The impact of geo-ingeneered transient flow on transport in natural aquifers

Di Dato, Mariaines; De Barros, Felipe P. J.; Fiori, Aldo; Bellin, Alberto

Source / Izvornik: **Common Foundations 2018 - uniSTem: 6th Congress of Young Researchers in the Field of Civil Engineering and Related Sciences, 2018, 46 - 51**

Conference paper / Rad u zborniku

Publication status / Verzija rada: **Published version / Objavljena verzija rada (izdavačev PDF)**

https://doi.org/10.31534/CO/ZT.2018.06

DOI: https://doi.org/10.31534/CO/ZT.2018.06

The impact of engineering-induced transient flow on transport in natural aquifers

Mariaines Di Dato[1], Felipe P. J. de Barros[2], Aldo Fiori[3] and Alberto Bellin[4]

(1) University of Split, Center of Excellence for Science and Technology - Integration of Mediterranean Region (STIM), Croatia, mdidato@gradst.hr
(2) Sonny Astani Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, CA, USA, fbarros@usc.edu
(3) Dipartimento di Ingegneria, Roma Tre University, Rome, Italy, aldo.fiori@uniroma3.it
(4) Department of Civil, Environmental and Mechanical Engineering, University of Trento, Trento, Italy, alberto.bellin@unitn.it

Abstract

In situ remediation is an effective technique to reduce risk caused by contaminated aquifers. However, low groundwater-flow velocity – typical in natural aquifers – hinders dilution, thereby reducing remediation efficiency. A possible strategy to overcome this problem consists of forcing the flow field by means of a geo-engineered system of alternate pumping. This work is aimed at investigating the coupled effect of geo-engineered unsteady flow and natural aquifer heterogeneity on remediation. Here we introduce an innovative analytical formulation to quantify dilution in 3D heterogeneous porous media under the effect of alternate pumping. Our solution relies on a simplified first-order framework, which limits the solution to point-like sources, weakly heterogeneous media, and slowly oscillating transient flows. Our results indicate that the efficiency of the unsteady flow field is mostly ruled by local-scale dispersion. Furthermore, we analyze several schemes of alternate pumping, thereby showing that inducing a forced rotation in the mean trajectory enhances remediation efficiency.

Keywords: aquifer remediation, unsteady flow, first order approximation, dilution

Utjecaj induciranog tranzijentnog toka na transport u prirodnim vodonosnicima

Sažetak

Sanacija podzemnih voda je uspješna metoda smanjivanja rizika uzrokovanog zagađenim vodonosnicima. Prirodni vodonosnici su obilježeni malim brzinama podzemne vode što otežava razrjeđivanje, a time i efikasnost procesa sanacije. Navedeni problem se potencijalno može riješiti prisilnim protjecanjem ako se uvede sustav izmjeničnog utiskivanja. U ovom radu će se istražiti povezani utjecaj takvog projektiranog nestacionarnog tečenja i prirodne heterogenosti vodonosnika na proces sanacije.

Uveden je inovativni analitički pristup za procjenu razrjeđenja u 3D heterogenom poroznom mediju pod utjecajem izmjeničnog utiskavanja. Predloženo rješenje spada u klasu prvog reda, što ga ograničava na točkaste izvore, blago heterogeni medij i tranzijentne tokove sa sporim promjenama. Ostvareni rezultati su ukazali da je efikasnost polja nestacionarnog tečenja dominatno pod utjecaj disperzije na lokalnoj skali. Nadalje, analizirano je nekoliko različitih shema izmjeničnog utiskivanja, što je ukazalo da induciranje prisilne rotacije u srednjoj trajektoriji toka povećava efikasnost procesa sanacije.
Ključne riječi: sanacija vodonosnika, nestacionarni tok, aproksimacija prvog reda, razrjeđenje

1. Introduction

One of the most important tasks of environmental sciences consists of developing efficient and cost-effective techniques for remediating soil and groundwater contamination. In general, groundwater contamination addresses two different objectives: preventing the contaminant migration from the source and, on the other hand, treating the polluted aquifer by removing or, at least, reducing the concentration of contaminants [1].

Remediation efficiency is mainly achieved by mixing, which induces velocity fluctuations that steep concentration gradient, thereby enhancing the dilution process conducted by local dispersion, e.g. [2][3][4][5][6]. An effective strategy to improve mixing can be through pumping systems, in order to magnify the velocity field [7].

With the purpose of developing an efficient model to restore polluted aquifers, Piscopo et al. [8] developed a novel remediation technique named *Engineered Injection and Extraction*. Their setup is designed as an array of wells that produces an unsteady flow, in which the plume is forced to move. Their model is based on numerical solutions and limited to the 2-D domain. Motivated by these considerations, this work is aimed at developing a 3-D analytical solution for aquifer remediation by engineering-induced injection and extraction system. Our solution is based on the concept of Lagrangian concentration introduced by Fiori [9]. Such framework allows us to calculate the value of local concentration without uncertainty. The efficiency of remediation is quantified by determining the dilution index, as proposed by Kitanidis [10]. Thus, the effectiveness of remediation is analyzed as a function of the characteristic parameters of the system, which describe the interplay between the statistical structure of the hydraulic conductivity, the mechanism of local dispersion, and the fluctuations in the mean flow. Figure 1 shows a sketch of the conceptual model.

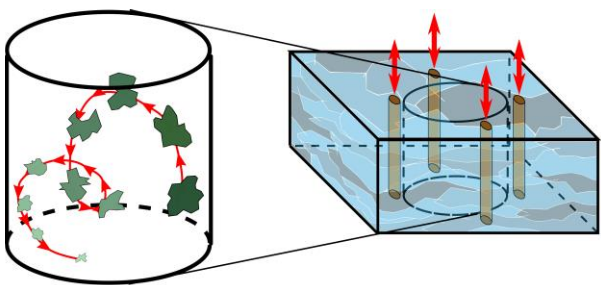

Figure 1. The conceptual model of combined alternate pumping and medium heterogeneity

2. Mathematical framework

The key assumptions of the analytical model are weakly heterogeneity of porous medium, point-like source and slowly oscillating transient flow. This formulation allows us to compare alternative flow configurations and identify those more efficient in term of mixing.

Assuming that better dilution implies more efficient remediation, we use the dilution index *E*, introduced by Kitanidis [10] as a global metric to quantify the efficiency of engineering-induced flow oscillations in reducing contaminant concentration. The dilution index quantifies the volume occupied by the plume and is defined as the entropy of the contaminant particles, as follows:

$$E(t) = exp[H(t)], \tag{1}$$

where *H* is the information entropy of the system.

In a recent paper, de Barros et al. [11] developed an analytical solution for Eq. (1) in a Lagrangian concentration framework. Such concentration was idealized by Fiori [5] and is defined as the local concentration projected in reference system that moves with the mass center of the plume. This transformation filters out advection so that only dispersion contributes to plume spreading. According to this framework, Eq. (1) reads as:

$$E(t) = (2\pi)^{3/2} exp(3/2) \prod_{i=1}^{3} \sqrt{W_{ii}}, \tag{2}$$

where W_{ii} are the covariance of the particle trajectory. For further details, the reader can refer to de Barros et al. [11].

Here, Eq. (1) is extended to transient flows. In order to obtain a simple relationship, we approximate the complex unsteady flow produced by alternate pumping with an oscillatory flow without sink and sources. Therefore, the mean pathline $\boldsymbol{\Gamma}$ is described by the following expression:

$$\boldsymbol{\Gamma}(t) = \left[Acos(\omega_o t)cos(\omega_f t), Acos(\omega_o t)sin(\omega_f t), 0\right], \tag{3}$$

where A is the amplitude of flow oscillation, and ω_o and ω_f are angular velocities, describing a linear oscillation and a circulation, respectively. Though approximated, such parametrization can describe reasonable flow configuration that may be created with array of pumping wells, operating alternatively. More precisely, 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 of the wells and their pumping rate). For further detail, see Di Dato et al. [12].

In order to generalize the results, the analysis will be conducted in a dimensionless form, with the integral scale I and the ω_o^{-1} as a reference of length and time, respectively. The level of medium heterogeneity is described by the hydraulic conductivity log-variance σ_Y^2. The relationship between advection and pore-scale dispersivity, indicated by α_d, is accounted by the Peclet number $Pe = I/\alpha_d$.

3. Results

In this section, we will illustrate the behaviour of dilution index as a function of several parameters, describing the engineered setup (i.e. $\lambda = A/I$ and $\Omega = \omega_f/\omega_o$) and the structure of the aquifer under natural conditions (i.e. σ_Y^2 and P).

3.1. Coupled effect of engineered parameters on dilution

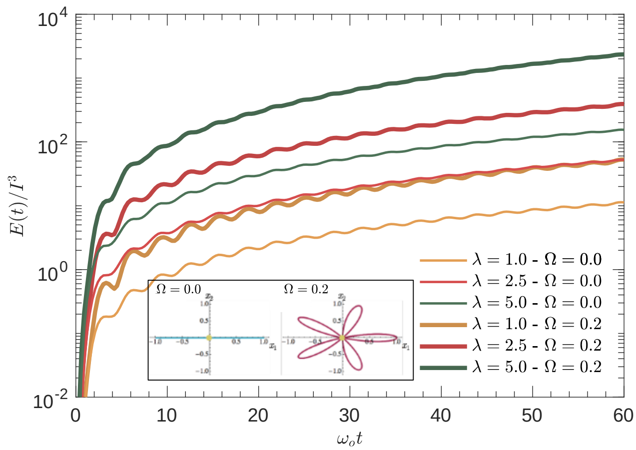

Figure 2. Temporal evolution of dilution index as a function of dimensionless time for several values of oscillation ratio and normalized oscillation amplitude

Figure 2 shows the effect of the engineering setup on dilution index. The engineering parameters are the normalized oscillation amplitude λ, which is related to the spatial arrangement of the wells, and the oscillation ratio Ω, which describes different pumping schemes. Remediation efficiency increases considerably with λ, since a larger oscillation amplitude indicate a wider mixing volume with fresh water. Therefore, there exists a trade-off between obtaining a larger dilution and increasing the contamination zone.

Moreover, Figure 2 depicts the effect of two different pumping scheme, represented by Ω. We compare $\Omega = 0$, corresponding to a back-and-forth scheme, and $\Omega = 0.2$, corresponding to a rotated scheme. The results indicate that inducing rotations in the transient flow enhances the effectiveness of remediation.

3.2. Coupled effect of alternate pumping and aquifer structure

Figure 3.a shows how hydraulic conductivity variance combined with several pumping schemes enhance dilution. As expected, the effectiveness of remediation increases with medium heterogeneity, which develops solute fingers that steepen the lateral concentration gradients and increase the mass flux between the contaminant and fresh water. The oscillation observed in Figure 3.a indicates that the plume is stretched and shrunk continuously as an effect of the forced fluctuation in the mean flow. Such an oscillating behavior becomes more and more evident by increasing σ_Y^2.

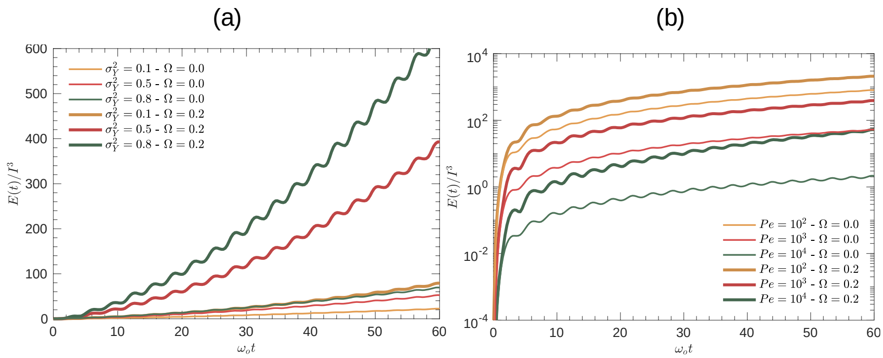

Figure 3. Temporal evolution of dilution index as a function of dimensionless time for several pumping scheme and (a) several values of medium heterogeneity and (b) several values of Peclet number

Next, Figure 3.b depicts the effect of Pe on contaminant dilution. Plume dilution shows a strong dependence on pore-scale dispersion, leading to a variation in dilution of about three orders of magnitude for the range of Pe typically found in natural field conditions. When the pore-scale dispersion is small ($Pe = 10^4$, see the green line in Figure 3.b) the main transport mechanism is advection, resulting in visible fluctuations in time evolution of dilution index. By decreasing Pe, thus increasing the impact of local dispersion on plume dilution, also such fluctuations were smoothed.

As already observed in Figure 2, we highlight that rotated scheme, corresponding to $\Omega = 0.2$, produces a larger dilution increment than back-and-forth scheme ($\Omega = 0.$).

4. Conclusions

The present work is aimed at developing an analytical solution for aquifers remediation by alternate pumping. Our results highlight that both the scheme of the oscillation path and the aquifer structure parameters control the remediation efficiency. We have observed that inducing a forced rotation in the closed flow paths enhances dilution. More precisely, the more braided is the flow trajectory, the more effective is remediation. Since the efficiency of remediation increases with the amplitude of the flow oscillation, there exists a trade-off between obtaining faster concentration decays and enlarging the contaminated area.

It is emphasized that, besides the theoretical interest, the proposed model can be adapted to enhance plume dilution by near-optimal control of groundwater flow patterns that may be reproduced in the field. The analytical features of the model enable to efficiently screen alternative flow configurations thereby alleviating the computational burden.

References

[1] Fetter, C. W.: Contaminant hydrogeology, Waveland Press, 2017.

[2] Kapoor, V., Kitanidis, P. K.: Concentration fluctuations and dilution in aquifers. Water resources research, 34(5), 1181-1193, 1998, doi: 10.1029/97WR03608

[3] Weeks, S. W., Sposito, G.: Mixing and stretching efficiency in steady and unsteady groundwater flows. Water resources research, 34(12), 3315-3322, 1998, doi: 10.1029/98WR02535

[4] Rolle, M., Eberhardt, C., Chiogna, G., Cirpka, O. A., Grathwohl, P.: Enhancement of dilution and transverse reactive mixing in porous media: Experiments and model-based interpretation. Journal of contaminant hydrology, 110(3-4), 130-142, 2009, doi: https://doi.org/10.1016/j.jconhyd.2009.10.003

[5] Fiori, A., Dagan, G.: Concentration fluctuations in aquifer transport: A rigorous first-order solution and applications. Journal of Contaminant Hydrology, 45(1-2), 139-163, 2000, doi: https://doi.org/10.1016/S0169-7722(00)00123-6

[6] Dentz, M., de Barros, F. P. J.: Mixing-scale dependent dispersion for transport in heterogeneous flows. Journal of Fluid Mechanics, 777, 178-195, 2015, doi: https://doi.org/10.1017/jfm.2015.351

[7] EPA, U.S. Field applications of in situ remediation technologies: Chemical oxidation. Washington DC, EPA, 1998.

[8] Piscopo, A. N., Neupauer, R. M., Mays, D. C.: Engineered injection and extraction to enhance reaction for improved in situ remediation. Water Resources Research, 49(6), 3618-3625, 2013, doi: 10.1002/wrcr.20209

[9] Fiori, A.: The Lagrangian concentration approach for determining dilution in aquifer transport: Theoretical analysis and comparison with field experiments. Water resources research, 37(12), 3105-3114, 2001, doi: 10.1029/2001WR000228

[10] Kitanidis, P. K.: The concept of the dilution index. Water resources research, 30(7), 2011-2026, 1994, doi: 10.1029/94WR00762

[11] de Barros, F. P. J., Fiori, A., Boso, F., Bellin, A.: A theoretical framework for modeling dilution enhancement of non-reactive solutes in heterogeneous porous media. Journal of contaminant hydrology, 175, 72-83, 2015, doi: 10.1016/j.jconhyd.2015.01.004

[12] Di Dato, M., de Barros, F. P., Fiori, A., Bellin, A.: Improving the Efficiency of 3-D Hydrogeological Mixers: Dilution Enhancement Via Coupled Engineering-Induced Transient Flows and Spatial Heterogeneity. Water Resources Research, 54(3), 2095-2111, 2018, doi: 10.1002/2017WR022116