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Some simple procedures for the calculation of the influence radius and well head protection areas (theoretical approach and a field case for a water table aquifer in an alluvial plain)

Alcune semplici procedure per il calcolo del raggio di influenza e delle aree di protezione attorno ai pozzi (sintesi teorica ed illustrazione di un caso pratico per un acquifero freatico alluvionale)

Alessio Fileccia

Riassunto: L'articolo descrive alcune semplici metodologie per delimitare le aree di protezione attorno ai pozzi per acqua potabile insieme ad un breve elenco della principale normativa in Italia ed Europa. Partendo da una spiegazione generale dei principali parametri, come il raggio di influenza e la zona di cattura in acquiferi omogenei ed isotropi, vengono poi illustrate delle procedure base presenti in letteratura. Le soluzioni hanno un diverso grado di approfondimento, dal criterio geometrico del raggio fisso di 200 m al più complesso metodo analitico e numerico. Le procedure illustrate e comparate, sono cinque e riferentesi ad un campo pozzi in acquifero freatico lungo un fiume. I risultati hanno mostrato che, mentre le procedure più semplici possono essere applicate in una prima fase dello studio, esse non sono in grado di considerare correttamente le eterogeneità locali. D'altra parte una descrizione più accurata dell'acquifero, ottenuta con un modello numerico completo, richiede tempo, esperienza ed una grande quantità di dati che non sempre è possibile riunire nel caso di piccole derivazioni idriche. Come molti Autori hanno sottolineato, uno dei maggiori vantaggi dell'utilizzo del modello è legato alla sua capacità di migliorare le conoscenze sulla dinamica del sistema acquifero, valutando la risorsa idrica realmente disponibile.

Parole chiave: raggio d'influenza, zona di protezione pozzi, punto di stagnazione, zona di cattura, zona d'influenza.

Keywords: *influence radius, well head protection areas, stagnation point, zone of capture, zone of influence.*

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Abstract: *The paper describes some simple methodologies for the delineation of well-head protection areas, together with an overview of the main regulations published in Italy and Europe.*
Starting from a general explanation of the main parameters, like the radius of influence and the zone of capture in homogeneous isotropic aquifers, basic methodologies suggested in the literature are then illustrated. Different criteria are involved: from the simple 200 m radius, to more complex analytical and numerical simulations. Five different approaches are applied and compared, to a well field in a water table aquifer along a river. Results have shown that, while simpler methods can be satisfactory at a first stage of the study, they fail to account correctly, for local heterogeneities. On the other hand the more accurate description of the aquifer obtained with a full numerical model requires extensive time, expertise and amount of data, that are not always available in case of small water supply systems. As many Authors have underlined, one of the most effective outcome of the numerical tool, lays in the capability to increase our knowledge on the groundwater dynamics of the system and the amount of the sustainable yield.

Introduction and purposes

Due to the increased development of urban areas, more attention is being paid, in recent years, towards pollution prevention as well as aquifer remediation. These new policies led hydrogeologists to focus their researches to a more precise definition of some basic parameters, like: influence radius, capture zone, zone of influence and time of travel. Knowing such parameters allows one to delineate, on the field, a protection area around a pumping well. From a practical point of view, it is important to know the average aquifer size influenced by pumping, or the distance from the water supply well where drawdown is negligible. By applying the Cooper-Jacob equation this nearly zero-drawdown distance is known as influence radius (Cooper and Jacob 1946). Another important concept is that of Wellhead Protection, based on the delineation of a capture zone: the volume through which ground water flows to a pumping well over a given time (Hansen 1991). The extent of the capture zone boundary can be determined using hydrogeological parameters and various procedures, from simple empirical formulas to complex analytical and numerical models. USEPA since 1987, has defined a regulatory version of this capture zone, the WHPA (Well Head Protection Area). WHPA can be described as that "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 wellfield" (U.S. Environmental Protection Agency USEPA, 1987). The aim of this paper is to describe different procedures of various complexity, for determining the extension of water well protection areas. Five different approaches are then applied to a real case of a well field in an alluvial aquifer in transient conditions. The different zones obtained are finally compared in terms of surface, time required for the field investigations, and accuracy of final results. At this stage of legal application there is some sort of expectation, in Italy, on the adequate level of widening to be applied for such studies. Furthermore water table aquifers are a common water supply source and the different methodologies described in this paper, could be easily be performed for many real cases in the country.

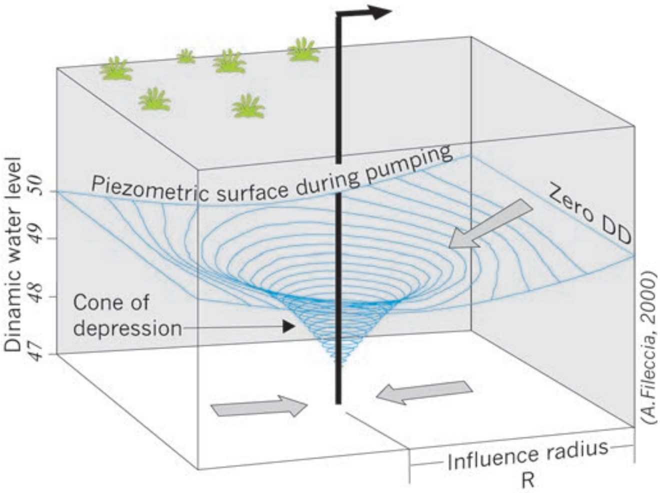
Legal framework

One of the first directive in Europe was the EC directive 80/778, adopted by the italian legislation with the DPR 236/1988. In the year 2007, European Economic Community published the Guidance on Groundwater in Drinking Water Protected Areas (Guidance Document n. 16) as an application of the Water Framework Directive (2000/60/EC) with an overall pragmatic approach defining the Drinking Water Protection Areas (DWPA), their size and general procedures for delineation. While the size of the safeguard zone can vary according to the hydrogeological properties of the aquifer, the amount of abstraction for consumption, the type of pollutant and source of contamination this last document underlines that the establishment of such zones is at the discretion of Member States. In Italy a provisional agreement between the Central Government and the Regional Councils (Accordo Stato Regioni, 2002) taking into account previous methodologies adopted in U.S. and other European countries, described precisely the main criteria to follow for the delineation of the safeguard zones.

These methodologies were later resumed in a national legislation (DL 152/2006) underlining the importance of the preliminary hydrogeologic assessment with the possibility to verify the delineation on a periodic scheme, at least every 10 years. The directive empowers the Regional Councils to practically perform the different studies. As a provisional intervention, two types of safeguard zones must be set around the spring or abstraction well: an inner (fenced) area with 10 m radius and an outer one of 200 m radius, for general protection. At present the majority of the ground water abstraction points, in Italy, has such geometric protection zone.

Theoretical background

By a theoretical point of view, in a confined homogeneous aquifer with initial flat potentiometric surface, a fully penetrating well produces a depression cone of constant volume. The circular area on the piezometric surface, the base of the cone in plan view, has a dimension defined by its radius, called the influence radius (R) in figure 1. At this distance the drawdown equals zero. When considering an initial sloping piezometric surface, the base of the cone has an elliptic shape. The well known approach of Thiem (Thiem 1906), allows the calculation of the R parameter during steady state. When considering a non-steady situation (transient), R is a bit more uncertain and of limited use (Dragoni 1998). In a non equilibrium state, R varies continuously due to the unbalance between recharge and discharge. The water levels in the well and nearby piezometers fluctuate with time until reaching a pseudoequilibrium at which the drawdown within a certain distance is small. This seemingly stable situation needs long periods of time and in reality is never reached. For practical purposes it is often necessary to find a "realistic" value for R giving a threshold value for a small drawdown that can be measured in the field (e.g. 5 cm).



(A.Fileccia, 2000)

Fig. 1 - Depression cone for a confined, homogeneous, isotropic aquifer with flat initial piezometric level and a fully penetrating well, without well bore storage (100 % efficient).

Fig. 1 - Cono di depressione per un acquifero confinato, isotropo, omogeneo con superficie piezometrica iniziale piatta e pozzo completo, senza il fenomeno dell'immagazzinamento in pozzo (efficienza 100%).

Many empirical formulas are provided giving an approximation for the radius of influence. They are based on:

- Mean grain diameter (d50)
- Hydraulic conductivity
- Water well discharge
- Drawdown at the pumping well

The following is only an overview:

1. $R=\sqrt{2.25Tt/S}$ for confined aquifers after a short period of pumping, is derived from Cooper, Jacob equation, (Cooper and Jacob 1946);
2. $R=\sqrt{1.9\ kht/n}$ for unconfined aquifers (Aravin and Numerov 1953);
3. $R=3000\ s\sqrt{k}$ Sichardt formula, for unconfined aquifers (Cashman and Preene 2001).

R = influence radius (m); T= transmissivity (m^2 /s);
t = time in s; S = storage;
h= height of the water table above substratum (m);
n = effective porosity; k = hydraulic conductivity (m/s);
s = drawdown in the borehole (m)

Is the author's opinion that Sichardt's formula applied with large s values can give unreasonable results. In this case it is important to separate between well and aquifer losses, using a more realistic drawdown.

R values less than 30 m or more than 5000 m should also be considered with caution and possibly carrying out a sensitivity analysis (Chapman and Preene 2001).

In the absence of a field test, a radius R = 500 m is considered for loose, medium to coarse grained sediments (Table 1, Bogomolov and Silin 1955). The figure 2 is calculated with Sichardt formula and shows the increase of R with the hydraulic conductivity when s remains constant. For long pumping tests (when u < 0.05) , R can be obtained from the Cooper-Jacob approximation (Cooper and Jacob 1946) considering a small drawdown (s = 0.05 m):

$$R = \sqrt{\frac{2.25Tt}{Se^{\frac{4\pi Ts}{Q}}}}$$

4.

Q = well discharge in l/s.

For all the above, 1 through 4, the usual simplified assumptions must be valid: confined aquifer of infinite area extent, homogeneous, isotropic, of uniform thickness, with flat initial piezometric surface, pumped at constant discharge by a fully penetrating well. For the unconfined case the drawdown must be small compared to the aquifer thickness (<10%) and in transient conditions, well bores storage is negligible and water removed instantaneously with decline of head.

Zone of capture, zone of influence, boat shaped zone

In figure 3 are sketched some important concepts dealing with the geometry of the cone of capture with an initial sloping piezometric surface. The basic guidelines are described in the EPA, 1987 manual, a milestone for all groundwater scientists. In the more realistic situation of a uniform flow (gradient i ≠ 0) the cone of depression has an elliptic geometry (boat shaped), with its major axis along the main flow line. The recharge area contributing to the borehole is defined as the Zone of Contribution (ZOC), while the Zone of Influence (ZOI) is the cone of depression within which the water table has been lowered due to the withdrawal. The ZOI is always within the ZOC. Delineating such areas allows one to calculate the contaminant travel of time (TOT) towards the well screens. In other words it greatly reduces the probability of pollution by industries and sewers. When the initial piezometric surface is horizontal the ZOC and the ZOI are coincident and have the same dimensions.

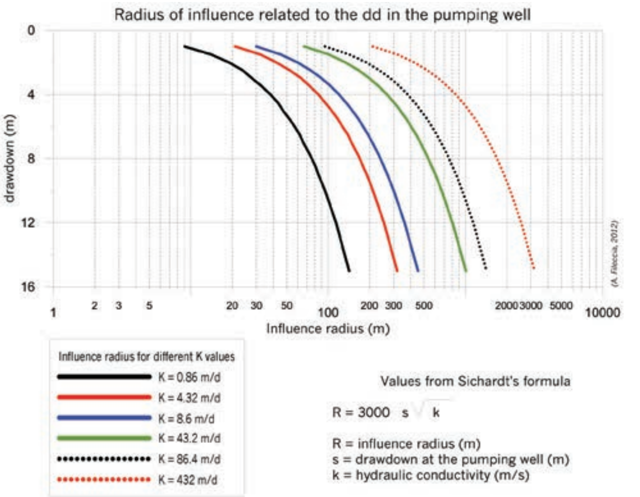


Fig. 2 - Variation of influence radius (coloured curves) due to a change in hydraulic conductivity and drawdown.

Fig. 2 - Variazione del raggio di influenza (curve colorate) a seguito del cambio di conducibilità idraulica e valore di abbassamento dinamico.

Geometry of groundwater protection zones

If we consider a piezometric surface around a pumping well and apply Darcy's law the shape of the curve is determined using:

5. $x = -y / tg(2\pi Tiy/Q)$

x, y are the coordinate as in figure 4

The width of the zone, perpendicular to the mean flow is

$$F = Q/Ti$$

Half width is:

$$y = \pm Q/2Ti$$

The distance from the well to the stagnation point is:

$$x_s = Q/ 2\pi Ti$$

Where T = transmissivity

Tab. 1 - Variation of radius of influence due to hydraulic conductivity (Bogomolov, Silin 1955).

Tab. 1 - Variazione del raggio di influenza con la conducibilità idraulica (Bogomolov, Silin 1955).

Soil type	min diameter (mm)	max diameter (mm)	K min (m/d)	K max (m/d)	min discharge (l/s)	max discharge (l/s)	Radius of influence (m)
silt	0,01	0,05	0,5	5	0,03	0,1	65
fine sand	0,1	0,25	10	25	0,14	0,5	75
medium sand	0,25	0,5	20	50	0,16	5,5	100
coarse sand	0,5	2	35	75	5	14	125
gravel	2	50	60	125	11	30	150

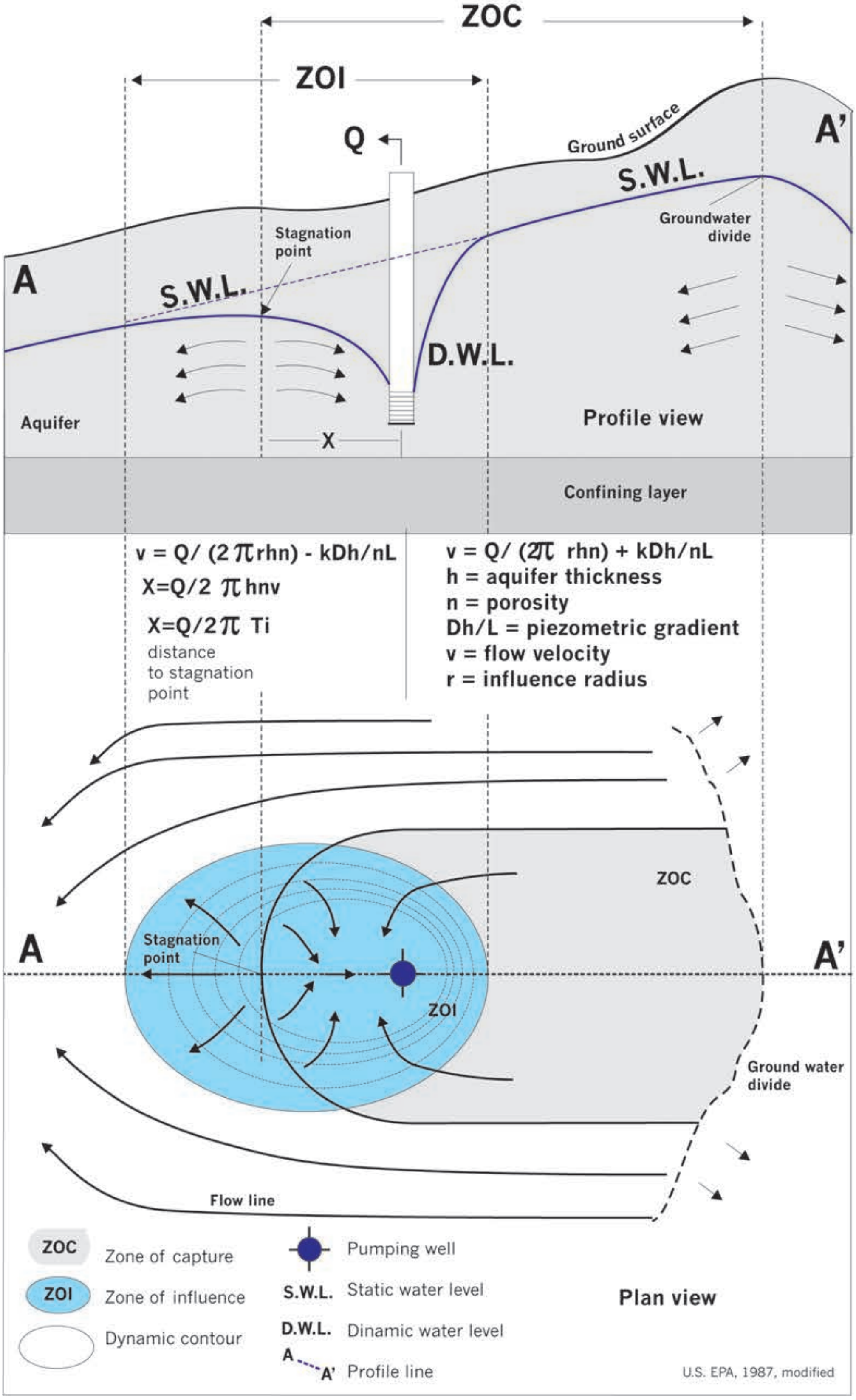


Fig. 3 - Zone of capture (ZOC) and zone of influence (ZOI) for a pumping well in uniform flow. Note how the ZOC and the ZOI do not coincide. The ZOC is the recharge area supplying water to the wellhead, from the stagnation point to the groundwater divide. The ZOI is simply the cone of depression (EPA, 1987, modified).

Fig. 3 - Zona di Cattura (ZOC) e Zona di Influenza (ZOI) per un pozzo in acquifero con flusso uniforme. L'estensione delle due aree (ZOC e ZOI) non coincide. La ZOC è quella di ricarica che fornisce il pozzo di acqua, dal punto di stagnazione allo spartiacque idrogeologico. La ZOI è semplicemente il cono di depressione (EPA, 1987, ridisegnato).

Grubb (1993), developed equations describing the capture zone for a water table aquifer, knowing the water level in at least two piezometers. The measuring points should be along the mean groundwater direction.

6. $x = -y / tg [\pi k (h^2_1 - h^2_2) y / QL]$
7. $y = \pm QL/k (h^2_1 - h^2_2)$
8. $xs = QL \pi k (h^2_1 - h^2_2)$

L = distance between the two control points h_1 ed h_2
k = hydraulic conductivity
tg = tangent in radian

To sum up briefly, the geometry of the groundwater protection zone, in a confined aquifer can be calculated, using flow velocity or transmissivity (Todd 1980):

9. $F = Q/T i = Q/k h i = Q/v n h$
10. $y = Q/2 T i = Q/2 k h i = Q/2 v n h$
11. $xs = Q/2 \pi T i = Q/2 \pi k h i = Q /2 \pi v n h$

As can be seen from figure 4, the stagnation point represents the downgradient limit of the capture zone and it is closer to the well with high velocity natural flows. It can also be seen that there is no limit for the capture zone upgradient from the pumping well.

Basic criteria for defining the setback zones

Every theoretical approach, when in operation must deal with "real world" conditions. Assuming, for example that microbial pollution becomes inactive in the aquifer after a certain time, say 3 months, a line of defense (setback zone) could be fixed upgradient. In this way the contaminants will take more than 90 days to travel the distance from this line to the pumping well.

Since a few decades EPA in its Guidelines for delineating Well Head Protection Areas (1987) has listed the following basic criteria:

a. distance
b. drawdown of the depression cone
c. Time of Travel (TOT)
d. Hydrogeologic survey
e. Assimilative capacity

a. **The criteria based on distance** is the simplest approach, fixing a radius from a pumping well to a point of concern (pollution potential) without the consideration of hydrogeological or hydrochemical issues.

b. **The criteria based on drawdown** is based on the distance reached by a protection zone corresponding to a particular drawdown. It must be underlined that, in practice, the real depression cone extends beyond that limit and it depends on the value of the u coefficient. Accuracy increases using late drawdown data or when $u \leq 0.03$.

c. **The criteria based on Time of Travel (TOT)** is based on the residence time. This approach calculates the average velocity of a water particle along a flow line ($v = Ki/n$) . The protection zone is within the distance covered in less than the fixed time (e.g. 90 days in case of microbial pollution).

d. **The Hydrogeologic survey criteria** is normally performed through:
   - Field hydrogeological surveys
   - Geophysics
   - Tracing techniques

   Its main task is the mapping of physical boundaries and it is applied at a preliminary stage of the investigations. Many authors consider it as an essential step when studying karst or fractured rock aquifers.

e. **The criteria based on assimilative capacity** is the last procedure and takes into account the progressive reduction of the pollution phenomena due to several chemical and physical reactions (dispersion, degradation etc.). It generally requires sophisticated models for flow and transport. In some cases multiple groundwater protection zones, each for a particular contaminant are calculated.

Basic methodologies for the delineation of the well head protection zones

Several procedures have been established since early '80s. Some of these approaches use the classical formulas coupled with more restrictive conditions and different variables (e.g.

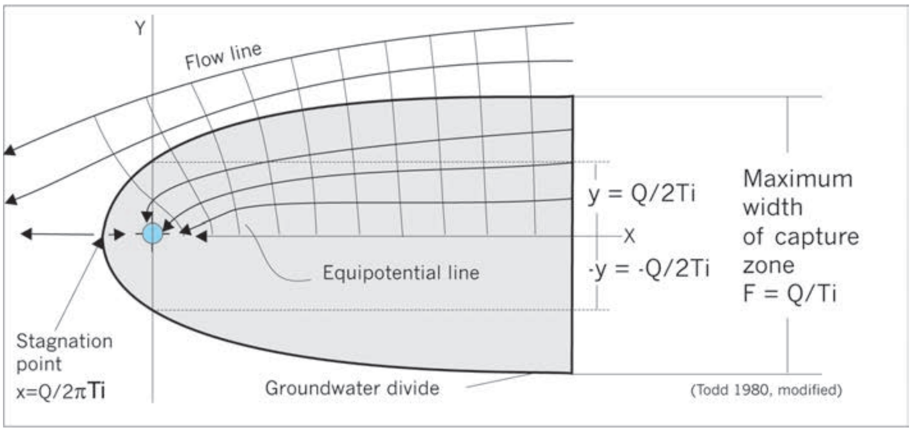


Fig. 4 - Geometry of the capture zone with initial flat piezometric surface (i = 0), showing the curvature of the flow lines due to pumping.

Fig. 4 - Geometria della zona di cattura per una superficie piezometrica iniziale orizzontale (i = 0). Notare la curvatura delle linee di flusso a causa del pompaggio.

boundary presence, lateral anisotropy etc.) The following list is not intended to be comprehensive but sufficient to correctly illustrate the problem. The initial step is to gather the necessary hydrogeological assessment and parameters, from previous researches and possibly through new field investigations. In a second phase and depending from local constraints, (the available budget, not to say the least), the charged professionals can "freely" decide to turn to one of the following:

1. Arbitrary fixed radius
2. Analytic method (empirical formulas, Calculated Fixed Radius, CFR)
3. Simple analytic element softwares
4. Sophisticated numerical models (finite difference, finite elements, 2D – 3D for flow and transport)

In this paper we will deal with the above methods for the cases of initial flat potentiometric surface and uniform flow. They are based on the Dupuit assumption that has demonstrated to be reasonable, when the capture zone dimension is more than 1.5-2 times wider than the saturated aquifer thickness.

Arbitrary Fixed Radius (AFR)

The Arbitrary Fixed Radius approach (AFR) considers an initial flat potentiometric surface and a 200 m fix radius around a pumping well. The distance has no hydrogeological or chemical background. In Italy, this methodology follows the provisional agreement between the Central Government and the Regional Councils (Accordo Stato Regioni 2002).

Analytical solutions

The analytical methods start with the preparation of a simple conceptual model and foresee the inclusion of progressively more restrictive conditions. In some cases simplified groundwater protection shapes with different geometries and distance time criteria are calculated (SVS, Simplified Variable Shapes, Hansen 1991). These forms are then superimposed to the ones in the field and oriented along the main flow direction. The following methods are classified as Calculated Fixed radius (CFR) and define the capture zone as a cylinder around the well screen. This volume corresponds to the volume of water in the aquifer pore and is equal to the well's discharge. A wide variety of analytical solutions exist and the following is only a selection.

a. volumetric method (USEPA 1987)
the fixed radius of groundwater contribution to the pumping well is accomplished by using the volumetric flow equation with a TOT criterion as follows (U.S. Environmental Protection Agency 1987):

12. $R = \sqrt{Qt/n\pi H}$ or considering a safety factor when $i \neq 0$: $R = 1.15\sqrt{Qt/n\pi H}$

Q = discharge (m^3/s)
H = constant aquifer thickness (m)
n = effective porosity (adimensional)
t = time (s)
R = influence radius, in m ($R >> H$)

For those cases where the capture zone has a dimension smaller than the double of the aquifer thickness or the well is not fully penetrating, the vertical component of flow becomes more important and the simplified approach is no more valid. For the unconfined situation the aquifer thickness is not constant with time and a correction factor must be used when drawdown is between 10-25% of initial H.

Figure 5 shows clearly the rapid increase of R, with thin aquifers or partially penetrating wells, when discharge remains constant. Conversely an increase of aquifer thickness, or screened length, reduces R and the cone of influence.

b. Method from Todd 1980 described previously and in figure 4, allows to consider an initial uniform flow and gradient

c. Method from Ceric, Haitjema (Ceric 2000; Ceric and Haitjema 2002) also known as "back of the envelope technique" couples with a procedure that clips the groundwater protection zone at a chosen distance upstream. The distance upgradient L_u is

13. $L_u = L_s\,[\tau + \ln(e + \tau)]$ $(e = 2.718)$

Ls = distance to stagnation point = $Q / 2\pi Q_0$
Q = well pumping rate (m^3/s)
Q_0 = unit aquifer discharge (m^2/s) =Ti

the shape of the boat shaped zone, with a particular travel time (isochrone) is related to the dimensionless parameter τ.

Simple analytical tools

This approach uses a computer software, adding the following advantages:

- Capture zones can be delineated for multiple wells in a uniform flow field, near a stream or no flow boundary with a variable shape
- Hydraulic resistance, K inhomogeneities, recharge and control points can be added

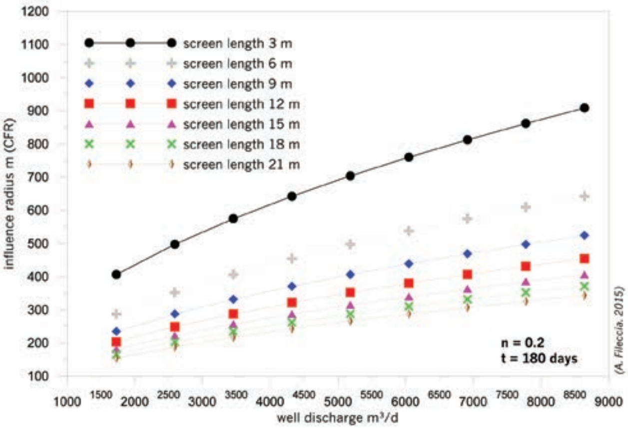


Fig. 5 - Graph showing the increase of the influence radius for progressively thin aquifers (or short screen lengths).

Fig. 5 - Grafico che mostra l'aumento del raggio di azione per acquiferi progressivamente più sottili o brevi tratti filtrati.

- The upstream boundary of the protection zone is calculated using a reverse particle tracking scheme for every streamline and using the relation v= dx/dt (where dt is the time-step, dx is the space increment); the calculation continues until a prescribed time or a head specified boundary, is reached

The incorporation of all the above capabilities is accomplished using the superposition of many analytic functions, each representing a hydrological feature. Some of well known public-domain analitic element models are WHPA, an improvement of the WHP program (Blandford and Huyakorn 1991) and WhAEM2007 (Kraemer, Haitjema, Kelson 2007). WhAEM2007 incorporates the modeling for steady pumping wells, including the infuence of hydrological boundaries, such as rivers, recharge, no-flow boundaries, and inhomogeneity zones, using the analytic element method. Reverse gradient tracelines of known residence time emanating from the pumping center, at screen's depth, are used to delineate the capture zones (isochrones). The basic assumption is still that the vertical flow is negligible (Dupuit), meaning that the piezometric head along a vertical line from top to bottom of the aquifer is constant.

Numerical model

This well-known approach uses differential equations for flow calculus in two/three dimensions. Many data is needed to approximate the aquifer behaviour. Modflow and subsequent updates from USGS (Mc-Donald and Harbough 1988), Feflow (Diersch and Hans-Jörg 2014), Microfem (Hemker and de Boer 2012) etc. are such codes.

Alto Trevigiano Servizi, (A.T.S.) well field case study

The Alto Trevigiano Servizi (A.T.S.), a water work authorithy, has requested a comprehensive research, to better assess the existing aquifer conditions and management issues. In practice, A.T.S. foresees an increase of water demand up to 100 l/s and needs to evaluate the actual drawdown induced by the supply system and the extension of the Zone of Influence (ZOI) for different travel times, assessing origin and amount of water available for abstraction. The area is located on a wide alluvial valley along the river bank of Piave, in north east Italy and this review provides a description of numerous procedures to practically delineate the protection zones around the wellfield. In case of a severe river pollution, the study should evaluate the time needed by the contaminants to travel the 900 m distance from the right river bank to the well field. More than one procedure was applied in the delineation process, with various levels of complexity and time of travel. The different areas obtained were then be compared with that from a 2D finite difference numerical simulation, in transient condition.

Geographical setting

The A.T.S. supply system consists of 7 wells along a river bank, near Nervesa (Treviso province). Four boreholes are active and pump alternately at an average total rate of 80 l/s. The remaining three are used as piezometers. The amount of water withdrawn is regulated by the volume of a reservoir located on the near hill, 70 m higher in elevation. The valley filled deposits are in lateral contact with the rocky area of Montello, a dome shaped mainly conglomeratic formation, rising up to 300 m (asl). A general hydrogeological description on the area, can be found on Fileccia A., Galassi P., Mazzola M. 2002.

Figure 6 illustrates the position of the wellfield and the main field investigations.

Groundwater hydrology and conceptual model

The area was simplified in terms of hydrostratigraphic units, water budget and flow system. Figures from 6 to 12 illustrate the main geomorphological and hydrogeological properties while figure 9 synthetize the hydrogeologic framework (on the left) and the derived model used to simulate the system behaviour (on the right). Within the investigated area, there are two main geologic units made by a recent upper alluvium and a lower rock formation of the Miocene. The main surficial unit is made up from the recent flood plain deposits of Piave River. These are made by coarse gravel and cobbles hydraulically connected to the watercourse and forming an unconfined aquifer with thickness ranging from 0 to 30 m. The aquifer bottom has a typical gully shape, deepening towards the west side, near the hill (Montello) and outcropping at the east along the river. The lower horizontal bedrock layer is made up of hard conglomerate and marl on unknown thickness. The main aquifer recharge is coming from the right bank of the river, in the upper north west boundary, along a 500 m strip. The Piave river has an alpine regime, with strong variation discharges during the year ranging from 40 m^3 /s to 120 m^3 /s, but limited to 5-10 m^3/s during most of the time. By applying Darcy formula, the average water volume entering the aquifer from the river, is in the order of 15000 to 25000 m^3 /d, in normal condition. The particular geometry of the substratum, suggests that during floods, when the river stage elevation is 2-3 m higher, some additional underground flow can come from the east side of the aquifer, where bedrock outcrops at the river bed (points Piave 1-2-3 on Fig. 6). The normal aquifer top is 5 m below ground surface (Fig. 7). The soil cover is a few cm thick while the unsaturated part is made of the same material as the underlying aquifer (coarse grained gravel and cobbles). The main factors affecting recharge are as follows:

- Infiltration from the river (the process is by far the most important and considered to take place all the year around, even at low river stages);
- Rain infiltration (probably less than 5% of the total);
- Underground flow from the karst formations on the west side (Montello hill); following preceding investigations (see also Fig. 6) this amount is very low and intermittent and it was not considered in the paper.

Figure 8 clearly shows the depression cone due to pumping of the 4 wells, with a total drawdown between 1-1.5 m.

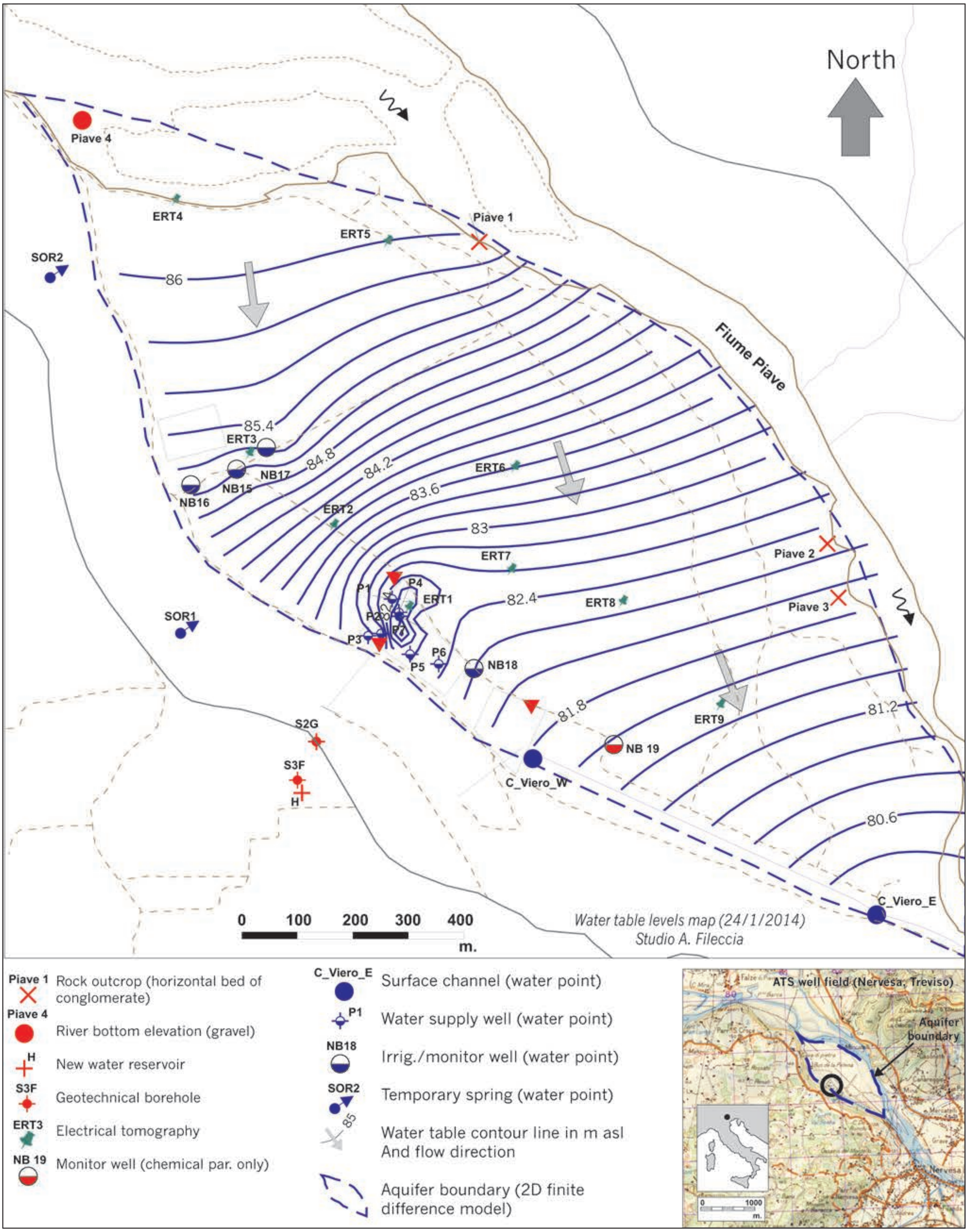


Fig. 6 - Water table map during flood (January 2014) and main investigation points. Note the cone of depression near the well field and stagnation point, east of the wellfield fence. The contours along the west side of the river indicate a no flow boundary.

Fig. 6 - Ubicazione dei principali punti di indagine e carta piezometrica durante una fase di piena (gennaio 2014). Notare il cono di depressione nel campo pozzi ed il punto di stagnazione ad est della recinzione.

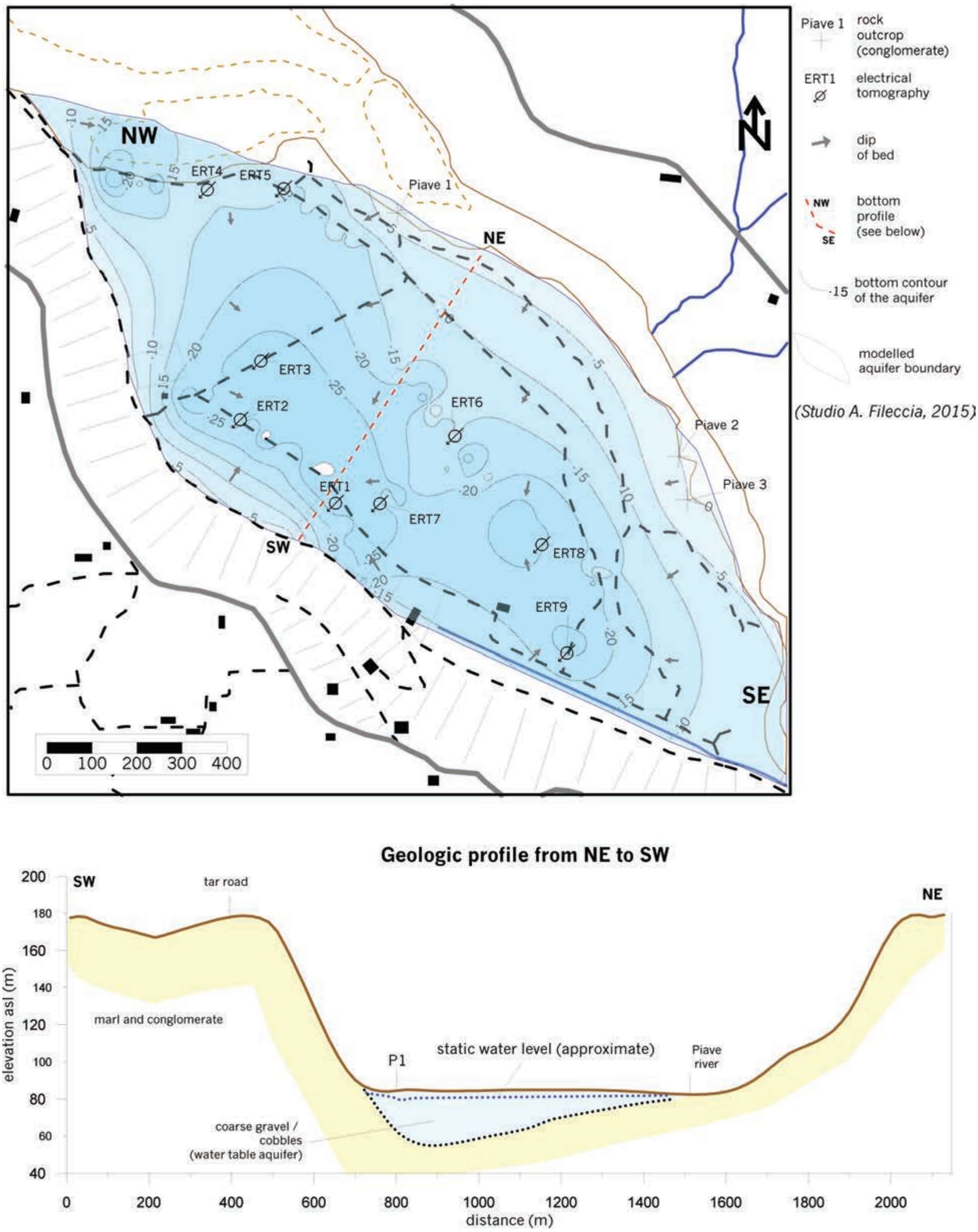


Fig. 7 - Contours of the aquifer bottom. Values were obtained from electrical tomography, field mapping, geotechnical drilling and hydrogeological maps. Note the long depression, 10 to 30 m deep, and parallel to the east slope of the hill, on the west side of the porous aquifer.

Fig. 7 - Isobate del letto dell'acquifero. I valori sono stati ottenuti dalla geofisica, rilievo di campagna, sondaggi e carte piezometriche. Notare la lunga depressione profonda 10-30 m e parallela al fianco orientale del Montello, lungo il lato ovest dell'acquifero poroso.

During a 12 month monitoring period it was noted that the aquifer response to the river stage fluctuations was rapid. The change in water level was recorded in the piezometers at 550 m distance with a lag time of less than 2 hours, giving an additional support to the high K values obtained from field investigations. The piezometric surface during pumping indicates a groundwater divide located 70-80 m downgradient from P1-P4 wells. A similar value was obtained by applying the analytical formula for the stagnation point (Todd 1980; USEPA 1987). An aquifer test with piezometers, gave a value for the hydraulic conductivity between 350 and 600 m/d while the effective velocity, after a two point dilution test, was in in the range of 8-10 m/d. Figure 9 synthesizes the conceptual model illustrated in the text. The sketch on the right shows that the river is losing water to the unconfined aquifer with variable thickness, laying on a low conductive layer made of hard rock (conglomerate and marl). Some recharge takes place also through the unsaturated and highly permeable top layer, from rain infiltration. There is a natural discharge from the aquifer to the river, along the south east, summed to that withdrawn by the wellfield. A value of 100 l/s (8640 m^3/s) was used in the calculations and corresponding to the future abstractions.

Field case approach

Five different methods were applied in order to evaluate the 30 days and 90 days capture zones for the ATS wellfield. The goal of the exercise is to underline pros and cons of the different approaches, providing considerations on time involved, extension areas and level of accuracy. Tables 2-3 synthetize the input parameters and the values used for the above approaches. The methods applied and described in the following paragraphs are:

A. Arbitrary fixed radius (AFR)

Figure 10 shows the protection area (blu line) with the arbitrary radius of 200 m prescribed by Italian regulation, (Accordo Stato Regioni 2002, DL 152/2006). The final zone derives from the overlapping of the circles around each well. This provisional methodology is the one adopted in many public abstraction points.

B. Calculated fixed radius (CFR), as described by Todd 1980, Ceric and Haitjema 2002 (see equation 13)

Figure 11 was designed for a total withdrawn discharge concentrated in a single well (P1) at 100 l/s; the maximum width of the capture zone is F=470 m and distance to stagnation point is xs=75-80 m. The boat shaped capture zone is clipped upgradient at the 30 and 90 days interval:

L_u (30 days) = 230 m

L_u (90 days) = 512 m

C. Analitic element software (WhAEM 2007)

The protected areas were drawn using an analytic element code of public domain released by the U.S. Environmental Protection Agency (EPA). The calculation was made increasing the complexity of the modelled area with the input of

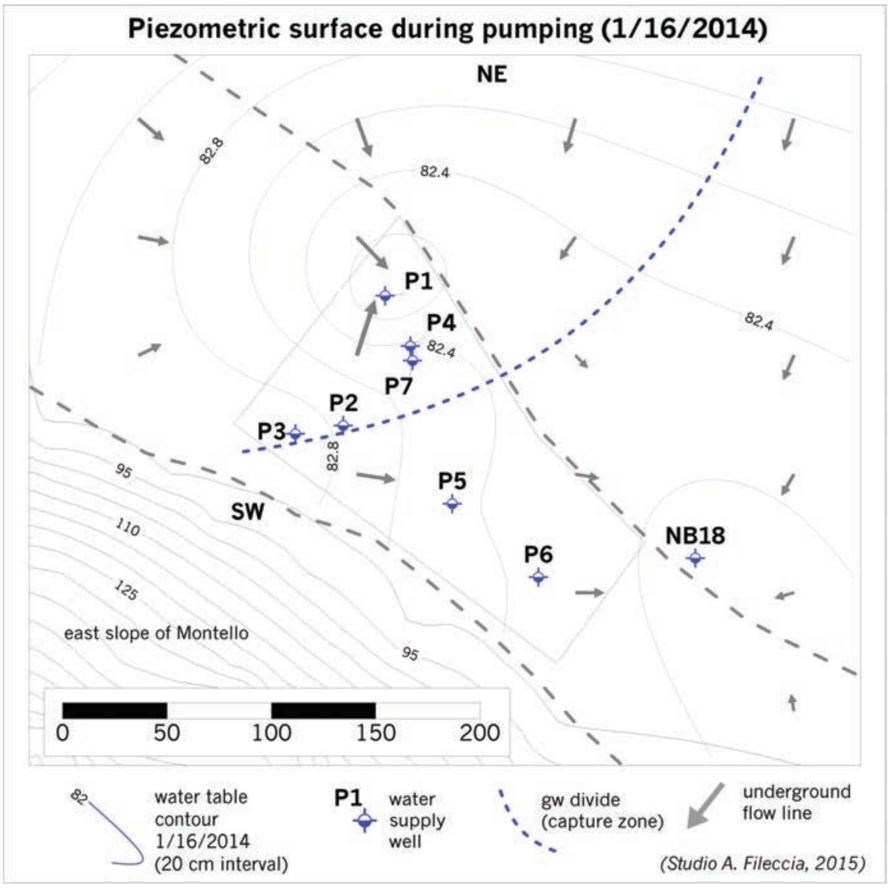


Fig. 8 - Piezometric surface during pumping and related groundwater divide. The distance to the stagnation point is at 70-80 m distance from P1.

Fig. 8 - Superficie piezometrica in condizioni dinamiche e spartiacque idraulico. La distanza del punto di stagnazione da P1 è di 70-80 m.

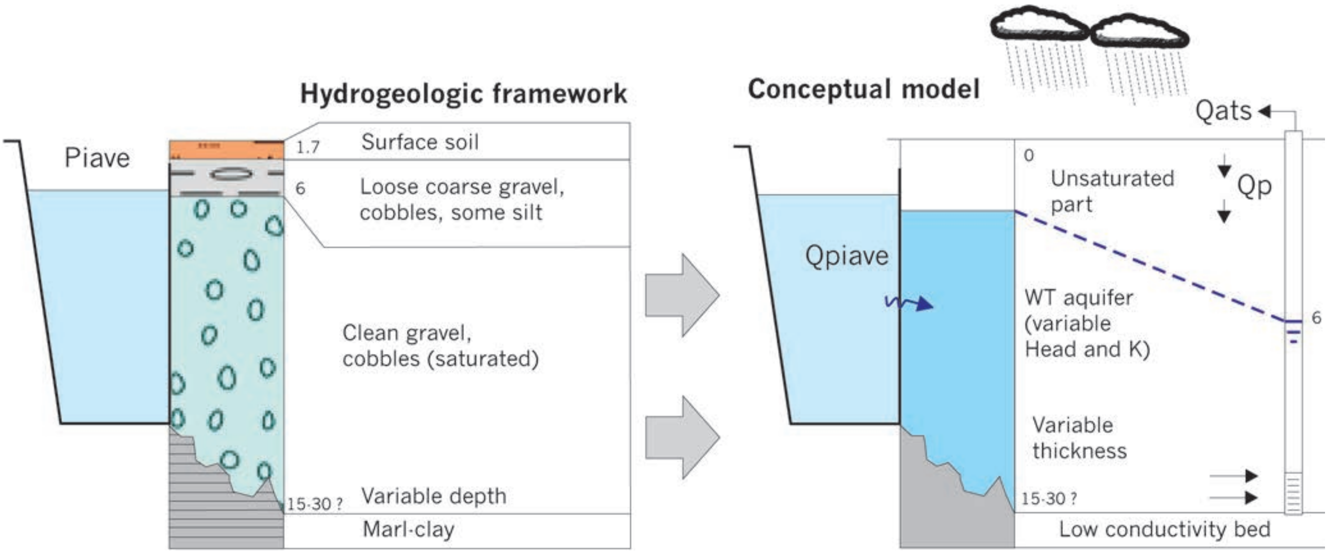


Fig. 9 - ***Hydrogeologic framework and conceptual model****: Aquifer extension: 1072667m*^{2}*. Aquifer volume: 993256 m*^{3} *(saturated volume, from febr. 2013 to jan. 2014) ;Aquifer volume:16075262 m*^{3} *(geologic reservoir, volume between low gw levels and aquifer bed). Recharge volumes: Qp from rain infiltration: 1000 m*^{3}*/d approx.; Qpiave, recharge from Piave river, 25000 m*^{3}*/d approx; Average river discharge, at low stage elevation: 5-10 m*^{3}*/s; min. and max discharges during the year (mean of 30 years): 40-130m*^{3}*/s. Aquifer discharge volumes: Qats, present withdrawn volume from the well field: 8640 mc/d, approx. (34% of the total infiltration rate) + Q natural (?)*

Fig. 9 - **Schema idrogeologico e modello concettuale:** Estensione dell'acquifero: 1072667m^2. Volume acquifero: 993256 m^3 (zona satura tra i livelli di minima e massima dal febbr. 2013 al genn. 2014). Volume complessivo dell'acquifero: 16075262 m^3 (riserve geologiche, volume tra il livello di minima e la base dell'acquifero). Ricarica: Qp dalle precipitazioni: 1000 m^3/d approx.; Qpiave, dal fiume Piave: 25000 m^3/d approx; Portata media del Piave in magra: 5-10 m^3 /s ; portate minime e massime durante l'anno medio: 40 – 130 m^3/s. Scarico naturale/Prelievi: Qats, volume pompato attualmente da ATS: 8640 mc/d, approx. (34% del totale infiltrato) + Q naturale (?).

multiple wells, observation points, a uniform flow field etc. (Fig. 12 and Tab. 2)

D. A 2D finite difference model (Aquifer Simulation Model, ASM, Chiang, Kinzelbach, Rausch 2000)

ASM is a fully finite difference model, similar to MODFLOW but restricted to two dimensions. Both codes have a user friendly interface that simplifies data input and final comparison. The advantage, in the given solution provided by ASM, of considering a variable aquifer thickness and transient conditions is evident in the dimension of the 90 days zone. This tool was introduced thanks to its relative simplicity, compared to a full 3D model and with the aim to better understand the system and evaluate the capture zone for different times. The assumption behind is that adding more complexity will give more realistic results. In choosing a 2D model, instead of a 3D, we also took into considerations some rules of thumb, underlined by Haitjema (Haitjema 2006) and valid for the case illustrated in this paper:

- The protection zone is not influenced by a surface water body, with a high conductance bottom layer, when the distance to the well is > 4 $(Qt/\pi bn)^{1/2}$ (t = residence time, isochrone; b = aquifer thickness; n = porosity);
- The vertical flow component is negligible when the well is positioned at a distance from the boundary, larger than $2b(Kh/Kv)^{½}$ (Kh, Kv are the horizontal and vertical hydraulic conductivities;
- When the width of the capture zone, or the aquifer thickness, is less than $2b(Kh/Kv)^{½}$, a 3D numerical model would be more realistic.

Case study delineation results and comparisons

Due to its simplicity the AFR does not protect effectively the area. In our case nearly one third of the zone belongs to a different aquifer which contribution is negligible. The hydrogeologic survey and the piezometric maps, has proven that the underflow from the karstified hill to the porous unconfined aquifer is nearly absent. At the same time the method does not consider a wide zone upstream, influencing the system. Method B using simple formulas, is a bit more accurate with the advantage of being quick and applicable without expensive field tests. One main drawback is that there is the risk of being used by non-technical staff without an initial hydrogeological judgment of the site. In some situations a preliminary quest for available data with the support of some basic investigations, would give a better reconstruction. E.g. the west border along the hill (Montello) could be left out from the zone contributing to recharge after a geologic survey and a set of piezometric maps in different seasons. Procedure C, (Analitic Element) gives almost the same result as that of the 2D numerical method, for the 30 days isochrone. The upstream capture zone extension is around 250 m. Last method D, gives the maximum extension for the 90 days Travel Of Time zone. The upstream boundary reaches the river bank at 800 m distance, in good agreement with the effective velocity obtained by a field test (8-10 m/d). The extensions calculated for the different areas are in table 4. It can be seen how close are the surfaces for the first 3 methods as regards to the last one (D). Many Authors recognize that procedures A and B do not represent a valid reconstruction, due to the large num-

Tab. 2 - Input parameters for different delineation methods.

Tab. 2 - Parametri di ingresso utilizzati in vari approcci di calcolo delle zone di rispetto.

Procedure	Input parameter	Symbol	Unit	Value	Assumptions
Arbitrary fixed radius (AFR) distance criteria	radius	R	m	200	knowledge of local hydrogeological parameters not necessary
Todd, 1980; Ceric, Haitjema, 2002 drawdown and TOT criteria	well discharge	Q	m^3/d	8640	steady state, uniform flow, one pumping well at constant discharge, one unconfined aquifer, H, K,n, constant, homogeneity and isotropy, advection process only
	gradient	i	-	0,002	
	aquifer thickness	H	m	23	
	hydraulic conductivity	K	m/d	400	
	time of travel	TOT	d	30 - 90	
Analitic element (WhAEM2007)	total well discharge (distributed in four wells)	Q	m^3/d	8640	steady state, multiple wells w. varying discharges, uniform flow, constant H,K,n, test points, various type of boundaries w. Variable head, pathlines starting from screen's depth
	gradient direction	a	degrees	-55°	
	aquifer thickness	H	m	23	
	hydraulic conductivity	K	m/d	400	
	porosity	n	-	0,2	
	test points (5)				
	various type boundaries (line sink at NW and SE w. Variable head, barrier at NE and W)				
	reverse particle tracking starting from screen depth				
	time of travel	TOT	d	30 - 90	

Tab. 3 - Input parameters for 2D finite difference numerical simulation (ASM).

Tab. 3 - Parametri di ingresso utilizzati con il codice numerico bidimensionale alle differenze finite (ASM), per il calcolo delle zone di rispetto.

Input parameter	Symbol	Unit	Value
dimension of the modeled area		m	1600 x 1700
number of rows			85
number of columns			80
grid dimensions		m	20x20
simulation time (transient in 3 stress periods at constant discharge)		day	30 - 60 - 90
aquifer type		unconfined	
anysotropy	Kx/Ky		1
various type boundaries (constant head along river at the NW and SE reaches, no flow along the hill at the W, and right bank at the E)			
recharge from precipitation	N	$m^3/d/m^2$	8,00E-4
observation points			3
variable aquifer thickness	H	m	0 - 30
variable hydraulic conductivity	K	m/d	300 - 650
porosity	n	-	0,2
total well discharge (distributed in multiple wells)	Q	m^3/d	8640

Main assumptions: gridded area of small cells, steady and transient conditions simulation, one unconfined isotropic aquifer, no riverbed resistance, various boundaries w. Constant/Variable head, constant recharge from precipitation, observation points, spatially variable K, spatially variable aquifer bottom, constant porosity, multiple wells discharge, backward particle tracking for advection (random walk method) calibration.

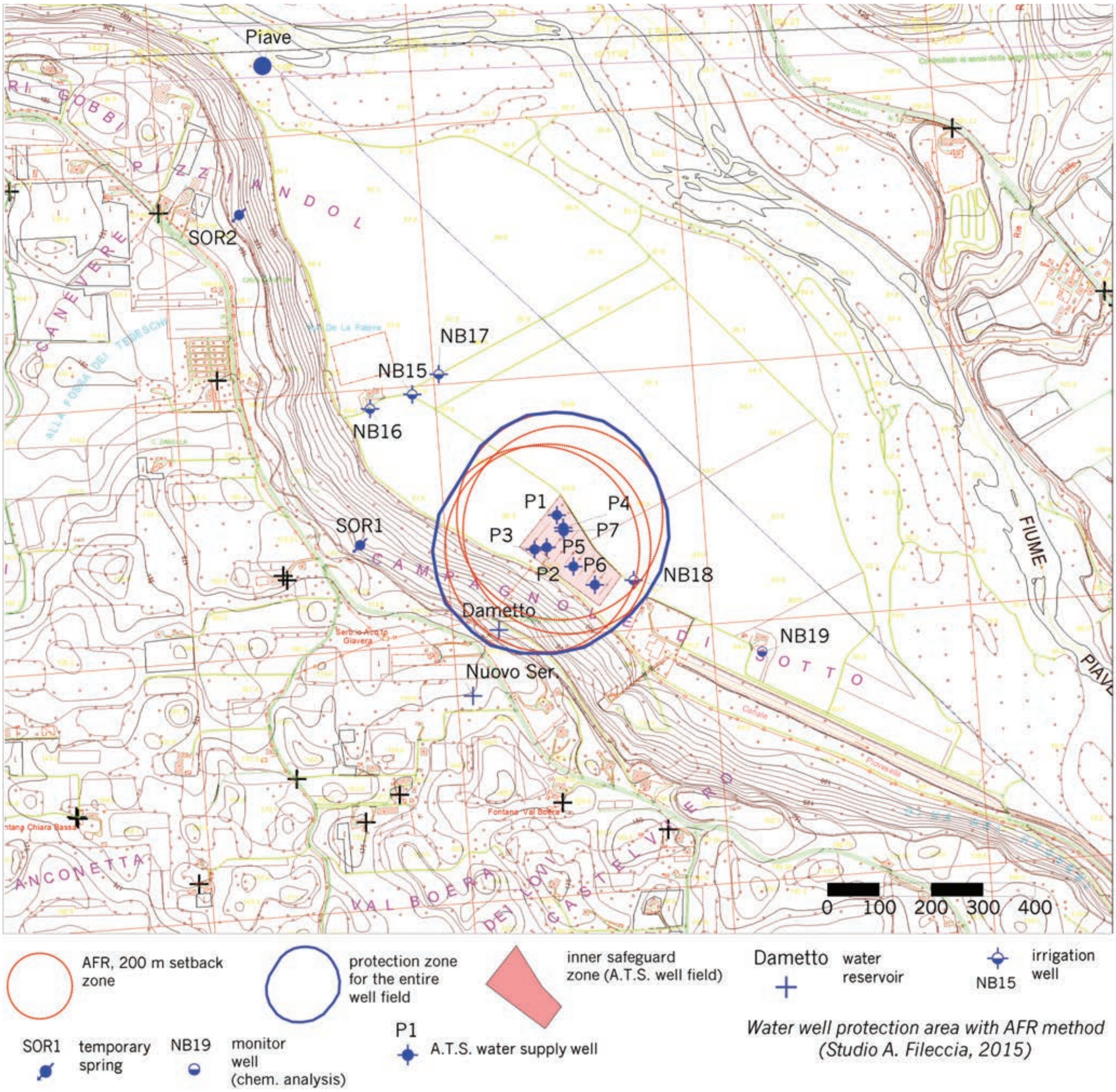


Fig. 10 - Arbitrary fixed radius delineation zone (200 m setback, adopted as a provisional intervention in the Italian legislation).

Fig. 10 - Delimitazione dell'area di protezione con criterio geometrico. La distanza di 200 m dal punto di prelievo è quella adottata in via provvisoria nella legislazione italiana.

ber of simplifying assumptions and in the lack of alternatives Braumiller (2000) advices to adopt a safety factor, ranging between 1.5 and 2.5 to multiply to the zone's bounding parameter (e.g. x_s , y_{max}).

Further remarks

At this stage of the investigations the use of a 2D model is restricted only to the evaluation of the capture zone in different times. A preliminary calibration made for heads (see the scatter diagram on Figure 13) has shown a good fit, while the water budget gives a recharge rate from constant head

Tab. 4 - Groundwater protection zone extensions with different methods.

Tab. 4 - Estensione delle zone di protezione con diverse metodologie.

	Method	TOT (days)	Area extension (m^2)
A	fixed 200 m radius		153000
B	Todd 1980, Ceric and Haitjema 2002	90	170000
C	WhAEM2007 (analitic element)	90	174000
D	ASM (2D finite difference)	90	213000

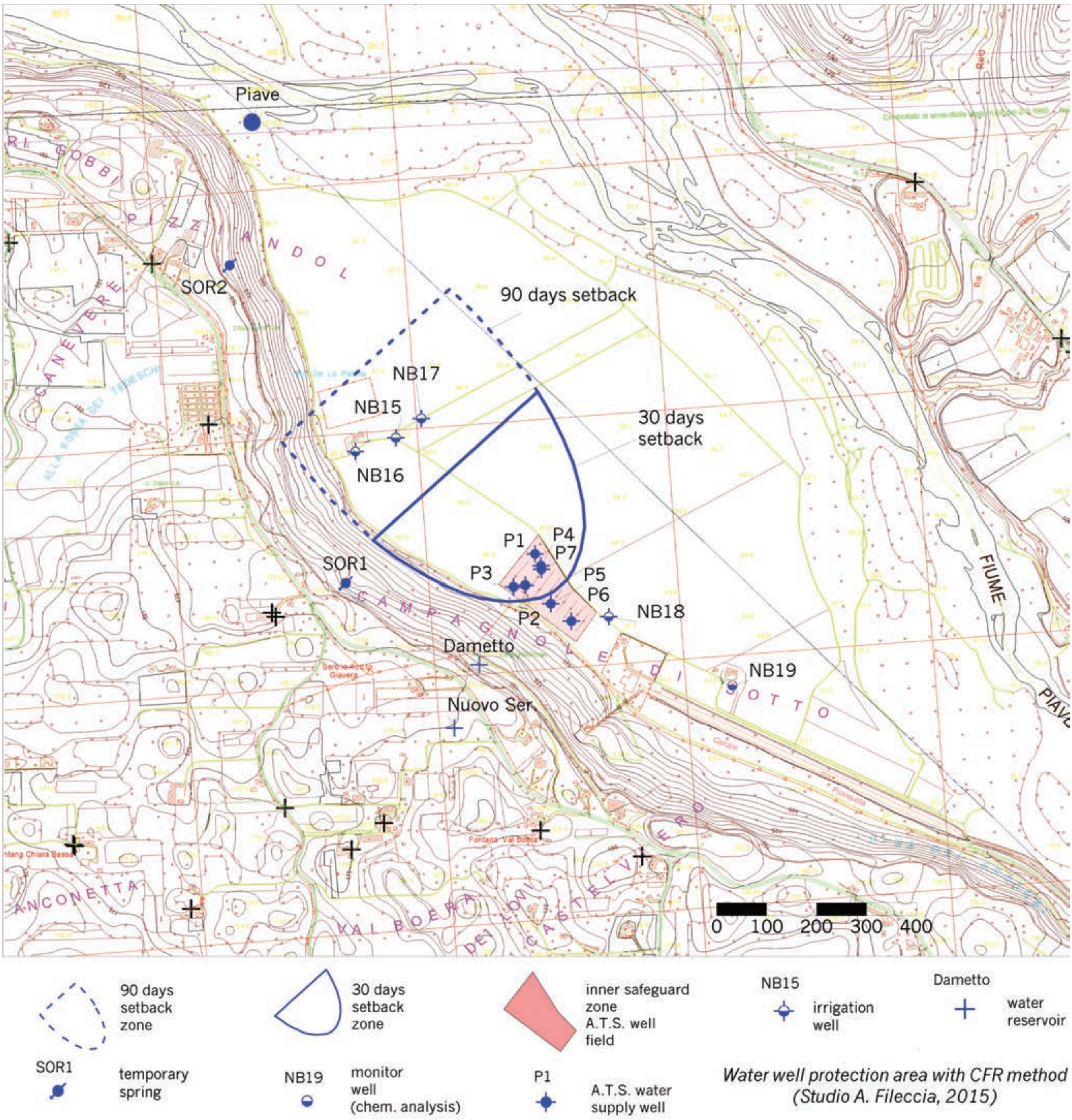


Fig. 11 - Boat shape capture zone (Todd1980, Ceric and Haitjema 2002). The capture zone is bounded upgradient for two different Times of Travel (TOT), using the procedure suggested by Ceric-Haitjema. The width of the capture is 470 m, the stagnation point is at 75-80 m distance and the 90 days setback zone is truncated 512 m upstream.

Fig. 11 - Calcolo della zona di cattura a forma di "scafo" (Todd1980, Ceric and Haitjema 2002). La zona è limitata a monte del flusso per due tempi di percorrenza (TOT) utilizzando la procedura suggerita da Ceric ed Haitjema. La larghezza è di 470 m, il punto di stagnazione a 75-80 m di distanza, e l'isocrona dei 90 giorni a 512 m.

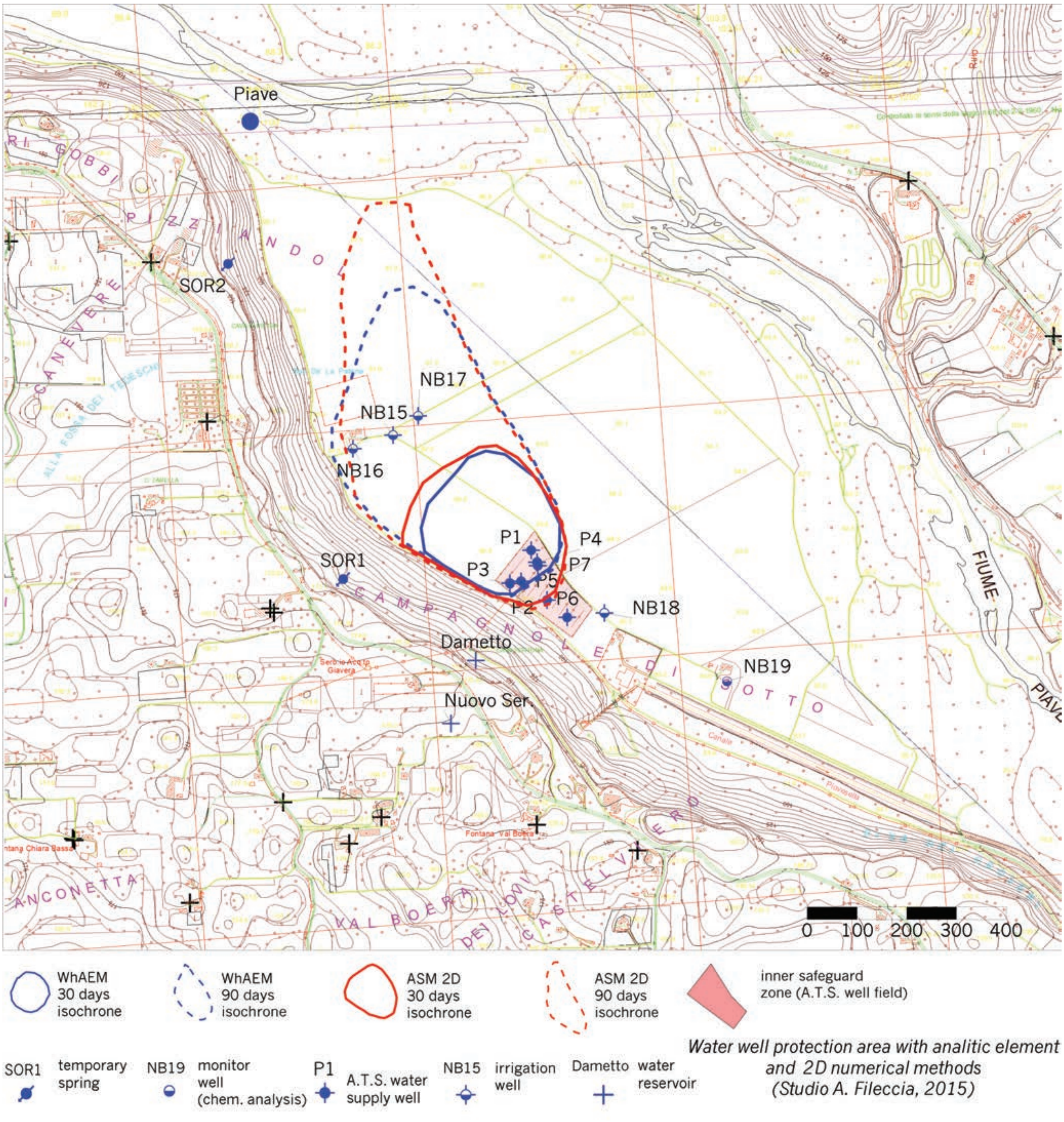


Fig. 12 - Capture zone delineation using two software tools: a simple analitic element code (WhAEM2007) able consider local hydrogeological parameters at steady state, like pumping wells, hydrological boundaries, K heterogeneities etc., and a bidimensional finite difference model (ASM).

Fig. 12 - Delimitazione delle zone di protezione con l'utilizzo di due codici numerici: un semplice modello del tipo "analitic element" (WhAEM2007) in grado di considerare alcuni parametri idrogeologici locali in regime permanente come pozzi in pompaggio, limiti idrogeologici, conducibilità idraulica variabile ecc. ed un programma bidimensionale alle differenze finite (ASM).

cells on the NW border, of 18000 m^3 /d in transient conditions. By considering Figure 9 we see that the water volume withdrawn annually, by the well field (2522880 m^3) exceeds that in the pore space between high and low water table levels (993256 m^3 , during 2013-2014). It follows that, the higher percentage of the supply system is derived from bank infiltration. One point that should be investigated deeper, relates, therefore, to the water budget and further runs and field tests are planned to better evaluate varying discharge and recharge, in time and space. Starting from Theis (1940) several Authors have set forth the importance of the dynamic response of an aquifer system and that a sustainable development can be larger than natural discharge. Bredehoeft (2002) has clearly explained that "it is only through the study and understanding of aquifer dynamics that one can determine the impact of an imposed stress on an aquifer system". In the same paper the Author underlines how much important is the position of the supply system in comparison with the recharge and discharge zones and the advantage in using a modeling tool, over simpler and conventional methods, lies therefore, in its capability to study the dynamics of groundwater systems and how capture changes with time.

Conclusions

The paper has presented some simple mathematical and numerical procedures to evaluate the shape and dimensions of the protection zones around water supply wells in an unconfined aquifer in transient conditions. Data collection and assessment and criteria selection have also been described. The extension of different zones obtained with five methods were evaluated and compared. From the above description it follows that the Arbitrary Fixed Radius (AFR) gives a representation of the protection area, not related to a real hydrogeological situation and therefore inaccurate. Methods based on analytical formulas and a simple analytic element software, (Calculated Fixed Radius, CFR and WhAEM2007) better if coupled with an hydrogeological survey, give a more adequate delineation. The last approach, based on a 2D numerical simulation has shown a much larger 90 days capture zone that could be judged more effective due to the increased number of hydrogeological parameters derived from field tests.

Being the CFR method rather straightforward in its application, it could easily substitute, during the first stages of the delineation process, the geometric 200 m fixed radius approach, adopted by the Italian regulation. The Author recognizes also that simple methods cannot account for complexities of real hydrogeological systems and their use can lead to over-or underestimate the capture zone, but an analytic element model, coupled with some field hydrogeology, represents an affordable compromise between deep investigations and outcome reliability. The general application of a complex numerical model for capture zone evaluations, is in many situations impractical due to its lengthy assessment, cost of the investigations and extreme chemical variability of contaminants, moreover the increase of input data, is associated to a certain degree of uncertainty reducing the validity of the assumptions.

It must be anyway recognized that this latter method, when correctly executed, allows a detailed, spatially distributed and accurate description of the aquifer and the wellfield with the great advantage to describe the groundwater dynamics of the system and a more realistic limit for the sustainable yield.

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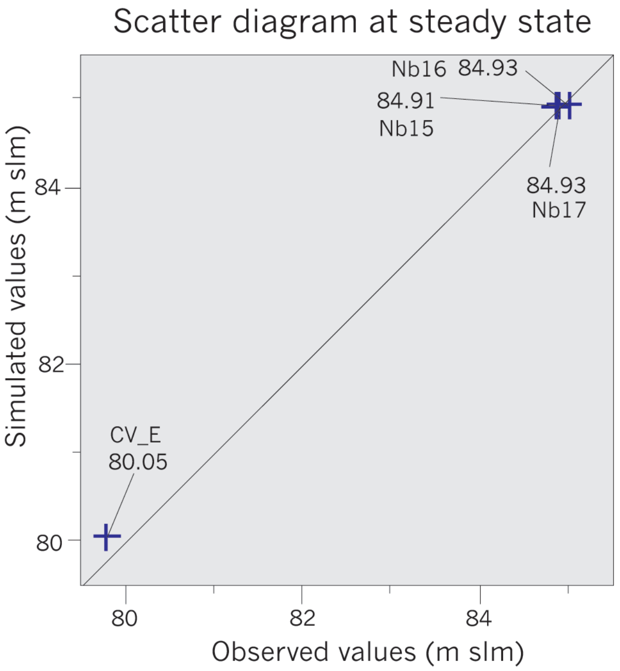

Fig. 13 - Scatter diagram at steady state.

Fig. 13 - Scatter diagram in regime permanente.

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