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# Design of Permeable Adsorbing Barriers for Groundwater Protection: Optimization of the Intervention

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The remediation of polluted groundwater can be proficiently achieved with an in situ technology based on the use of Permeable Reactive Barriers (PRBs). In particular, this work deals with the design of a PAB made with activated carbon for the remediation of an aquifer contaminated by tetrachloroethylene (PCE). The design and optimization of barrier parameters (location, orientation and dimensions) were defined by an iterative procedure using a CFD (Computational Fluid Dynamics) approach, allowing the description of direction flow and dynamics of the aquifer and of the adsorption phenomena occurring inside the barrier. With the aim of optimizing the barrier, three different barrier configurations were considered, namely with constant thickness (continuous barrier, PAB-C), with sections of different thickness, tuned on pollutant inlet concentration (semi-continuous barrier, PAB-SC) and an array of deep wells (discontinuous barrier, PAB-D). The results of simulations demonstrated that an accurate selection of barrier configuration based on the shape of the pollutant plume, determines a substantial reduction of barrier volume, hence allowing a significant saving on the intervention.

## 1. Introduction

A Permeable Reactive Barrier (PRB) for groundwater remediation is an in-situ technology that consists in the insertion of a wall of reactive material having a hydraulic conductivity higher than that of the surrounding soils. In this way, the contaminated groundwater, moving under natural hydraulic gradient, is forced to pass through the barrier without any external energy input and is passively treated (Chattanathan et al., 2013). The use of sorbent materials as PRB reactive media is gaining growing interest when dealing with high water volumes and low pollutant concentrations. In particular, the contamination from toxic organic compounds and metals, often deriving from the accidental discharge of leachate from solid waste landfills, can be effectively reduced by adsorption (Di Natale et al., 2011; Leone et al., 2014). This process combines good efficiency and high versatility with a simple configuration (Di Natale et al., 2009; Molino et al., 2013). Clogging phenomena are the main disadvantage of PRBs (Prisciandaro et al., 2009).
In this case, the PRBs are commonly referred to as Permeable Adsorbing Barriers (PABs) and activated carbon is unanimously considered as the most suitable sorbent material, coupling a high adsorption capacity with a wide adsorption spectrum, which allows an efficient groundwater protection (Yua and Choub, 2000; Erto et al., 2012). The operational costs of a PAB installation are mainly represented by site excavation and building material, both directly dependent on the PAB volume. Hence, the optimization of process parameters and barrier dimensions is a mandatory step in order to make the entire treatment as cost-effective and hence widely applicable.
This work deals with the design of a PAB made with activated carbon for the remediation of an aquifer contaminated by tetrachloroethylene (PCE), which is one of the chlorinated organic compounds more often found into groundwater (Erto et al., 2010a). The design and optimization of the barrier aimed at defining

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the main PAB parameters, i.e. location, orientation and dimensions. These parameters were obtained via an iterative procedure with a CFD (Computational Fluid Dynamics) approach.
A specific analysis of the dynamics of the aquifer and the extent of site intervention was carried out in order to minimize the total barrier volume to allow for cost optimization. To this aim three different barrier configurations were considered, namely with constant thickness (continuous barrier, PAB-C) (Erto et al., 2011a), with sections of different thickness, tuned on pollutant inlet concentration (semi-continuous barrier, PAB-SC) and an array of deep passive (un-pumped) wells (discontinuous barrier, PAB-D) (Bortone et al., 2013b). The results of simulations over an observation time of 60 years showed that, in all the cases, the PAB designed is effective to keep PCE concentration below the regulation limit. Moreover, it is demonstrated that an accurate selection of barrier configuration based on the shape of the pollutant plume, determines a substantial reduction of barrier volume, hence allowing a significant saving on the intervention. Finally, a preliminary cost analysis of all PAB systems designed was carried out.

## 2. PAB method design

The remediation of a polluted site is a very expensive process hence a careful design based on the knowledge of specific site characteristics is necessary. Moreover, the optimization of process parameters is a mandatory step in order to make the entire procedure cost-effective and widely applicable. Therefore, a good compromise between technical and economic issues has to be found (Gavaskar, 1999).
The design of continuous, semi-continuous and discontinuous PABs requires a previous characterization of the polluted aquifer, by collecting its hydraulic, geotechnical (e.g. soil properties, aquifer depth, etc.) and contamination information (i.e. type and amount of contamination, length of contaminant plume, etc.) in order to optimize PAB location and orientation to define the PAB dimension parameters (i.e. length, height and thickness) and to individuate a suitable adsorptive material for the capture of pollutant. In addition, the evolution in time of the pollutant plume in the aquifer considered has to be defined in order to design an efficient and time-during intervention. A CFD (Computational Fluid Dynamics) approach can be efficaciously adopted. In Figure 1, the main PAB geometrical parameters are represented. The design of a barrier mainly consists in the optimization of these parameters, minimizing the overall volume and by checking that downstream of the barrier the pollutant concentration is always and everywhere lower than regulation limits. To this aim, the following general rules can be adopted:

- distance from contaminant, X: barrier has to be the closest possible to the pollutant plume;
- orientation, *m*: barrier has to be orthogonal to groundwater flow direction, in order to ensure the capture of the whole pollutant by having the same residence time of fluid through it, and by ensuring the minimum dimensions of the barrier itself;
- length, *L*, and height, *H*: equal to the corresponding pollutant plume dimensions;
- thickness, T: to be chosen considering that the contaminated flow passing through the barrier should be long enough for adsorption process to take place.

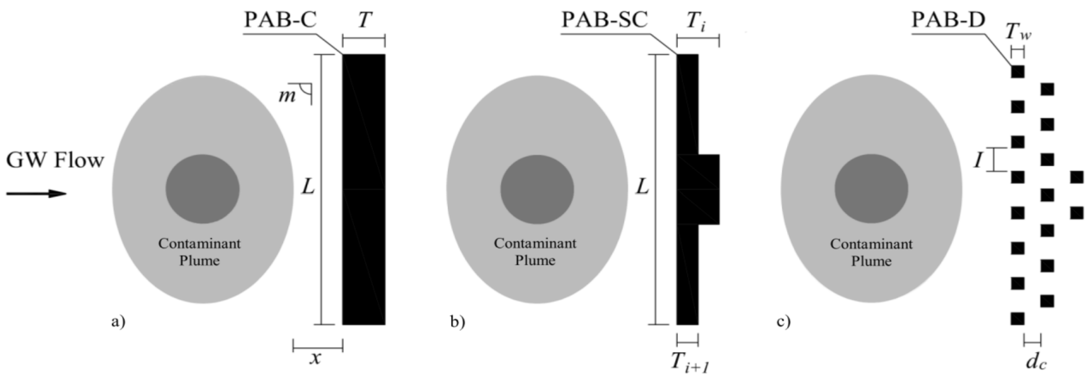


*Figure 1: Schematic representation of: a) Continuous PAB (PAB-C); b) Semi-Continuous barrier (PAB-SC) and c) Discontinuous barrier (PAB-D).*

For a continuous PAB (PAB-C), the thickness is constant for the whole pollutant plume and the value is defined on the maximum pollutant concentration. For a semi-continuous PAB (PAB-SC), the thickness is variable along the length of the barrier in dependence of the contaminant plume shape (i.e. concentration value distribution), therefore a certain number of sections can be fixed. For a discontinuous PAB (PAB-D),

the parameters to be considered are: the well diameter, $T_w$; the well-to-well distance, $l$; the number of well lines in the array, $n_c$; the number of wells in each line, $n_w$; and the line-to-line distance, $d_c$ (Figure 1). PAB-D design consists in the determination of the optimal number of lines and the overall number of wells, in order that the capture zone of all wells intercepts the pollutant plume (Hudak, 2008).
PAB design is generally time-invariant because, once the barrier is positioned and its dimensions set, the scheme does not change during the entire remediation process.

### 2.1 Transport modelling

In an aquifer the transport of solute contaminants is described prevalently by an advection and dispersion mechanism. For a porous media with a uniform porosity, taking into account a two-dimensional system, the contaminant transport equation can be written as in the following (Bear, 1979):

$$\frac{\partial C}{\partial t} = \nabla(D_h \nabla C) - \frac{u\nabla C}{n_s} + R \qquad (1)$$

where $C$ is the concentration of pollutant (e.g. PCE) dissolved in groundwater, $t$ is the time, $D_h$ is the hydrodynamic dispersion coefficient, $u$ is the seepage or linear pore water velocity, $n_s$ is the porosity while $R$ is the generation/depletion rate by chemical phenomena. The hydrodynamic dispersion coefficient, $D_h$, is a second-rank tensor consisting in the sum of mechanical dispersion tensor and the molecular diffusion coefficient (a scalar). The linear pore water velocity, $u$, can be calculated by the Darcy equation, and it depends on the hydraulic conductivity of the aquifer, $k_h$, and the hydraulic heads.
In a PAB, the term $R$ in equation (1) is represented by adsorption phenomena and it can be expressed as follows:

$$R = k_c a\left[C - C^*(\omega)\right] \qquad (2)$$

Eq.(2) describes the variation with time of the contaminant concentration over the adsorbing solid, where $C^*=C^*(\omega)$ derives from the adsorption isotherm and defines the mass transfer driving force in the transport model equation, $k_c$ represents the overall mass transfer coefficient for adsorption and $a$, the specific surface area of adsorbent particles. Throughout the entire flow domain, the initial PCE concentration in the groundwater is known and it is assumed to be zero on the surrounding soil.
In order to design the different configurations of PAB, the modelling equations with their appropriate boundary conditions were solved via the finite difference method by adopting a commercial 3D software for groundwater flow and pollution dynamics simulation, i.e. PMWIN. In particular, PMWIN-MODFLOW toolbox allowed the calculation of the hydraulic flow in the computation domain, while PMWIN-MT3D toolbox was used to solve the mass transport equation (1). A second code called ADSORB-CODE was developed on purpose by the Authors to describe the adsorption phenomena involving the pollutant within the PABs. A granular activated carbon (GAC) commercially available, the Aquacarb 207EA™ (provided by Sutcliffe Carbon), was adopted as adsorbing material. The experimental characterization of the GAC for PCE adsorption, at a temperature of 10°C typical of groundwater, was reported in previous papers (Erto et al., 2010b), and the Langmuir adsorption model resulted to be the most suitable for the system under analysis (Erto et al., 2011b).

## 3. Case study

A PCE-contaminated aquifer near a solid waste landfill in Giugliano in Campania, in the metropolitan area North of Naples (Italy), was examined as a case study. In this area (2.25 km$^2$), several solid landfills are located and an enormous amount of solid wastes was deposited in last decades. A complete characterization of the groundwater was previously made (Bortone et al., 2013a). The aquifer is contaminated by several pollutants, both inorganic and organic, and PCE accounts for the highest concentration. The PCE concentrations are variable into the area and a maximum value of more than 20 times higher than the Italian regulatory limit for groundwater quality, established at 1.1 µg l$^{-1}$, can be individuated. The soil was considered as made of a single mineral type (Neapolitan yellow tuff), with a hydraulic conductivity of $5{\cdot}10^{-5}$ m s$^{-1}$. Throughout the entire flow domain, the pollutant concentration onto soil, instead, was considered to be zero due to its very low adsorption capacity towards organic compounds. The aquifer flux into the area is east-west oriented, with piezometric heights ranging between 5 and 12.5 m a.s.l., under a piezometric gradient of 0.01 m m$^{-1}$. Once identified the volume of the contaminated aquifer, the PABs design procedure can be performed.

## 4. Results

Several iterations based on different geometrical parameters of all the PABs considered were necessary to determine the optimal position and dimensions. Once the three different PABs were designed and optimized, a comparison among them is possible so to individuate the best solution under an economic and technical point of view. To achieve the best capture efficiency of the contaminated plume, each PAB was disposed perpendicularly to the groundwater flow, and in particular with an inclination angle $m$=90°, coincident with North direction; the height, H, was always stated equal to 10 m and all PABs were put at a distance from the PCE plume, X of 6m. PAB-C and PAB-SC resulted to be a continuous trench penetrating the aquifer at full-depth up to the aquitard with a total length, $L$, of 900 m. In order to define the optimal thickness, $T$, further simulations were carried out in the range T=0 to 4 m, with a ΔT step of 0.1 m, allowing to minimize PAB thickness. For the PRB-C, the best thickness obtained was equal to 3 m, constant for the whole trench. Differently, for PAB-SC, the continuous trench was divided into 5 sections (namely T1, T2, T3, T4, T5) whose optimal dimension (i.e. thickness) is reported in Table 1, tuned on the different PCE concentration reaching the barrier itself. The most critical section of PAB-SC resulted to be section T3 where the highest PCE concentration is reached during the run time. Finally, for PAB-D, a constant diameter, $T_w$, of all wells forming the array equal to 2m was considered. Moreover, in order to optimize the overall number and position of the wells, 6 sections of the plume were identified and, for each of them, a different set of parameters (i.e. $T_w$, $I$, $n_c$, $n_w$, and $d_c$) was defined. The six sub-arrays resulting were all characterized by a well to well distance, I, constant and equal to $4 \cdot T_w$. The final calculation allowed to estimate a total number of 553 wells and a maximum number of well lines, $n_c$, equal to 8 (i.e. corresponding to the zone where the highest PCE concentration reaches the barrier) (Bortone et al., 2013b). In Figure 2, the PCE inlet and outlet concentrations as a function of the working time for PAB-C, PAB-SC and PAB-D, for the most critical barrier point (i.e. the one reached by the highest PCE concentration), are reported as breakthrough curves. As can be observed, for all the PAB configurations analysed, during a run time of about 60 years the out-flowing PCE concentration is always lower than the Italian regulatory limit, also taking into account the possible occurrence of desorbing phenomena from GAC to groundwater deriving from a variable PCE inlet concentration (cfr. Figure 2).

In addition, a preliminary cost analysis for all PABs dimensioned, was carried out. The main variables considered were the construction cost, the adsorbing material cost, ranging from 100 to 500 € $m^{-3}{}_{GAC}$ and the monitoring costs. Construction cost for the PAB-C and PAB-SC were considered ranging from 70 to 100 € $m^{-2}$, while for the PAB-D from 120 to 150 € $m^{-1}$ each well. The overall cost estimated for each PAB configuration is reported in Table 2. According to this preliminary cost analysis, the use of a PAB-C appears to be less cost-effective. Furthermore, it is not possible to establish with certitude which barrier configuration, among those remaining, is the most cost-effective for the case study presented. This is principally due to the wide margin of variation of the unit cost of the main variables examined. The easier realisation of the PAB-D, according to the commonly used excavation techniques, would suggest this configuration in comparison with the others, although a more accurate optimization and site specific cost analysis would contribute to a more precise and reasoned choice.

*Table 1: PABs parameters*

| PAB | $n_T$ | | H [m] | L [m] | T [m] | $v_{PAB}$ [$m^3$] | $V_{PAB}$ [$m^3$] |
|---|---|---|---|---|---|---|---|
| PAB-C | 1 | | 10 | 900 | 3.0 | | 27,000 |
| PAB-SC | 5 | $T_1$ | 10 | 204 | 1.4 | 3,570 | 21,462 |
| | | $T_2$ | 10 | 108 | 2.1 | 2,835 | |
| | | $T_3$ | 10 | 264 | 3.0 | 9,900 | |
| | | $T_4$ | 10 | 138 | 3.0 | 5,175 | |
| | | $T_5$ | 10 | 186 | 2.3 | 5,348 | |
| PAB-D | 553 | | 10 | 2 | 2 | | 22,120 |

*Table 2: Preliminary cost analysis for all PABs (service life about 60 years)*

| | **Cost [€]** | | | |
|---|---|---|---|---|
| | PAB Construction | Adsorbing material | Monitoring | **Total** |
| PAB-C | 1,890,000- 2,700,000 | 2,700,000- 13,500,000 | 100,000- 250,000 | 4,690,000- 16,450,000 |
| PAB-SC | 1,528,800- 2,184,000 | 2,146,200 - 10,731,000 | 100,000 - 250,000 | 3,775,000- 13,165,000 |
| PAB-D | 663,600- 829,500 | 2,212,000-11,060,000 | 100,000 - 250,000 | 2,975,600- 12,139,500 |

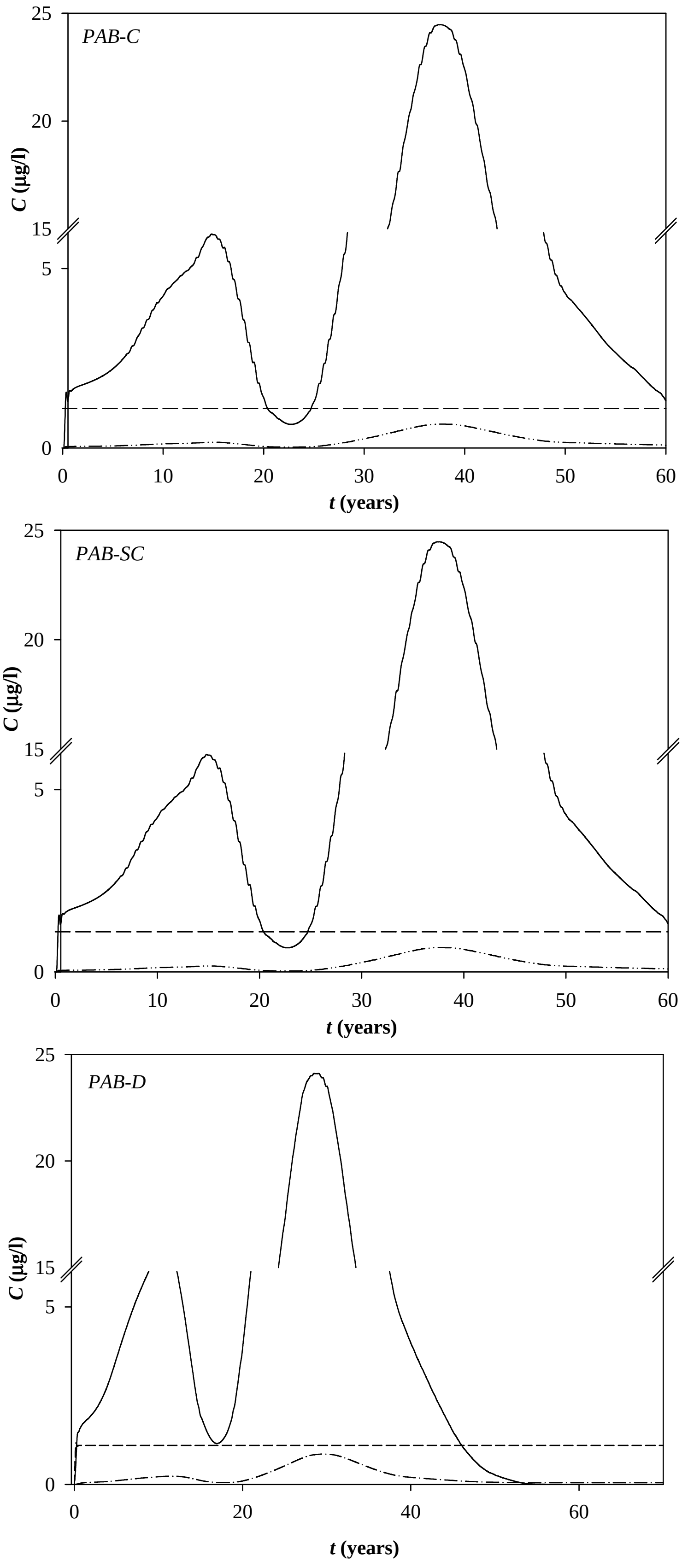


*Figure 2: PCE inlet and outlet concentrations as a function of the working time for PAB-C, PAB-SC and PAB-D. ( ) Cin ( )Cout ( ) Clim*

## 5. Conclusion

In this work, a comparison between different configurations of Permeable Adsorbing Barriers (PABs) made of a commercial activated carbon for the remediation of a PCE contaminated aquifer was carried out. In particular, three different PABs were considered, namely with constant width (continuous barrier, PAB-C), with sections of different width tuned on pollutant inlet concentration (semi-continuous barrier, PAB-SC) and an array of deep passive wells (discontinuous barrier, PAB-D). All the PAB systems were applied to a real case-study, represented by polluted aquifer in the metropolitan area North of Naples (Italy). The design was carried out using the Computational Fluid Dynamics (CFD) by adopting specific software for groundwater flux simulation and adsorption phenomena inside the barrier. A technical and a preliminary cost analysis was reported in order to determine the optimal solution for the remediation of the aquifer. Numerical results showed that all the PAB configurations can be suitable to remediate the groundwater, by reducing PCE concentration under the regulatory limit, and therefore respecting water quality standards. A comparison among all the optimized solutions showed that the adoption of a PAB-C is the least cost-effective. However, the performed preliminary cost analysis is not sufficient to establish which remediation methods is the most cost-effective, and a more accurate analysis site-specific is required.

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