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Natural aquifers as hydrogeological mixers

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Pollution of natural aquifers poses serious threats to human and ecosystems health. The risk caused by polluted groundwater can be decreased by remediation, which has the double objective of containing the source while reducing the concentration of the contaminant. A cost efficient remediation technique is in situ oxidation, which however requires a good mixing between the oxidant and the contaminant, ideally as in a chemical reactor. However, reaching the ideal conditions of a chemical reactor is prohibitive in groundwater, since mixing is impeded by the very low local dispersivity, which limited effect is only partially enhanced by formation heterogeneity. Mixing may be enhanced by using an engineered sequence of extractions and injection at an array of wells. The alteration of the velocity field caused by a carefully designed sequence of pumping at a battery of wells is expected to interact non-linearly with formation's heterogeneity and finally enhance mixing between the injected oxidant and the contaminant. In the present work, we investigate the coupled effects of externally induced flow transients and natural heterogeneity of the geological formation, epitomized here by the hydraulic conductivity structure, local-scale dispersion and formation anisotropy, on dilution. Given the large number of parameters that may control the processes and the need to perform the analysis in a three-dimensional setup, we opted for investigating dilution instead of mixing (the two processes are however strictly related) by means of a simplified analytical solution of the dilution index. Our solution is based on a simplified first-order approach, such that the model is limited to weakly heterogeneous aquifers, small (compared to the logconductivity integral scale) plumes and slowly oscillating engineered flows. The unsteady flow produced by alternate pumping is approximated by an oscillatory behavior without sinks or wells. More precisely, the plume is forced to move in a closed trajectory, characterized by two frequencies, one controlling the rotational and the other the oscillatory components of the mean trajectory. In such a way, we are able to compare alternative flow configurations and identify those producing the larger dilution index. We show that in the presence of the only oscillatory component, i.e. for a back and forth type of mean path, dilution is reduced with respect to the natural mean flow configuration and this is the price to pay for plume containment between the two parallel array of wells creating the oscillatory motion. However, if a rotational component is added, dilution is enhanced and becomes larger than in the reference natural condition, though plume containment is guaranteed. We believe this result important because it shows that not always engineered enhanced flows introduce a benefit in term of dilution (they do it in term of plume confinement, of course) and that a rotating component should be introduced in order to enhance dilution with respect to natural conditions. The next step is to explore as such relatively complex mean flow fields may be obtained by using a battery of wells.