Ground Water Monitoring&Remediation

Automatic Delineation of Capture Zones for Pump and Treat Systems: A Case Study in Piedmont, Italy

by Tiziana Tosco, Antonio Di Molfetta, and Rajandrea Sethi

Abstract

The design of a pump and treat (P&T) system for the hydraulic control of a contaminated plume in a confined aquifer is presented here. Being the system designed for the emergency containment of a nonaqueous phase liquid plume, the evaluation of the system's short-term efficiency was considered an important issue. For this reason, both time-related and ultimate capture zones were defined. They were traced using the automatic protection area (APA) model, a capture-zone delineation tool based on a hybrid forward-backward particle tracking algorithm, that provides an automatic post-processing encirclement of capture zones. Two simple indexes are here proposed for the evaluation of the performance of the hydraulic barrier, that is, the efficacy and efficiency indexes, calculated from the capture areas provided by APA. The discharge rates of the wells were dimensioned applying the APA algorithm, maximizing efficacy and efficiency of the barrier. Results proved both visually (via plotting of capture zones) and numerically (via calculation of the indexes) that the P&T system can provide a complete capture of the contaminated area and minimizes the volume of extracted water. Consequently, the APA algorithm was proved to be a useful tool in capture zone delineation. As a future perspective, it could be coupled with the real-time measurement of pumping rates and water levels and be implemented as a part of a tuning tool for the management of the hydraulic barrier.

Introduction

Pump and treat (P&T) is a conventional, well-established technique for containment and reduction of groundwater contamination. Although other technologies are more effective in the presence of a nonaqueous phase liquid (NAPL) phase (Rabideau and Miller 1994; Saez and Harmon 2006; Di Molfetta and Sethi 2006; Tiraferri et al. 2008; Dalla Vecchia et al. 2009; Zolla et al. 2007, 2009), it can be successfully applied when the migration of a contaminated plume is to be intercepted, and receptors are to be protected downgradient the contaminated site. Then, it is often chosen for plume treatment and containment, when the source position is not well known, and when the costs of other remediation techniques are high. The application is more convenient in the presence of highly mobile compounds, in particular for species that can be hardly treated via in situ remediation techniques. However, if the contamination is due to strongly adsorbing compounds, and/or when a nonaqueous phase acts as a continuous source, the barrier design is to be lead with particular care (Hall and Johnson 1992). Long-term costs associated with the barrier management and the extracted water treatment can then increase dramatically. A wide literature is available on this topic (Zhang and Brusseau 1999; Johnson et al. 2003). In many cases, a P&T system is used as an emergency solution for plume containment, whereas other more efficient and rapid remediation techniques are directly applied in the contaminated area.

For a correct and reliable P&T system design, a detailed characterization of the aquifer system and of the contamination is the first, most important step. Then, a "target area," that is, the area to be captured by the pumping wells, must be identified, and number, location and discharge of the wells are to be determined, in order to capture all water flowing through the target area. A number of optimization tools are nowadays available for the definition of the optimum set of wells and discharges (Zheng and Wang 2002; Bayer and Finkel 2006; Potter et al. 2008). The capture zone delineation for the pumping wells of an hydraulic barrier is usually performed with particle tracking-based techniques (Pollock 1989). If this approach is used, particles are located within the model domain and traced (backward or forward) along the flow lines, and a time of travel (TOT) is associated to each point of the trajectories. A backward particle tracking is

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commonly used when evaluating the capture efficiency of an hydraulic barrier: a circle of particles is located around each well, and then traced backward in the reversed flow direction. Ultimate capture zones, that is, for virtually infinite travel times, are usually employed. Less often, a set of particles is located in the contaminated area, and then traced forward, to evaluate whether they are all captured by the wells.

In this work, a TOT-based approach for the optimization of pumping rates of an existing hydraulic barrier, and for the delineation of the corresponding capture zones is presented. The hydraulic barrier was realized for the emergency containment of a plume of mixed organic NAPL compounds, released into in a strongly heterogeneous, confined alluvial aquifer in Piedmont (Italy). Calculations of time-dependent and ultimate capture zones were calculated using the automatic protection area (APA) method (Tosco et al. 2008), based on backward tracking from the pumping wells. The APA method was originally developed for the delineation of protection areas for drinking water supplies, but it can be successfully applied also in case of hydraulic barrier design and management. The delineation of ultimate capture zones, commonly employed in the design of P&T systems and for long-term efficiency evaluation, can be improved and automated if the APA algorithm is used: provided a flow model, the APA algorithm calculates closed capture areas in terms of (x, y) coordinates. Consequently, no further post-processing of the results is required, which is often necessary, on the contrary, when using most of the available particle tracking codes. Moreover, this method can be also applied in defining time-related capture zones, that will be later shown to be useful when evaluating the short-term performance of the hydraulic barrier. Short-term performance of the system is particularly important when the barrier is designed for an emergency plume control, as the case study herein presented.

Two synthetic indexes (namely, efficacy and efficiency of the barrier) are here proposed, that can be of particular importance when the hydraulic barrier is realized for an emergency control. These indexes, together with a rapid and automatic tool for capture zone encirclement, can be useful for a real-time evaluation of the performance of the barrier, allowing prompt adaptations of well discharges.

Automatic Capture Zone Delineation: The APA Algorithm

APA is a hybrid forward-backward two-step algorithm, based on the identification of the stagnation points. Multiple pumping wells can be managed simultaneously. It was developed with the purpose of solving two problems that often arise in the delineation of capture zones:

- A large number of particles are always required for a good quality delineation of the areas, in particular when dealing with complex flow fields and a large number of pumping wells. In these cases, circles of equally spaced particles, that are commonly employed by all most popular particle tracking software, can often turn out to be inefficient, due to the large number of particles required for a good resolution of capture zones in particular regions (e.g., close to stagnation points). The first step of the APA algorithm was consequently developed to define optimized starting positions for circles of nonequally spaced backward particles. The choice of starting points for the final set of backward particles is based on a first run of a limited number of backward (from wells) and forward (from stagnation points) particle tracking (Tosco et al. 2008).
- A manual delineation of capture zones is time demanding, when a large number of particles is used, and the implementation of an automatic encirclement algorithm is not simple: when defining capture zones for multiple wells, perimeters must not overlap, cross pathlines, include points with a travel time higher than the fixed one, include part of capture areas of the other wells, etc. The second step of the APA algorithm provides a completely automatic encirclement tool that addresses all these issues.

Details on the structure of the APA algorithm and synthetic test cases are reported elsewhere (Tosco et al. 2008; Tosco and Sethi 2009).

The APA algorithm was implemented in a Matlab environment. The finite-differences code MODFLOW 2000 (Harbaugh et al. 2000) was used for the flow model, whereas MODPATH (Pollock 1989, 1994) was employed for particle tracking. However, the algorithm can be adapted to any flow and particle tracking code with minor modifications. Free download of the code for Matlab users is available in the web at http://www.polito.it/groundwater/software/index.html.

Site Description

The studied site is located in Piedmont (north-west of Italy), in the plain at the foot of the Alps. The geology and hydrogeology of the site are quite complex. Quaternary alluvial deposits are characterized by an alternance of sandy-gravelly materials and silty to clayey levels. As a general rule, grain size of the more coarse layers decreases as the depth increases. In the first 25 to 30 m, two aquifer systems can be identified: a first, unconfined aquifer, and a second, confined one, with a lower conductivity. Silty, discontinuous lenses can be locally found in the deeper system. The grain size varies significantly both in depth and across the aquifer system. Geological logs clearly revealed the presence of a dividing clayey layer between the two aquifers, approximately at 10 to 15 m below ground surface, whose thickness slightly decreases moving southward (Figure 1).

The contamination of the alluvial aquifers is due to past spills coming from a petroleum transformation plant, which is still active. A variety of organic contaminants was released in the vadose zone and spread in the underlying aquifer systems. Nowadays, a wide plume of mixed NAPLs is present both in the unconfined and in the second aquifer system below the plant. Although several piezometric investigations support the hypothesis that the hydraulic connection between the two aquifers is negligible, in the last decades part of the contaminants spilled out in the upper system reached the lower one through the clayey aquiclude via diffusion. Migration due to advective transport was excluded. Based on the results of the characterization of the contamination in the lower aquifer (data not reported

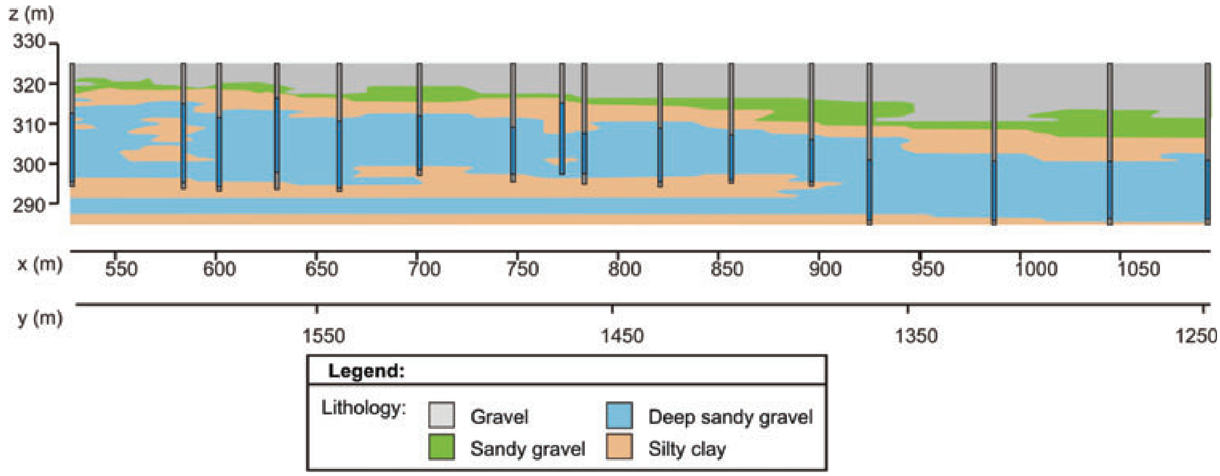

Figure 1. Cross section describing the lithology in proximity of the barrier.

here), the whole area below the factory was consequently identified as the "target area" to be captured by the P&T system, that was installed as an emergency intervention for hydraulic control of the dissolved phase. Targeted remediation activities were implemented in the most critical source areas in the upper aquifer. A few kilometers south of the plant, a drinking water supply area is present and its protection against pollutant migration was identified as a primary scope of the P&T intervention.

The hydraulic barrier was designed in two steps. First, the position and pumping rates of the wells were determined. The choice of the location of the wells was strongly limited due to the presence of different plant facilities in the area. The APA model was then applied in order to solve several issues that arose in the management of the barrier: some wells revealed not to be able to provide the required discharge rates in different seasons. Consequently, the APA algorithm was employed to check whether the pumping rates provided by the wells were sufficient for a complete capture of the contaminated area.

The hydrogeological characterization of the aquifer was undertaken by multi-well tests and slug tests. Slug tests were performed in 36 piezometers and the results were interpreted using the Kansas Geological Survey (KGS) method (Hyder et al. 1994). Moreover, 12 multi-well multi-step drawdown tests were performed in the wells of the hydraulic barrier, to determine both the hydrodynamic parameters and the well efficiency (Bierschenk 1964; Kruseman and Ridder 1970). Measurements of hydraulic levels in the upper aquifer after the realization of the hydraulic barrier were not influenced by pumping in the lower aquifer. This confirmed the initial hypothesis of an hydraulic separation of the upper from the lower aquifer system.

Numerical Modeling

Flow Model

The flow field for the second aquifer was solved using the finite-differences numerical code MODFLOW 2000 (Harbaugh et al. 2000). Being the second aquifer system clearly isolated from the upper one, it was modeled using a unique layer. The morphology of the top and the bottom was reconstructed on the data from 39 boring logs. The top of the aquifer is located at an average depth of 14 m below ground surface and is characterized by an average thickness of 15 m. The model domain is 1700 m × 1180 m wide (Figure 2) and the grid spacing varies from 10 m to 3 m. Consequently, the model accounts for 202 rows and 328 columns. First type flow boundary conditions were applied at the limits of the domain, imposing a linearly changing, constant-in-time, head. Effective porosity was assumed to be constant all over the model domain, equal to 0.2, according to the lithology of the solid matrix. Multi-well and slug tests revealed that the hydraulic conductivity K is strongly variable across the site. Consequently, 10 homogeneous zones were identified. K values for all zones were determined via calibration of the flow model over 20 undisturbed piezometric measurements, taken during the wet season. The calibration process resulted in hydraulic conductivities ranging from $3.0 \times \cdot 10^{-5}$ m/s to $8.4 \times \cdot 10^{-5}$ m/s. The simulated undisturbed hydraulic head is reported in Figure 2, as well as the subregions of homogeneous hydraulic conductivity. The calibration of the model was performed using PEST (Doherty 2002), minimizing a root-mean-squared-error function. The obtained absolute residual mean is 0.293 m and the standard error of the estimate is 0.076 m.

Capture Areas

The hydraulic barrier was positioned immediately downgradient the target area (Figure 2), for a total of 21 wells, along the southern and eastern limits of the target area, numbered 1–21 from east to west. As the spacing among wells was irregular, due to the presence of a number of pipelines and other plant utilities, the final discharge rates resulted not to be regularly distributed among wells.

The piezometric investigations indicate that the seasonal fluctuation of the piezometric level is around 1 m. This value was taken into account in order to develop two "limit" scenarios for the delineation of the capture areas: one for the summer season (low level configuration, usually

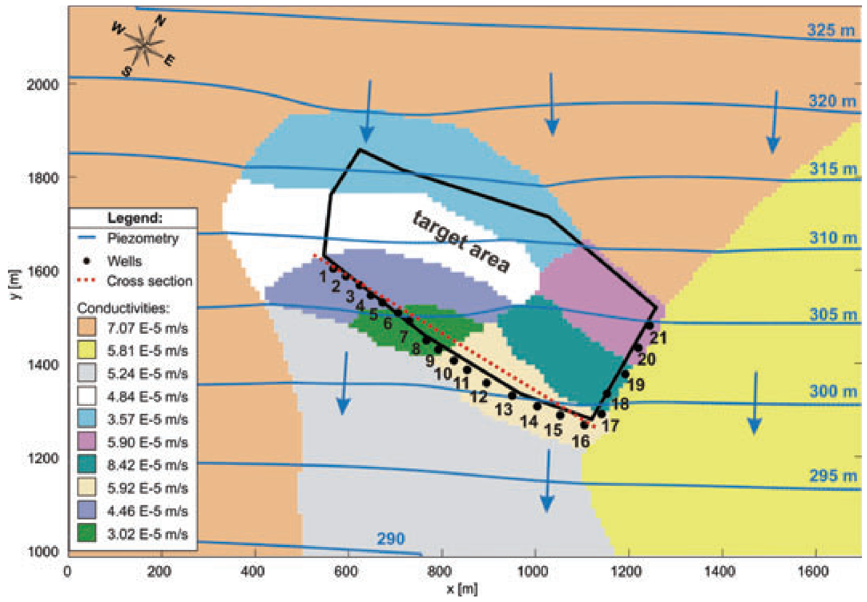

Figure 2. Model domain reporting the subregions with homogeneous conductivity, the perimeter of the target area, the position of the cross section reported in Figure 1, and the undisturbed water table elevation (high level condition).

found in late summer) and one for the wet season (high level configuration, usually found in early spring). During most part of the year intermediate water levels were found. After the calibration for the conductivity values, the barrier was dimensioned on the wet season, as this is the more critical one for a complete capture of the target area.

The APA model was then used for the capture zone delineation in both high and low level configurations, with a total number of about 2500 backward particle runs for each simulation. Dimensioning of the well discharges was lead considering the following constraints:

- Complete capture of the target area (i.e., capture efficacy equal or close to 1. See the following section for the definition of this parameter).
- Discharge rates compatible with the low level configuration.
- For some wells, maximum discharge rates limited due to a partial damage of the permeability, as observed in the field after drilling and development of the wells.

Results for optimized ultimate and time-related capture areas are reported in Figure 3 (high level configuration). Capture zones for the low level configuration are not

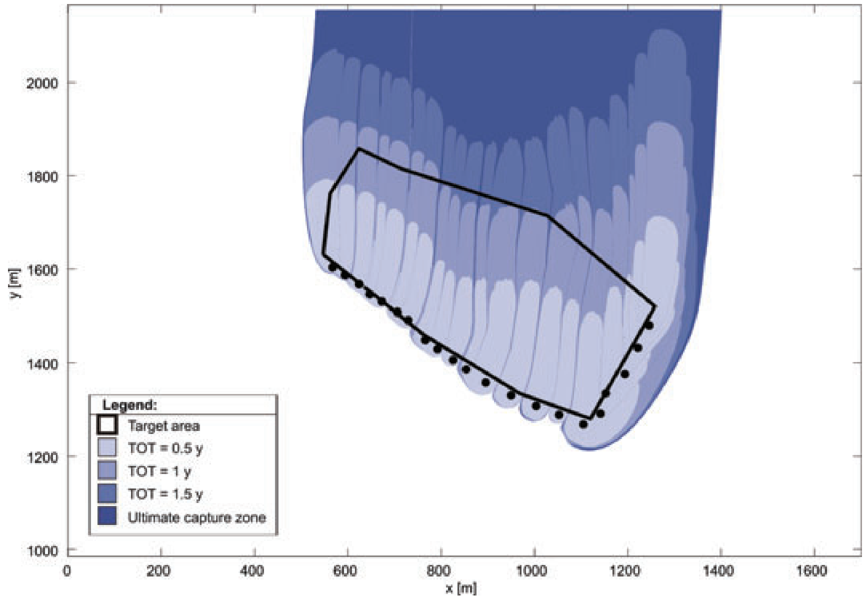

Figure 3. Capture zones for the 21 wells of the hydraulic barrier as they result from the dimensioning of the barrier (high level season). The time-related capture areas are calculated for travel times of 180 days, 1 year, and 1.5 years. The target area limits are also reported.

shown here, because they are not significantly different from the ones obtained for the high level (see the Results and Discussion section).

Results and Discussion

Capture zones were calculated for travel times of 180 days, 1 and 1.5 years, and for a virtually infinite travel time. Ultimate capture areas were considered when defining the discharge rate of the barrier wells, as it is usually done in a P&T system design. However, time-related zones were also defined because, for this application, the short-term performance of the system was considered as an important issue.

As for the ultimate capture zones, the two head configurations lead to very similar capture zones, both in extent and in shape. During the summer season, they show an evident overlap and include a relevant area downgradient the wells. As for time-related capture zones, the whole target area is covered for a travel time of 1 year.

Efficiency indexes were defined to evaluate the effectiveness of the barrier in capturing the target area. The performance of a P&T system can be measured using several indexes, based on both flow considerations (e.g., hydraulic efficiency) and contaminant concentration monitoring (e.g., chemical and hydrochemical efficiency) (Cohen et al. 1994; Di Molfetta et al. 2002). In this application, a short-term efficiency, rather than the long-term one, is of concern, the purpose being the containment, and not the remediation, of the contamination. Thus, the barrier performance is evaluated on the basis of hydraulic indexes, and concentrations are not taken into account.

Capture efficacy and efficiency, as defined in the following section, were calculated from the output of the APA model and the flow field provided by MODFLOW. As the perimeter of the capture areas in terms of (x, y) coordinates is one of the outputs of the APA algorithm, calculation of their extent is immediate. It can be therefore used in numerical indexes that estimate the performance of the hydraulic barrier design. In particular, two parameters were used:

- The capture efficacy, expressed as the fraction of the target area captured by each pumping well, indicated with $(E_s)_i$, or by the whole barrier, indicated with E_s. The total capture efficacy E_s is the sum of the $(E_s)_i$ of the single wells in the barrier. It can be represented as

$$E_s = \sum_{i=1}^{N_w} (E_s)_i = \sum_{i=1}^{N_w} \frac{\left(S_{TA,b}\right)_i}{S_{TA,tot}} = \frac{S_{TA,b}}{S_{TA,tot}} \quad (1)$$

where N_w is the number of pumping wells, $(S_{TA,b})_i$ is the surface of the target area captured by the ith well, $S_{TA,b}$ is the surface of the target area captured by the whole barrier, and $S_{TA,tot}$ is the total extent of the target area. This parameter can be evaluated for time-related capture zones as well as for the ultimate capture area. Results for the capture efficacy in this application are discussed in the following section and reported in Figures 4 and 5.

- The capture efficiency, expressed as the ratio of the aquifer discharge that crosses the target area against the total discharge captured by the wells. The parameter can be evaluated for each well, indicated with $(E_Q)_i$, or for the whole barrier, indicated with E_Q. It can be expressed as

$$E_Q = \frac{Q_{TA}}{Q_b} \quad (2)$$

for the whole barrier, where Q_{TA} is the total discharge that crosses the target area, and Q_b is the total discharge extracted by the barrier. For the single well, the capture efficiency can be expressed as

$$\left(E_Q\right)_i = \frac{\left(Q_{TA}\right)_i}{\left(Q_b\right)_i} \quad (3)$$

where $(Q_{TA})_i$ is the discharge that crosses the target area and is captured at the ith well, and $(Q_b)_i$ is the total discharge exacted at the ith well. These parameters can be evaluated for the ultimate capture zones. In this application, the total capture efficiency is 0.85. Differences between high and low level configurations are negligible. Capture efficiency for the single wells is reported in Figure 5b.

In ideal conditions, both parameters should be equal to 1, if calculated over the whole barrier. In practice, when changing the well discharges in order to increase one index, the other one decreases. The higher is the capture efficacy, that is, the more precautionary is the system design, the higher is the over-dimensioning of the discharge rates for the hydraulic barrier, and the higher is the portion of "clean" groundwater that will be captured by the wells.

As stated before, the capture efficacy E_s was here calculated for time related as well as ultimate capture zones, and results are reported in Figure 4. In both high and low level configurations, the capture efficacy for the whole hydraulic barrier approaches 1 and can be considered satisfactory. The long-term value is slightly lower for the high level configuration, which has, in contrast, a higher capture efficiency. E_s increases linearly for short travel times, when the capture zones gradually include the target area. The asymptotic value is reached after approximately

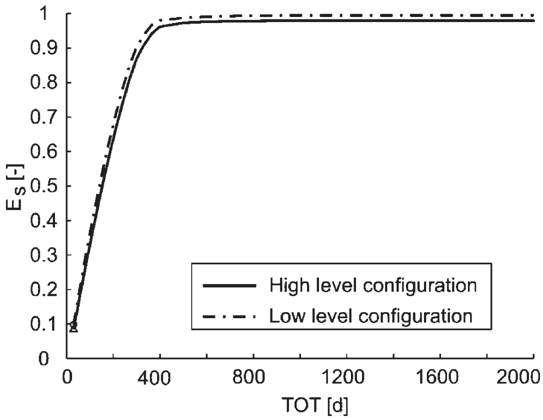

Figure 4. Capture efficacy E_s of the hydraulic barrier, for high and low level configurations. The capture efficacy is reported as a function of the travel time at which the capture zones are calculated.

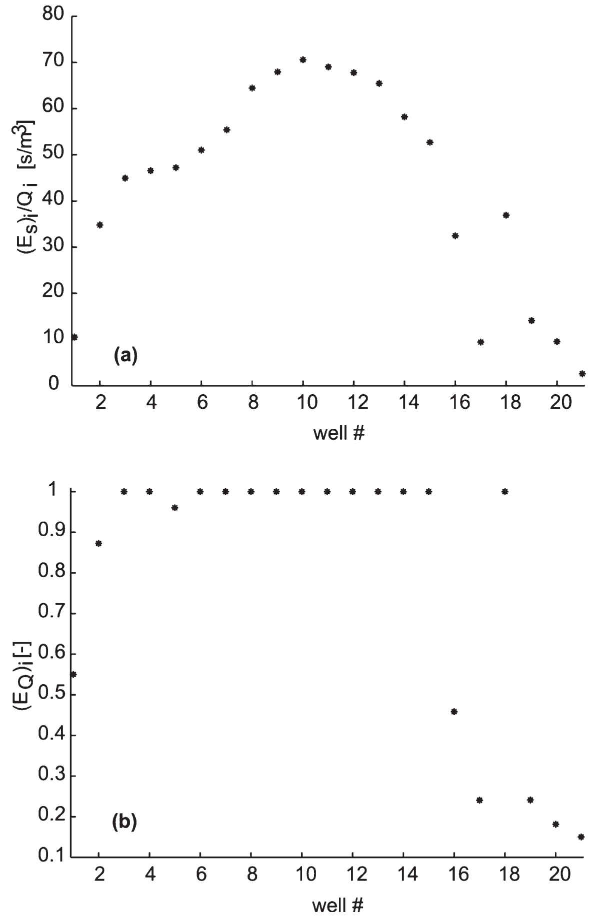

Figure 5. Capture efficacy $(E_s)_i$ (a) and efficiency $(E_Q)_i$ (b) of the single wells, for long-term capture zones, reported as a function of the well ID number. Wells are numbered west to east, as reported in Figure 2. Capture efficacies are normalized by the discharge rates Q_i.

400 days, when the target area is completely included into the capture zones.

The capture efficacy and efficiency of the single wells can be evaluated using plots like those reported in Figure 5. Indexes are reported for the long-term area (infinite travel time). The parameters are plotted against the well order along the hydraulic barrier (as reported in Figure 1, wells are numbered 1 to 21 starting from the western side of the barrier). In Figure 5a capture efficacies $(E_s)_i$ are reported, normalized with respect to the well discharge. The sum of the single, not normalized, efficacies is, obviously, equal to the total value. Intuitively, a well-defined trend should be found in the plot of normalized capture efficacies, $(E_s)_i/(Q_b)_i$: the efficacy should be higher in the central part of the barrier, whereas it should decrease to lower values toward the outer wells. At the extremes, the fraction of "clean" water captured by the wells is the higher, and consequently the efficacy is lower. This is exactly the trend of capture efficacies calculated for the barrier (Figure 5a), that confirms the suitability of this parameter to evaluate the performance of the barrier.

As for the capture efficiency $(E_Q)_i$, a similar trend is highlighted in Figure 5b. Again, efficiency is lower for the outer wells, and higher for the inner ones, as intuition would suggest. In this case, the wells can be divided into two groups: the outer wells, that is, well #1 at the extreme west and wells # 16 to 21 in the eastern part of the barrier, and the inner wells. The outer ones have a lower efficiency, because part of the flow captured did not cross the target area. Wells in the central portion of the barrier have, obviously, an efficiency of 1, because all captured discharge is contaminated. Based on these considerations, we can state that capture efficiency is also a valuable parameter to quantify the performance of a hydraulic barrier.

Conclusions

The capture zone delineation is the basic tool for the design of a P&T system, and for the valuation of short- and long-term performance of the barrier. In this work, the system was designed mainly for an emergency containment of the contamination, rather than the remediation of the aquifer. Thus, the design and efficiency evaluation of the system were focused on flow modeling, and solute transport was not included. The short-time performance was considered of great importance, and consequently time-related capture zones were calculated and used for the evaluation of the barrier efficacy. Two water level configurations were considered: high level (wet season) and low level (summer season). The first one was used for the dimensioning of the barrier.

Both ultimate and time-related capture zones were calculated using the APA algorithm. It was initially developed as a tool for a rapid, accurate, and automatic encirclement of wellhead protection areas, and is here applied for the first time to P&T systems design. Thanks to the automatization of the algorithm, parameters like the capture efficacy and efficiency can be easily calculated, and then used not only in the design, but also in the management of the barrier. The APA model allows to easily re-calculate the capture zones for any change in flow conditions (like the seasonal changes in undisturbed piezometric surface), and in discharge rates of the pumping wells. Consequently, also efficiency and efficacy parameters can be immediately calculated, and changes in the discharge rates can be evaluated both visually, through the capture zone encirclement, and numerically, based on graphs, like the ones presented in Figure 5. As a future perspective, such tools would allow an immediate quantification of how the effectiveness of the whole barrier would be affected by technical problems (which could require, for example, lowering the discharge rates, or switching off some wells in the barrier), and could be used as an automatic tuning tool for the hydraulic barrier.

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