Design of a passive hydraulic containment system using FEFLOW modelling

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ABSTRACT: Within an operating industrial platform located in south-eastern France, a pollution plume affecting groundwater has been identified. Due to the high velocity of the local groundwater flow, the solution involving in-situ chemical treatment considered by the industrial operator would not be effective, because of limited contact time between the treatment product and the groundwater. Thus a passive hydraulic containment system (patented HydrauFaraday® system) is suggested to slow down groundwater velocity locally.

The system consists of a set of upstream drains connected to a set of downstream drains through a central pipe. Between these drains, groundwater flow in the contaminated area will be reduced, thereby making the in-situ chemical treatment more efficient.

The number, diameter, length and spacing of the drains depend on the local hydrogeological parameters and on the intended efficiency. Hence, numerous designs have to be tested to determine the best solution from a technical and economic perspective.

In order to assess the efficiency of the forecasted system, i.e. groundwater velocity reduction, a numerical model was built using FEFLOW. As the drains are thin objects contrasting with the porous medium, representing them was a challenge. Several representation options were tested and compared for this specific purpose. Finally, the discrete feature elements (DFE) of FEFLOW were the most appropriate in this context, and were thus chosen to represent the drains. Dense 3D layering was used to compare different designs in a relevant manner, and as a result accurate vertical mapping of the groundwater velocity was obtained.

The modelling approach led to the selection of the most appropriate representation of the drain pipes, to the selection of the best containment system design and also provided general rules regarding the influence of different factors (anisotropy, permeability, etc.) on the efficiency of the system.

INTRODUCTION AND CONTEXT

Context of the study

The area of study is located in south-eastern France, within an operating industrial platform. Pollution affecting the groundwater has been identified. The source of the pollution is located in the unsaturated zone under a former chemical production building. The lateral extent of the soil polluted area is about 100m x 100m. The pollutants have reached the 10 m deep aquifer and are now continuously migrating downstream. A permanent plume has thus formed from the polluted zone to a production well, which captures most of the pollution. The pumped water is then mixed with water provided by other wells and is used for the industrial process. Finally, industrial water is discharged into the nearby river, with relatively high pollutant concentrations.

In this context, the former operator has to present a remediation solution to the French authorities to reduce the pollutant flow discharged into surface water.

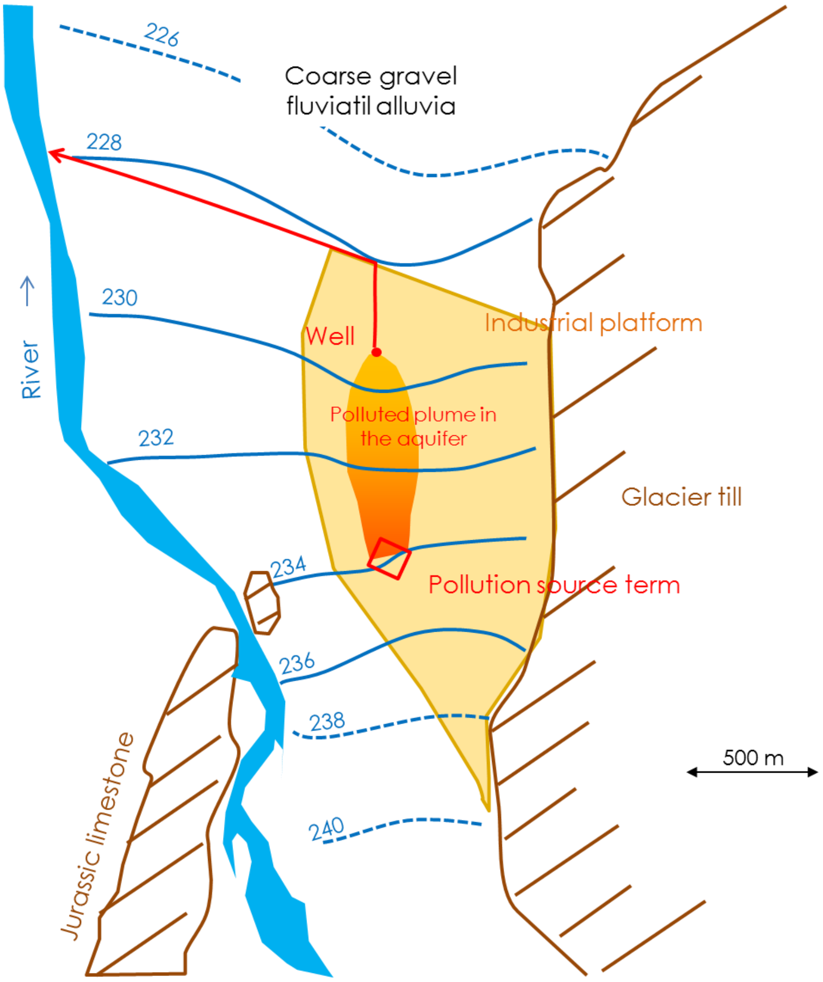


Figure 1: Schematic geological situation of the studied area.

The hydrogeological context is the following: the platform lies on a thick alluvial formation composed mainly of very coarse gravel and cobbles in the first 35 metres and then of silty and clayey sand in the next 35 to 40 metres. The water table is about 10 m deep. The measured permeability of the main aquifer is from 10^{-3} m.s^{-1} to 10^{-2} m.s^{-1}. The aquifer is surrounded by low-permeability glacier till on one side and by a river and limestone on the other side. The upper formation contains significant groundwater flow that is mostly fed by the river.

One of the alternative solutions considered by the operator for the remediation works is to use in-situ chemical treatment that will degrade the pollutant. However, the chemical reactant has to be in contact with the pollutant a certain amount of time for it to be efficient: given the high groundwater velocity, the contact time may not be sufficient until polluted groundwater reaches the downstream well: relatively high hydraulic conductivity levels and large river input result in high water velocity, which has been estimated in previous studies at 5 m.d^{-1} to 50 m.d^{-1}.

As lower groundwater velocities are necessary to allow the chemical reaction to occur within the aquifer, a passive hydraulic containment system was considered as a way of reducing the hydraulic gradient.

Characteristics of the passive hydraulic containment system

In collaboration with the CEA (the French Atomic Energy Agency), Artelia (previously Sogreah) developed an innovative passive hydraulic containment system patented under the name HydrauFaraday® (Boisson et al. 2002). The operating principle is to divert groundwater flow into upstream drains connected with downstream drains, as illustrated below.

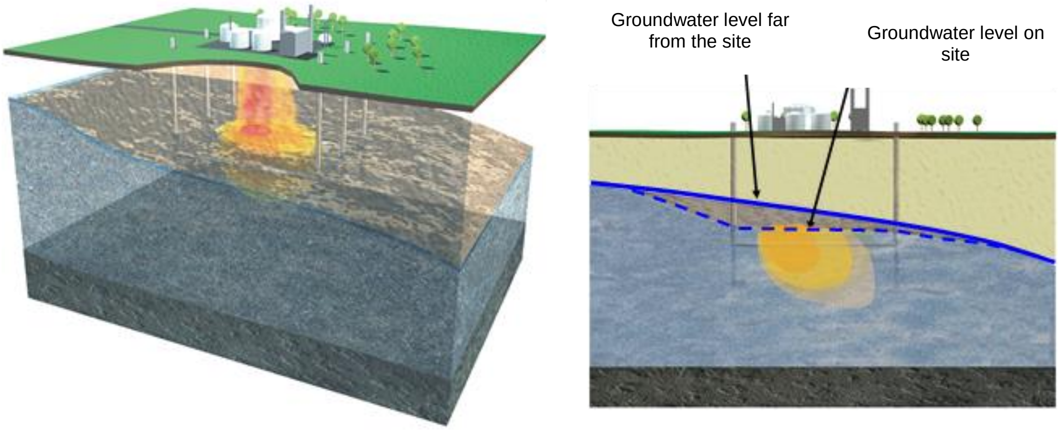


Figure 2: General principle of passive hydraulic containment system patented under the name HydauFaraday®

In this particular context, the technical solution provided by the HydauFaraday® process would be to create a drainage cage (with low head losses pathways) around the source area to reduce flow rates within it. In parallel with this "slowing down" effect, the process will involve a downstream flushing effect that will lead to dilution of the pollutant plume.

It is necessary to take into account industrial activity at the site when implementing the containment system. As it is not possible to stop production, the containment system cannot include large-scale excavations that would mean cutting off industrial networks and might disturb traffic. The need to find a technique taking up a minimum amount of space on the ground surface therefore led to a trenchless method being chosen.

To minimize the cost of drilling, which includes horizontal guided drilling, the geometry of the confinement system was adapted, as shown below. The proposed design consists of horizontal drains connected to collecting wells, which are themselves connected by a central pipe (cf. figure 2).

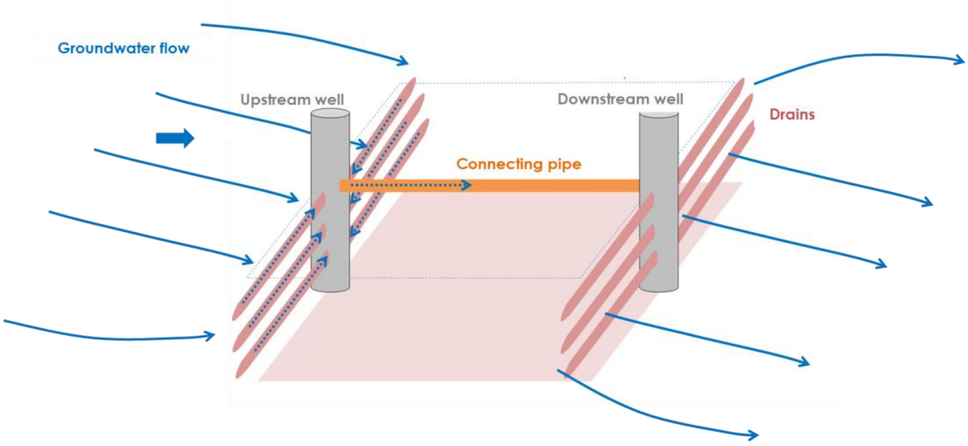


Figure 2: Schematic view of the adapted HydrauFaraday® passive hydraulic containment system.

The sizing of the drains (number, diameter, length, depth and spacing) may vary with the intended efficiency and depends on hydrogeological parameters. In fact, the impact of each design choice was not known in detail initially. That is why a numerical model of the groundwater flow was developed. A trial-and-error method was then used with numerous designs to define the most cost-effective design.

A NUMERICAL TOOL TO TEST THE EFFICIENCY AND OPTIMIZE THE DESIGN

General principle

The model developed for the design of the containment system was 600x450 metres wide and set to 80 meters in depth. The model borders did not correspond to real hydraulic borders to avoid unnecessary numerical effort. At the same time, the dimensions of the model were sufficient to avoid side effects since containment system effects in theory occur nearby. Anyway, the final design was verified in a larger, aquifer-scale model to check the validity of the local model.

The model represented the upper aquifer and lower formations, both supposedly at constant thickness. Hydraulic conductivities were assumed to be constant within the formation and constant heads were set upstream and downstream in order to obtain the hydraulic gradient measured on site.

As the drains are thin objects contrasting with the porous medium, representing them in a numerical model was a challenge. However, accurate representation was necessary as they are the main feature that should control flow in an efficient system. FEFLOW includes a powerful tool for representing singular object in a numerical model of a porous medium, namely the Discrete Feature Elements (DFE). This is used to assign specific hydraulic laws to edges, faces or arbitrary paths between nodes (Diersch 2009). In the current study, DFE at the edges could be used as drains (i.e. groundwater can flow from (/to) the aquifer to (/from) the drain) and arbitrary node paths could be used as closed pipes (i.e. no exchanges exist with the aquifer) for the central pipe and the collecting wells. Figure 3 shows the model resulting from drain representation using DFE.

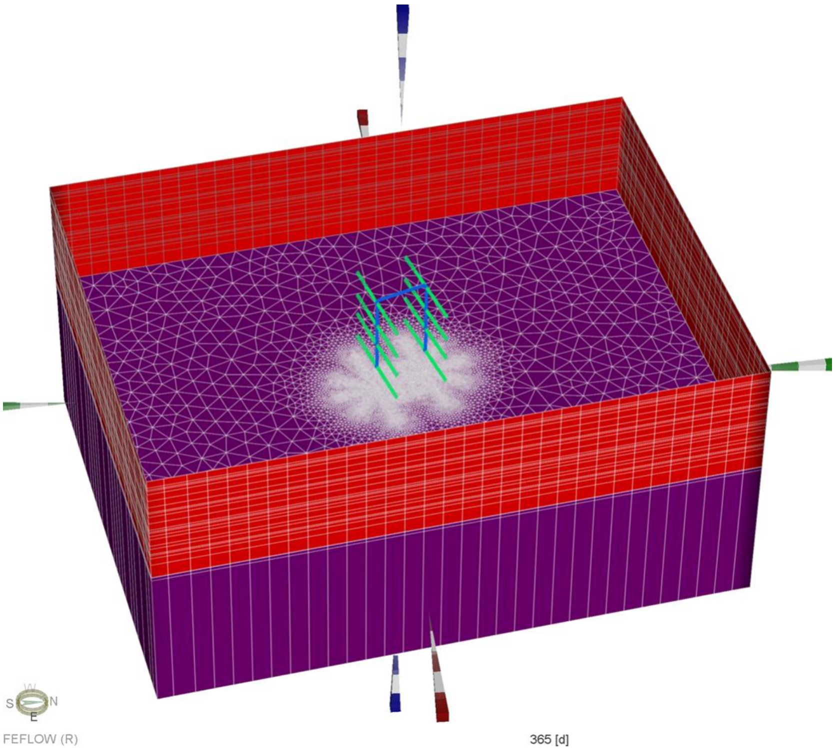


Figure 3: Truncated view of the passive hydraulic containment system implemented in FEFLOW.

Drain representations

The relevance of the use of DFE had to be checked with other representation options in FEFLOW. A simplified model was developed with very dense meshing around the drain to test 4 drain representation options (cf. figure 4):

1. Set high-permeability elements within a surface area akin to the actual drain. This option requires more computational effort due to contrasts in permeability and the need for a refined mesh. Additionally, this option is less flexible than the use of DFE.

2. Set a single DFE in the centre of the represented drain,
3. Set 2 DFEs at the top and bottom of the represented drain,
4. Set 4 DFEs at the edge of the represented drain.

The characteristics of the DFEs were chosen according to the number of DFEs.

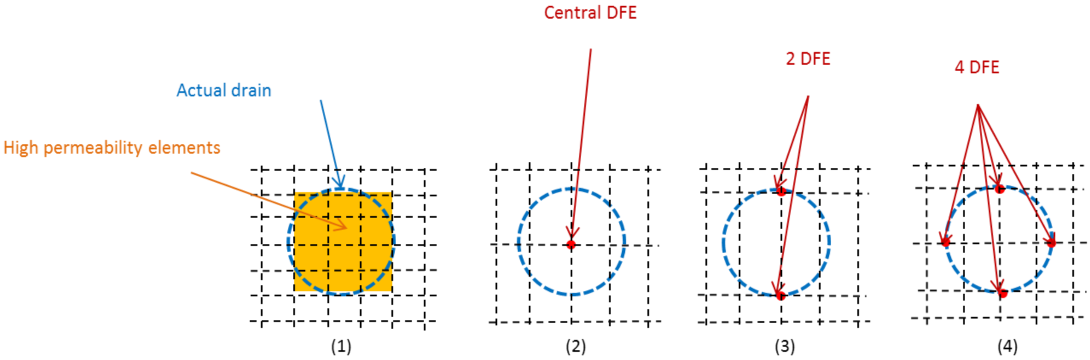


Figure 4: Cross-section view of drain implementation options tested

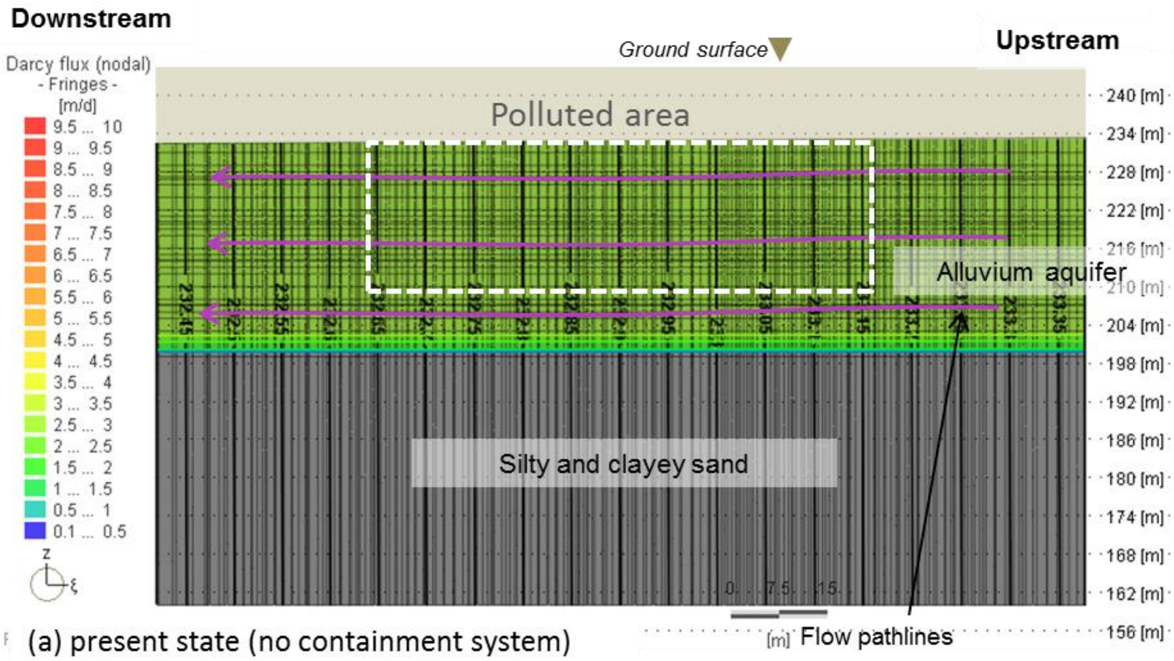
The tests showed that the velocity rate distribution in option 2 differed significantly from that in option 1, and the flow rate obtained in the drain was about 5 to 10% less (depending on the characteristics of both the drain and model). This was due to the additional – and artificial – porous material that the flow had to cross in order to get to the modelled drain. Conversely, options 3 and 4 showed similar results to those of option 1, with the flow rate differing by less than 1%.

In order to represent the drains accurately, without excessive numerical effort, it was therefore decided to use 2 DFEs at the upper and lower edges of the represented drain.

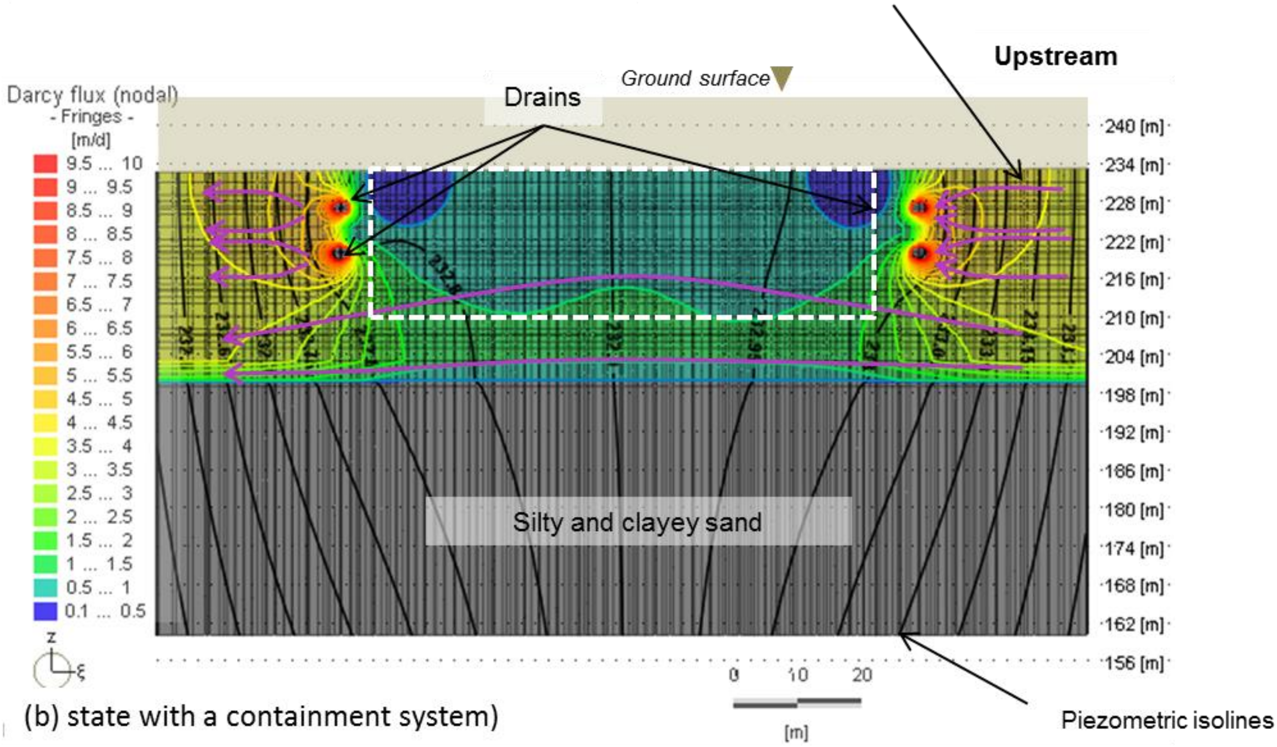
Numerical aspects

3D visualisation of groundwater velocity was necessary to assess possible enhancement of the design. Furthermore, detailed information on the velocity vectors was needed in order to deduce relevant flow pathways and thus estimate the efficiency of the system. Hence, a high-definition velocity field was obtained with dense layering, involving 25 to 30 layers for the upper aquifer, i.e. an average layer thickness of 1.2 m to 1.4 m.

The result of the dense layering on the simulated groundwater velocities is illustrated in figure 5. In this example, the spatial distribution of the velocities showed that most of the flow inside the containment system came from the bottom of the area of interest due to bending of the streamlines. To improve the efficiency of the system, the drains should therefore be placed deeper.



(a) present state (no containment system)



(b) state with a containment system)

Figure 5: Cross-section view of groundwater velocity simulated without (a) and with (b) one of the passive hydraulic containment system designs

Two methods were used to quantify the flow through the polluted zone:

(1) node-averaging of groundwater velocity

(2) internal budget of FEFLOW.

First, the two methods gave slightly different results due to the fact that averaging method used in the current study did not take into account the spatial heterogeneity of the mesh. This observation led us analyse the regularity of the mesh (horizontally and vertically) within the evaluated area. Thus, when taking the regularity of the mesh into account, the differences between the two quantifying methods were not significant.

The efficiency of a given containment system was then assessed comparing resulting flows with the reference situation (i.e. no containment system).

Main results and general rules inferred from tests

After optimization, two designs were finally suggested:

- a design that could reduce groundwater velocity inside the system to about 30% of its initial value with 8 drains (40 meters each) allocated on 2 levels at depth of 13 meters and 20 meters.
- a more efficient design that could reduce the velocity to about 10% of its initial value with 16 drains (40 meters each) allocated on 4 levels at depth of 11 meters, 19 meters, 26 meters and 33 meters.

Sensitivity tests were then carried out to assess the uncertainty of several parameters on the expected efficiency of the system. These showed that the permeability and general level of the groundwater, within the range of possible values in the current context, do not really affect the relative efficiency of the system.

Conversely, vertical anisotropy, that was taken as nil in the model, may influence and reduce the efficiency of the system. Indeed, as the drains are installed horizontally, vertical flows are of importance: vertical anisotropy may limit these flows and thus lower the efficiency.

CONCLUSIONS

A polluted aquifer was to be treated chemically. In order to make the treatment possible it was necessary to slow down the local groundwater velocity. A passive hydraulic containment system called HydrauFaraday® was suggested. The containment system aims to divert groundwater flow into upstream drains connected with downstream drains. It was suggested that the drains and connecting pipes should be installed with an auger drilling system within a large collecting well to avoid disturbing industrial activity.

The passive hydraulic containment system was designed by adopting a 3D-modelling approach with the aid of the FEFLOW modelling system, and especially the DFE and internal flow budgets. The numerical tool developed in this way enabled different designs to be tested and the efficiency of the system to be evaluated. With a sensibility analysis, the modelling approach also allowed parameters that are not well known, such as anisotropy, to be considered in detail.

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