A Washing Machine for contaminated aquifers: How engineering-induced flow fluctuations combine with medium heterogeneity to improve mixing

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Motivation

Polluted groundwater may seriously threaten human health and environment, if contaminant level exceeds a certain concentration threshold. The risk caused by contaminated groundwater can be reduced considerably by designing efficient and cost-effective groundwater remediation system. Among all possible remediation strategies, in situ oxidation and natural attenuation are preferred because of their low-cost and environmental sustainability. On the other hand, the low groundwater-flow velocity hampers mixing and dilution, rendering in situ remediation time-consuming, in particular if the plume is contained with hydraulic barriers [1].

In a pioneering work, Neupauer et al. [2] developed a novel in-situ remediation technique, named *Engineered Injection and Extraction*. Such technique makes use of a system of alternate pumping to reduce solute concentration. In this way, the aquifer acts like a *natural mixer*, in which geo-engineered flow fluctuations combine with medium heterogeneity to enhance dilution. However, the model proposed by Neupauer et al. [2] is numerical and limited to 2D aquifers.

Here our purpose is to develop a model which couples geo-engineered transient flows to medium heterogeneity in 3D systems, while reducing the computational effort. In particular, the present model aims to systematically investigate the coupled effect of geological features of natural aquifer (i.e., porosity, hydraulic conductivity, geostatistical variables) and engineered induced flow fluctuations on plume mixing and dilution. A sketch of such model is represented in Figure 1.

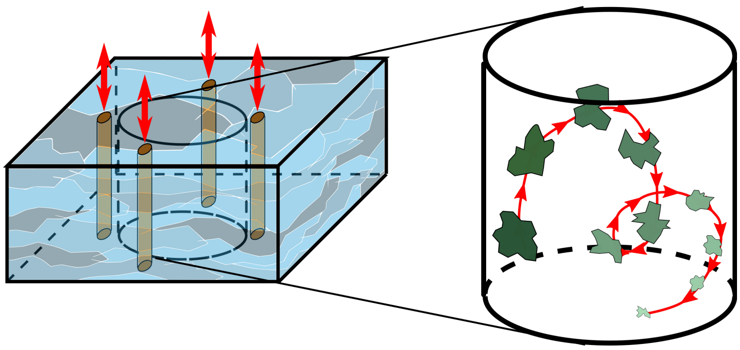

Figure 1: A sketch of the conceptual model for a system of alternate pumping.

Modelling Approach

To obtain a solution for 3D systems at reasonable computational cost, we model transport analytically. It is emphasized that analytical framework, though approximated, allows to seek the optimum flow configuration among all possible schemes of alternate flow. The accuracy of the analytical model is limited to weak heterogeneity and small plumes (compared to the heterogeneity scale). Furthermore, under the hypothesis that the transient mean flow is slowly oscillating, the mean flow field is modeled as a succession of steady states.

It is widely accepted that effective remediation is related to larger solute dilution. As such, we adopt the dilution index E, introduced by Kitanidis [3], as a global metric to quantify the efficiency of engineering-induced flow oscillations in reducing contaminant concentration. To achieve this objective, we extend the analytical solution for dilution index developed by de Barros et al. [4] to transient flows.

We assume that the complex unsteady flow generated by array of wells can be modeled as oscillatory flow without sink and sources, such that the mean pathline $\mathbf{\Gamma}$ is described by the following expression:

$$\mathbf{\Gamma} = [A\cos(\omega_o t)\cos(\omega_f t),\ A\cos(\omega_o t)\sin(\omega_f t),\ 0], \tag{1}$$

where A is the amplitude of the oscillation and ω_o and ω_f are angular velocities, describing a linear oscillation and a circulation, respectively. Although simplified, such parameters refer directly to the engineering system of pumping. In particular A is related to the spatial arrangement of the wells, while ω_o and ω_f depend on the engineered pumping schedule (i.e., the number and the pumping rate of the operating wells). Figure 2 depicts several closed pathlines obtained by varying the engineering parameters.

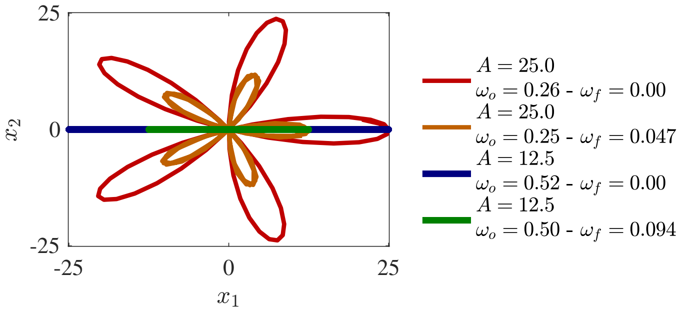

Figure 2: An example of closed pathlines in the $(x_1 - x_2)$ plane.

Bagtzoglou and Oates [5] indicate that the oscillatory frequencies range between weeks^{-1} and years^{-1} and are limited by operational constraints. We highlight that such relatively small values are in line with the hypothesis of slowly varying transient flow at the basis of this model.

Results

We investigate the how engineering transient flow combines with geological variables to enhance mixing and dilution. In particular transient flow is modeled by an oscillatory model, as described in the previous section, while the geological parameters are the Peclet number Pe, the variance of the logconductivity field σ_Y^2 and the anisotropy ratio e.

In line with the results for steady flows [4], the heterogeneity in the hydraulic conductivity increases plume deformation, thereby augmenting dilution. We observe that the engineered oscillating flow combines with medium heterogeneity to further enhance dilution. In particular, by enlarging A, i.e. the amplitude of flow oscillation, the plume experiences more heterogeneity, resulting in an increasing of its residence times and deformation rates. Since A is directly related to the distance between the pumping wells, it exists a trade-off between obtaining faster concentration decay while constraining the plume. Furthermore, we analyze several schedules of injection/extraction, represented here by the frequencies of oscillation ω_o and ω_f. Our results show that inducing a forced circulation in the mean transient flow, contributes to enhance dilution. Moreover, we highlight that the efficiency of such alternate pumping system is mainly controlled by local dispersion, represented by Pe.

In conclusion, engineering-induced fluctuations in mean flow may considerably help to improve groundwater in-situ treatment and plume containment, thereby constituting a valuable alternative to other remediation strategy.

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