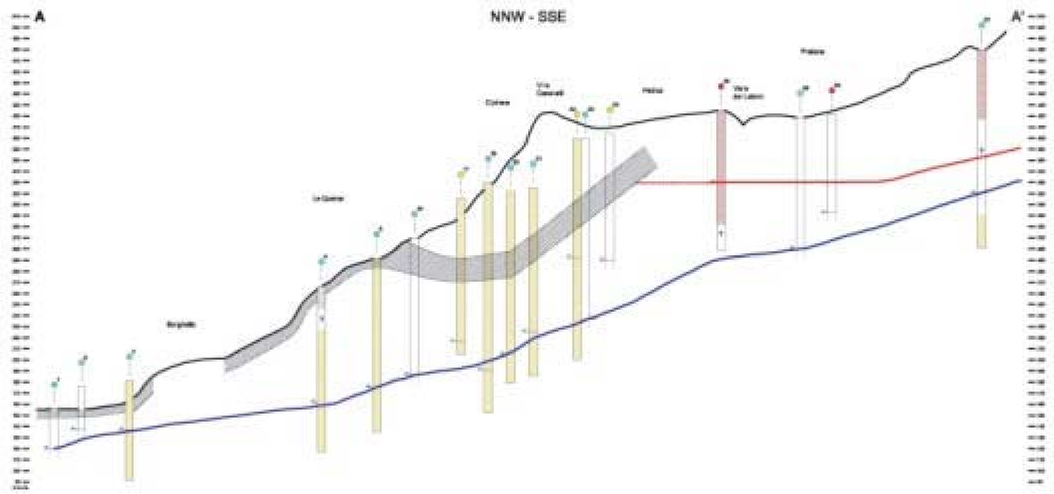


**Figure 3.** Hydrogeological section A-A' (see Figure 2 for location). Red line represents the upper regional aquifer potentiometric line; blue line represents the lower regional aquifer potentiometric line. Red and blue dots show location of the wells intercepting the upper and/or lower aquifer. Yellow dots show wells with piezometric levels not connected with known aquifers. Grey areas correspond to aquiclude layers.

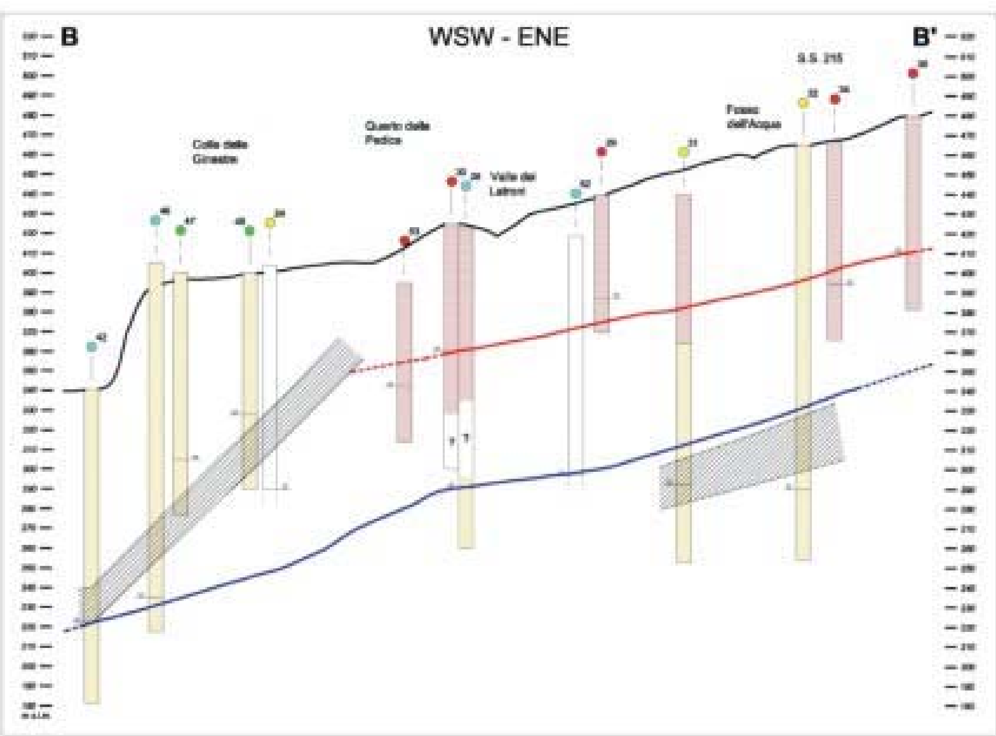


**Figure 4.** Hydrogeological section B-B' (see Figure 2 for location). Red line represents the upper regional aquifer potentiometric line; blue line represents the lower regional aquifer potentiometric line. Red and blue dots show location of the wells intercepting the upper and/or lower aquifer. Green dots show wells of the perched aquifer. Yellow dots show wells with piezometric levels not connected with known aquifers. Grey areas correspond to aquiclude layers.

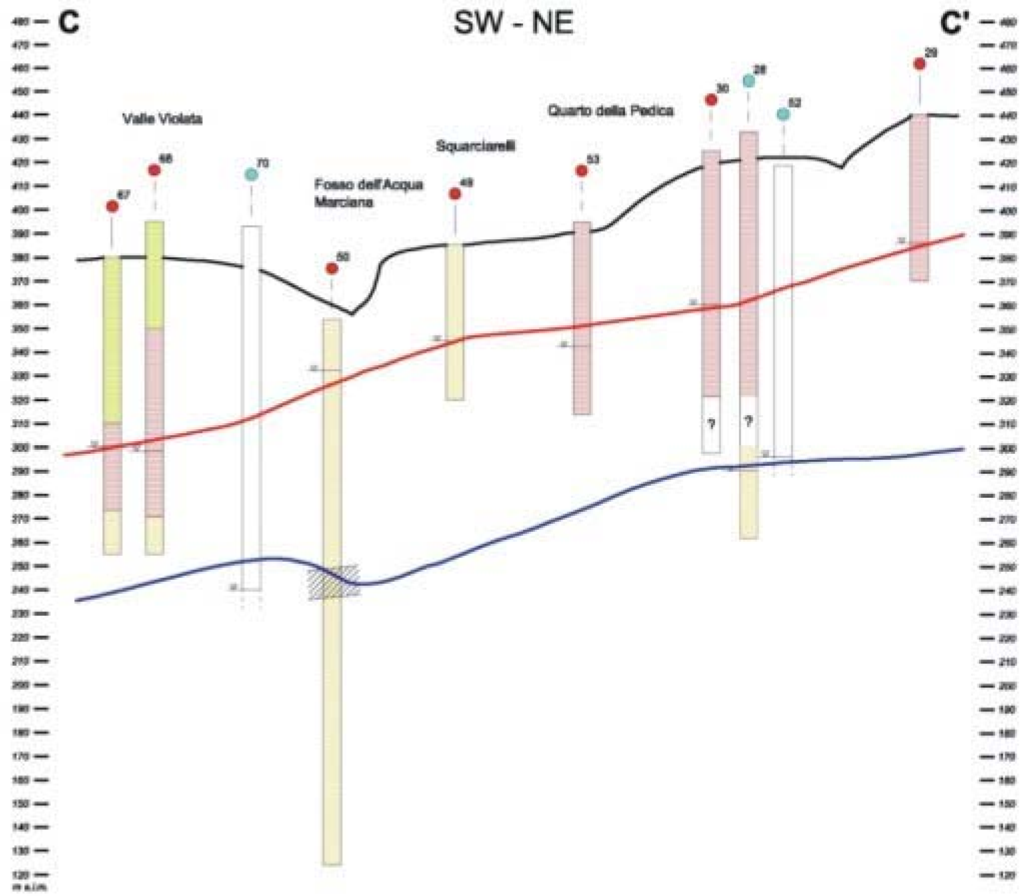


**Figure 5.** Hydrogeological section C-C' (see Figure 2 for location). Red line represents the upper regional aquifer potentiometric line; blue line represents the lower regional aquifer potentiometric line. Red and blue dots show location of the wells intercepting the upper and/or lower aquifer. Grey areas correspond to aquiclude layers.

The complexities of a multi-layer aquifer system that is in possible hydraulic continuity over a limited area, makes the choice of the right conservation criteria difficult. The deeper wells intercept the various aquifer horizons and therefore provide a potential hydraulic connection between the intercepted layers. These vertical hydraulic links allow poor quality waters from upper aquifers to mix with waters from deeper aquifers, which are considered to be of high quality and are suitable for human consumption.

The results of physio-chemical analyses on water samples (collected from 18 wells in the Municipal Territory) validate the proposed groundwater circulation model. Most of the analysed waters may be classified as calcium-bicarbonate, tending to bicarbonate-alkaline: three samples only (2, 20 and 13) fall under the bicarbonate-alkaline class (Figure 6). Within this classification, a few samples are enriched in sulphates and chlorides, while the remaining ones have more or less the same bicarbonate content.

The $SO_4^{=}$/TDS diagram (Figure 7) exhibits two different groundwater types, referred to the evolution of the lower regional aquifer. The first type includes waters from the deep regional aquifer (outside the caldera area), which are markedly enriched in $SO_4^{=}$. The second type corresponds to wells whose waters are less enriched in sulphates and which intercept the deep aquifer (caldera area). The wells intercepting the upper aquifer (red dots) and the perched alluvial aquifer (pink dot) have extremely high $SO_4^{=}$ content but do not fall within these two types.

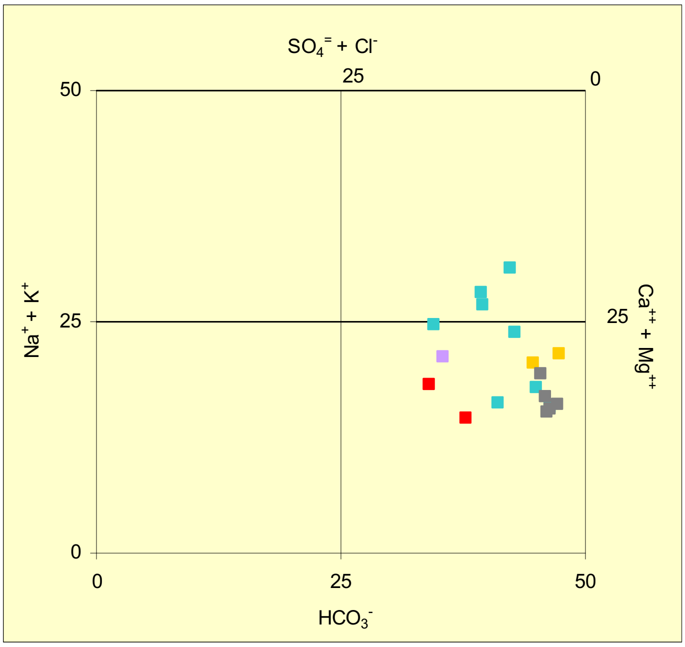


**Figure 6.** Reaction diagram of sampled waters. Blue dots: waters from lower regional aquifer; red dots: waters from upper regional aquifer; grey dots: waters coming from well of unknown aquifer; yellow dots: waters from local aquifer; pink dot: water from alluvial aquifer.

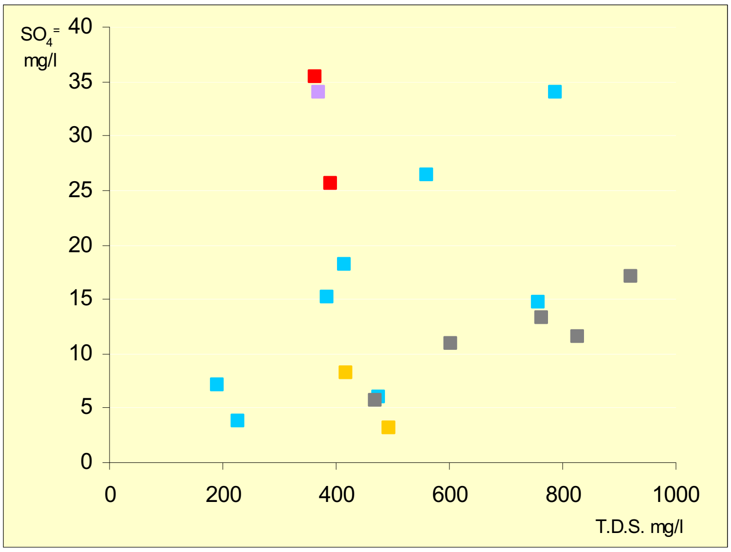


**Figure 7.** $SO_4^{=}$ vs. TDS diagram. Blue dots: waters from lower regional aquifer; red dots: waters from upper regional aquifer; grey dots: waters coming from well of unknown aquifer; yellow dots: waters from local aquifer; pink dot: water from alluvial aquifer.

The two hydrogeochemical water types are also seen, albeit less clearly, in the $Na^+$+$K^+$/TDS comparative diagram (Figure 8); here, samples from the eastern area outside the caldera are more enriched in alkaline ions than those taken from the caldera area.

As enrichment in $SO_4^=$ and alkaline ions characterises deep groundwater circulation, it may be assumed that, in the eastern sector, waters from the lower regional aquifer become mixed with those from the upper regional aquifer. Conversely, in the area outside the caldera, the higher enrichment noted in the samples from the lower regional aquifer suggests that little if any mixing is taking place.

The hydrogeochemical interpretation supports the distribution of the aquifers described above comprising two separate aquifer layers in the caldera area. The possible exchange of waters from the upper aquifer towards the lower one may be caused both by the natural phenomenon of vertical leakage and by flow along deep private wells that intercept both aquifers and permit indiscriminate water mixing.

Static and dynamic water levels were monitored in a well drilled into the lower regional aquifer (Figure 9). Groundwater level rose by 2.65 m from September to the end of June and subsequently diminished in summer months. One year later, the water level fluctuation (September 2003-September 2004) was equal to + 2.10 m. The recorded sharp decreases in water level are due to pumping by the owner of the well used for monitoring.

It is worth pointing out that the monitored aquifer reflects a double recharge: direct recharge by rainwater infiltration (responsible of the observed seasonal fluctuations) and lateral underground recharge by the regional groundwater of the Alban Hills (based on the recorded time lag with respect to the rainy season).

Finally, previous monitoring tests indicated the following transmissivity value range for the deep aquifer: 1-3 x $10^{-3}$ $m^2/s$.

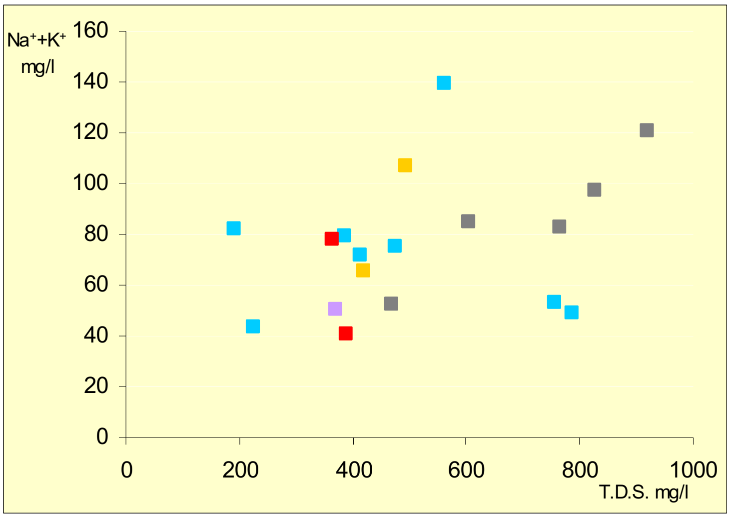


**Figure 8.** $Na^+$+$K^+$ vs. TDS diagram. Blue dots: waters from lower regional aquifer; red dots: waters from upper regional aquifer; grey dots: waters coming from well of not known aquifer; yellow dots: waters from local aquifer; pink dot: water from alluvial aquifer.

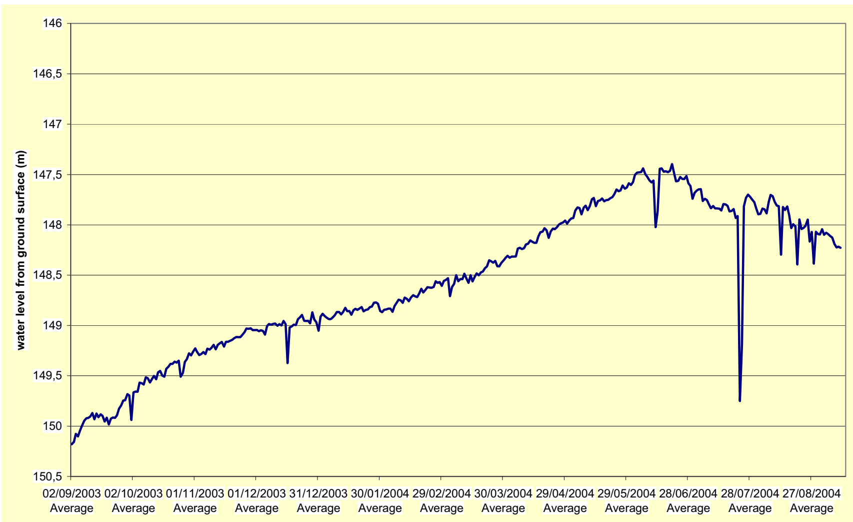


**Figure 9.** Groundwater level of the lower regional aquifer, monitored in a single private well. Sharp daily variations indicate pumping; positive daily variations indicate recharge from precipitation; long-term regimen indicates lateral recharge from the regional aquifer of Albani Hills.

# ASSESSMENT OF THE GROUNDWATER RESOURCE

As the identified aquifers extend well beyond the administrative boundaries of the Grottaferrata Municipality, water balance and budget computations should be made over this larger area.

Capelli *et al.* (2005) made a water balance and budget assessment on the hydrographic basin scale. They identified that the maximum available groundwater to ensure hydrological equilibrium is some 1.5 $m^3$/s, a value that is less than the total abstraction actually withdrawn from aquifers (1.85 $m^3$/s). The current deficit of over 0.35 $m^3$/s is thought to be exhausting the renewable water resources and to be depleting the permanent water reserves. This over abstraction is thought to be causing the gradual lowering of the Albano Lake water level by about 40 cm per year. These considerations have led to the adoption of specific conservation rules for the Alban Hills sector (Regione Lazio, 2004). The assessment of water availability in the Grottaferrata Municipality is broadly similar, pointing to a water deficit in the entire hydrogeological basin of which Grottaferrata is part.

The average groundwater discharge from the part of the lower regional aquifer that corresponds to the Grottaferrata Municipality was calculated on a preliminary basis by using the Darcy equation in the form Q = T L i, where:

- Q: discharge in $m^3$/s
- T: transmissivity in $m^2$/s = 1.4 x $10^{-3}$ $m^2$/s (average of available values)
- L: length of groundwater front in km = 3 km (perpendicularly to the direction of flow)
- i: hydraulic gradient (3.5 %, average of measured gradients).

This calculation suggests that the available discharge for the lower regional aquifer amounts to roughly 0.15 $m^3$/s. The contribution from the other aquifers is considered to be significantly less than the lower regional aquifer and in the absence of data the potential discharge is assumed to be in the range of about 0.005 $m^3$/s.

The present abstraction via the aqueducts is 0.5 $m^3$/s. In addition there are some 250 private wells, mostly used for irrigation, with an estimated combined abstraction of 0.5 l/s and gives a total abstraction of 0.125 $m^3$/s. Although grossly approximated, these figures suggest that the average groundwater withdrawal in the Municipality is at least equal to 0.275 $m^3$/s and gives rise to an average water supply deficit of over 0.1 $m^3$/s.

Some of the private wells were drilled into the upper regional aquifer, which also has a limited recharge. The consequences of this abstraction are progressively falling groundwater levels reduced water availability. Moreover, as this aquifer supplies both Albano Lake and its neighbouring area, its exploitation in the territory of the Municipality indirectly decreases the flows to the lake area.

The fact the lower regional aquifer is recharged from outside the municipal territory does not justify massive abstraction for both drinking water supplies and to an increasing extent by private wells for irrigation. Indeed, withdrawals from this deep aquifer are increasing caused by pressure on the dwindling supplies from the upper regional aquifer, and also by the unavailability or poor productivity of local shallower aquifers. The end result in terms of available water resources is a deficit: the upper regional aquifer is certainly being overexploited, while the lower regional aquifer, albeit not seriously threatened, is being exploited beyond the rate that is sustainable within the municipal territory. Stringent measures are therefore needed to adequately protect presently available water resources.

# WATER RESOURCE PROTECTION IN URBAN AREAS

The designation of drinking water protection areas was introduced into the Italian legislation by the Decree of the President of the Republic no. 236/88, subsequently revised by Legislative Decree no. 152 of 11 May 1999, as amended by Legislative Decree no. 258 of 18 August 2000. Protection areas are divided into absolute protection areas (where all activities are banned), intermediate areas (where activities are regulated) and enlarged protection areas (corresponding to the catchment of the water system or intake).

The delineation of *"intermediate protection areas"* is the most problematic, since it uses different criteria: geometrical (distance from the water system or intake), hydrogeological (based on the characteristics of the aquifer and hardly applicable), time-related (the choice of the size of the area depends the time required for groundwater to cover a given distance ("safe travel time"). With regard to the latter criterion, a sufficiently long travel time facilitates dilution, dispersion or removal of pollutants (Derouane & Dassargues 1998). A pre-requisite for correct sizing of the intermediate area is the assessment of the safe travel time, calculated by considering only the distance that groundwater pollutants travel in the groundwater flow. In areas undergoing urbanisation and where water abstraction systems have been surrounded by hazardous human activities (Vazquez-Sune & Sanchez-Vila, 1999), pollutants can be controlled only in the medium-long term and with specific measures. The intermediate area may have unavoidable hazards, which is conflict with the applicable legislation.

In the case under review, almost all of the wells of the Grottaferrata municipal aqueduct represent a major issue in terms of enforcement of the legislation. In effect, these wells are mostly located in the urban centre, making aquifer protection hardly practicable, unless considerable social and economic costs are incurred. Under the legislation, if water systems or intakes from urban aquifers are located in protection areas with hazardous activities that cannot be relocated and if such hazardous activities, despite all efforts, cannot operate under safety & security conditions, they should no longer be used. For managing these systems, delineation of protection areas is always necessary but the mere existence of intermediate areas around the wells and related constraints do not guarantee the quality of groundwater over time. These are the so-called "limitedly effective intermediate areas", which require "dynamic" protection measures, i.e. monitoring water quality via adequate surveillance networks. Such networks should have the following main features:

- sampling and analysis at short intervals;
- reliance on contingency plan in the event of pollution;
- where feasible, interconnection of the water distribution system with other water supply sources.

To determine the applicability of the methods specified in the legislation to a particular situation, such as the one of "urban aquifers", an assessment was made of the protection area of the "Bivio Tuscolo well" (red well in Figure 2) water system (withdrawing over 25% of the municipal drinking water resources) and its possible intermediate area was defined. The investigated well, like most of those used by the Municipality, intercepts both the lower and upper aquifers and interconnects the two groundwaters. More significantly however, the regional aquiclude is missing in this area (Figures 3 and 4) and does not separate the two aquifers. As a result the lower aquifer is not protected by the upper one and is susceptible to pollution.

Based on analyses of geological and stratigraphic data and on results of hydrogeological and hydrochemical investigations, the aquifer that is exploited by the investigated well may be regarded as a semi-confined aquifer. This means that the aquifer is partly protected from surface contamination by the overlying geological formations that have a relatively low permeability compared with that of the aquifer. However, as these geological formations are not continuous, they do not isolate the upper aquifer and permit the seepage of a significant amount of water. Given the great depth of the static water level, the aquifer can be regarded as semi-protected, thus requiring an adequately sized protection area.

Furthermore, as the intercepted aquifer is laterally recharged at depth by the regional groundwater of the Alban Hills, its water may be contaminated by pollutants released in the upstream area. Putting in place a monitoring network would therefore be useful, if not essential.

In this instance, the application of the time-related criterion to the investigated well should take into account that the groundwater has its own motion (well drilled into an inclined aquifer); therefore, a uniform flow overlapping a radial flow causes the deformation of the flow net (Figure 10).

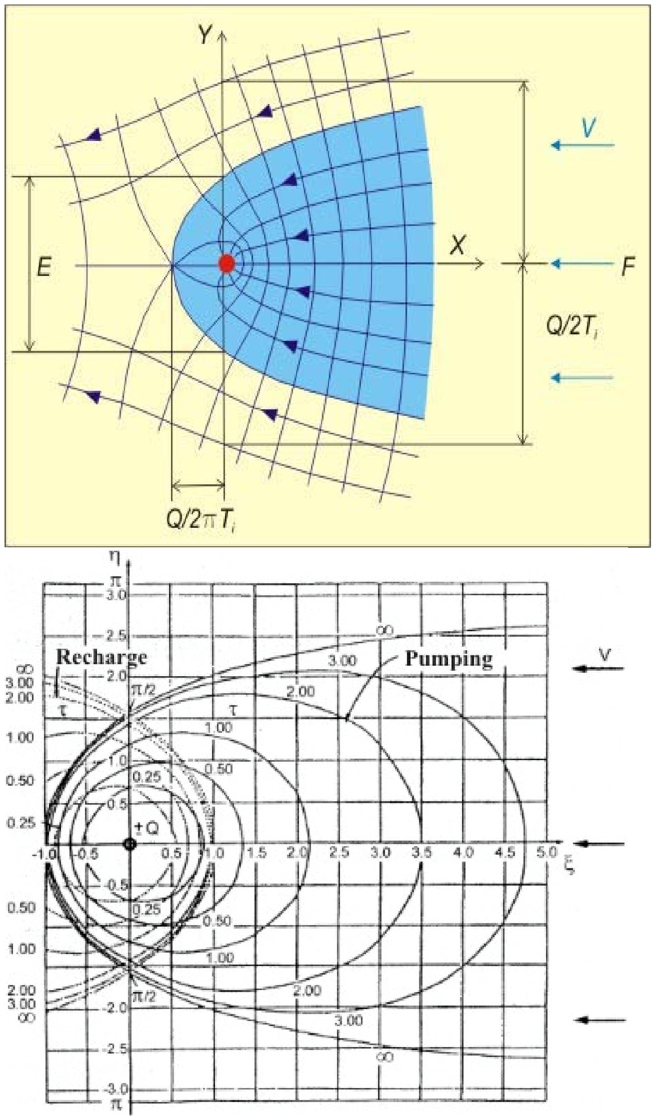


**Figure 10.** At the top: Flow net for wells in inclined aquifer (redrawn from Francani & Civita, 1988). At the bottom: diagram to calculate arrival time for wells in inclined aquifer (from Bear, 1979).

The influence of pumping propagates downstream as far as stagnation point A with coordinates (xs, 0) and upstream to the flow lines that are included in the width F of the recharge front. In these cases, by orienting the reference system with axis x along the flow line passing through the well (preferential flow line), the abacus of Figure 10 (Bear 1979) may be used to identify the transit time. As the groundwater has its own motion, knowing its Darcy flow velocity is essential to compute the parameters to be entered into the abacus. This process is based on prior identification of the curve τ on the abacus (Figure 10) to be assigned to a given safe travel time. After reconstructing the locus of the points of equal travel time, the values of the corresponding planar coordinates Xi, Yi may be derived (Bear 1979) and the combination of these coordinates gives the perimeter of the intermediate areas.

The data used for the computation and related assumptions are reported below:

- "Bivio Tuscolo" well (coordinates 0,0);
- discharge withdrawn: Q=0.025 $m^3/s$;
- aquifer thickness: 70 m;
- transmissivity value used: 2.6 x $10^{-3}$ $m^2/s$ from which K=T/h=3.8 x$10^{-5}$ m/s;
- porosity value used (merely indicative): n=0.22;
- hydraulic gradient: i= 0.03 computed from the hydrogeological map.

In this way, isochrones were determined after 60 days for the restricted intermediate area (about 10,000 $m^2$) and after 360 days for the enlarged one (about 60,000 $m^2$) (Figure 11).

The result is provisional, due to the uncertainty of some parameters such as transmissivity (taken from the literature and not confirmed by field tests), and also because the potential interference between the two adjacent wells (25m apart) could not be defined from field measurements.

The occurrence of hazards (state road, sewerage system, streams, possible spreading of fertilisers and/or pesticides) makes it necessary to design and install an appropriate monitoring network along the perimeter of the areas. These "dynamic" protection measures are justified by the evolution of local human activities. The use of such monitoring points is expected to identify any polluted water flow before it reaches the wells in view of the calculated travel times from the monitoring points to the wells. The monitoring network should consist of piezometers or wells that are only open to the aquifer that is to be monitored, or separately in the two aquifer layers (multilevel piezometers).

The spacing between piezometers along the perimeter of the intermediate area should be determined on the basis of a trade-off between the technical requirement of monitoring each flow line (infinite umber of piezometers) and the financial resources allocated for pollution prevention and control. In this respect, law no. 36 of 5 January 1994 introduced an important notion into the water supply service tariff, i.e. the notion of "operating costs of protection areas".

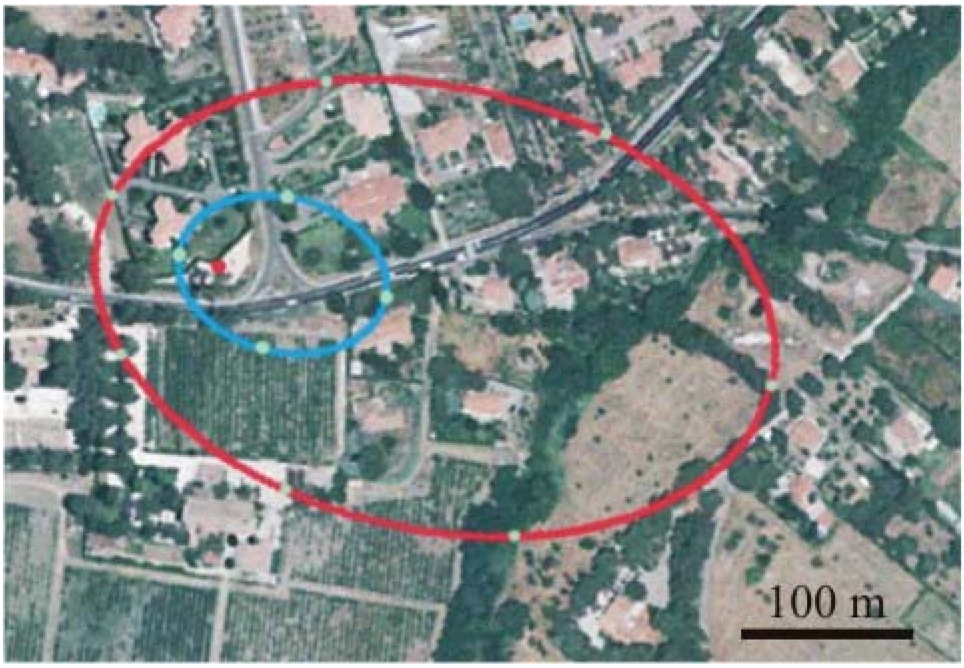


**Figure 11.** Intermediate protection areas of the "Bivio Tuscolo" well; blue line represent 60 days arrival time area; red line represents 360 days arrival time area; green dots show location of monitoring piezometers.

A compromise solution may be found bearing in mind that:

- the pollutant front (distance between the two outermost flow lines, converging towards one of the water systems to be protected) should be monitored;
- the width of such front is a function of the arrival time, characterising the intermediate area; this width changes with geometry of the piezometric surface, hydrogeological features of the aquifer, extent of withdrawals, density of water abstraction systems;
- the distance between check points should also take into account the risk of pollution represented by human settlements uphill of the areas to be protected, as well as aquifer vulnerability.

The proposed solution for the investigated wells consists of a monitoring point every 90 m along the boundary with 60 days travel time (perimeter: 365 m; 4 piezometers) and every 150 m along the boundary with 360 days travel time (perimeter: 1,000 m; 7 piezometers) (Figure 11). All the piezometers should be at least 150-m deep and equipped with openings at the points of intersection with the two aquifer layers.

Another aspect of paramount importance, in terms of effectiveness of the monitoring area, is the frequency of sampling and analysis. Also for this parameter, the optimum solution is a trade-off between maximum frequency (pollution is detected as soon as it crosses the perimeter of the intermediate area) and minimum frequency (corresponding to the arrival time characterising the intermediate area).

Supposing that the sampling frequency should be adequately lower than the arrival time, so as to leave a safety & security and early warning margin, the following frequency is proposed:

- sampling frequency of 1.5 months for the intermediate area after 60 days;
- sampling frequency of 3 months for the intermediate area after 360 days.

Another option may be on-line monitoring, although this option is definitely more expensive than "conventional" methods, owing to the high-tech equipment that it requires. However, such system might signal possible groundwater contamination in real time and significantly cut the time needed for activating contingency plans for remediation.

## CONCLUSIONS

Investigations were conducted in the territory of the Grottaferrata Municipality in order to determine the intermediate protection areas of the "Bivio Tuscolo" drinking water system. These investigations identified two groundwater systems ("multi-layer aquifer", divided into upper and lower aquifer) that are separated by a low-permeability layer across the investigated area, although at local level the aquiclude is absent. In the case study, the absence of this aquiclude in the well does means that the lower aquifer is not protected by the upper one.

Complex multiple aquifer systems in an area of limited size and with some possible hydraulic continuity with one another makes the selection of appropriate protection criteria difficult. These difficulties are increased by fact that the potentially polluting activities cannot be relocated. Based on the applicable legislation, a "limitedly effective" intermediate area (urbanised site) was defined for the well under review and the required piezometric network for monitoring the exploited aquifer layers was designed.

An area with arrival time after 60 days (approximately 10,000 $m^2$) and an area with arrival time after 360 days (roughly 60,000 $m^2$) were defined. The installation of four and seven monitoring piezometers were planned along the perimeter of these areas. The piezometers, each about 150-m deep, were equipped with multilevel devices, capable of separately monitoring the waters from the two distinct aquifer layers. The frequency of water quality monitoring and detection of possible pollutants from existing hazard sites should be lower than the arrival time; this frequency was set to 1.5 moths for the 60-days area and to 3 months for the 360-days area.

The above project is proposed as a prototype for enforcing groundwater protection rules throughout Italy. Based on analyses conducted prior to the design of the monitoring network, this solution can i) guarantee the quality of groundwater intended for human consumption; concurrently ii) comply with the applicable legislation, and iii) take into account the particularly complex hydrogeological setting of volcanic multi-layer aquifers that are located in urbanised areas. In these areas, pre-existing human activities, which represent groundwater pollution hazards, make it difficult to regulate land use around water abstraction systems.

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