water

Supplementary Materials

Can Borehole Heat Exchangers Trigger Cross-Contamination between Aquifers?

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1. Effect of the hydraulic conductivity of the deep aquifer

Simulations were conducted imposing a hydraulic conductivity $K_1 = 10^{-3}\ m/s$ in the shallow aquifer and $K_2 = 10^{-4}\ m/s$ in the deep aquifer, separated by an aquitard with $K' = 10^{-9}\ m/s$.

A higher hydraulic conductivity of the deep aquifer is expected to result in lower contaminant concentrations, since the leaked contaminant flow rate coming from the borehole would be diluted in a higher aquifer flow rate.

For the most severe scenario, i.e. with the highest borehole filling conductivity ($K_{fill} = 10^{-2} m/s$) and the smallest value of the aquitard thickness ($b' = 4\ m$), we set up different values of hydraulic conductivity in the deep aquifer:

$K_2 = K_1 = 10^{-3}\ m/s$

$K_2 = 10K_1 = 10^{-2}\ m/s$.

The resulting concentrations at the top of the deep aquifer, 200 m downstream the borehole outlet, are reported in **Error! Reference source not found.**. As expected, a higher value of the hydraulic conductivity of the deep aquifer (K_2) results in lower concentrations and in an earlier arrival of the contaminant.

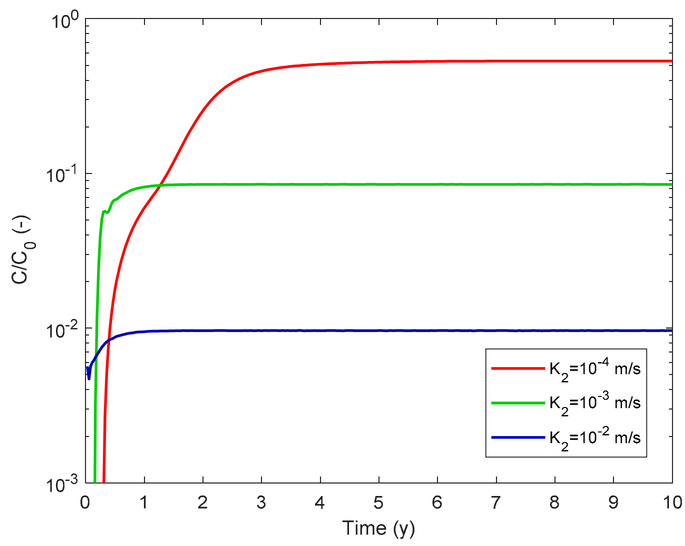

Figure 1. Effect of the hydraulic conductivity of the deep aquifer on the contaminant concentrations at the top of the deep aquifer, 200m downstream the borehole outlet.

2. Effect of the contaminant dispersivity

All simulations were conducted assuming a contaminant dispersivity $\alpha_L = 5\,m$ and a transverse dispersivity $\alpha_T = 0.1\alpha_L = 0.5\,m$. This dispersivity value was chosen since the spatial scale (L) of the propagation phenomenon observed (i.e. the contaminant plume) is expected to be in the order of a few tens of meters downstream the borehole outlet; using the correlation $\alpha_L = 0.1L$ suggested in Sethi and Di Molfetta (2019, [1]) would therefore lead to a contaminant dispersivity in the longitudinal direction (α_L) in the order of a few meters.

Knowing the real value of dispersivity in an aquifer would require tracer tests which are seldom performed.

A sensitivity analysis was conducted considering the most severe scenario, i.e. with the highest borehole filling conductivity ($K_{fill} = 10^{-2} m/s$) and the smallest value of aquitard thickness ($b' = 4\,m$). The longitudinal dispersivity was set to $\alpha_L = 0.5\,m$, $\alpha_L = 1\,m$, $\alpha_L = 2\,m$ and results were compared with the simulation with the default value $\alpha_L = 5\,m$. The transverse dispersivity was set to $\alpha_T = 0.1\alpha_L$ for each case.

The resulting concentrations at the top of the deep aquifer, 200 m downstream the borehole outlet, are reported in **Error! Reference source not found.**. As expected, lower values of the contaminant dispersivity result in higher concentrations and in a delayed appearance of the contaminant.

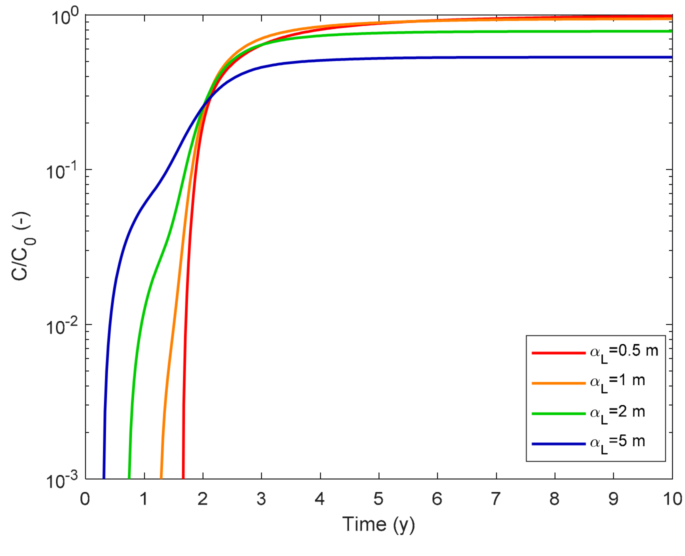

Figure 2. Effect of the contaminant longitudinal dispersivity value α_L. The transverse dispersivity is set to to $\alpha_T = 0.1\alpha_L$ for each case.

3. Effect of the vertical resolution

Numerical modelling of contaminant transport requires to find a trade-off between numerical precision, which improves with a higher resolution of the mesh (both planar and vertical), and computational effort, which increases with the model resolution. The standard vertical resolution chosen for the simulation run is of 5 m for aquifer layers and of 1 m for aquitard layers.

Some results already prove that the vertical resolution adopted is enough, e.g. the leakage flow rates (see Section 3.1 and Figure 4 in the paper) and the long-term transient concentrations observed in the deep aquifer (see Section 3.4 and Figure 7 in the paper) which show a good agreement with analytical formulae.

A higher resolution was tried in order to understand whether this could significantly change results. Again, the most severe scenario was simulated, i.e. with the highest borehole filling conductivity $K_{fill} = 10^{-2} m/s$ and the smallest value of aquitard thickness $b' = 4\ m$.

The resulting concentrations at the top of the deep aquifer, at different distances (40, 80, 120, 160 and 200 m) downstream the borehole outlet, are reported in **Error! Reference source not found.**. The asymptotical concentration and the arrival time do not differ, whereas some difference is observed in the breakthrough curve. For the purpose of the analysis conducted, which aims at understanding the long-term behaviour of the contamination in the deep aquifer, the vertical resolution adopted therefore proved satisfactory.

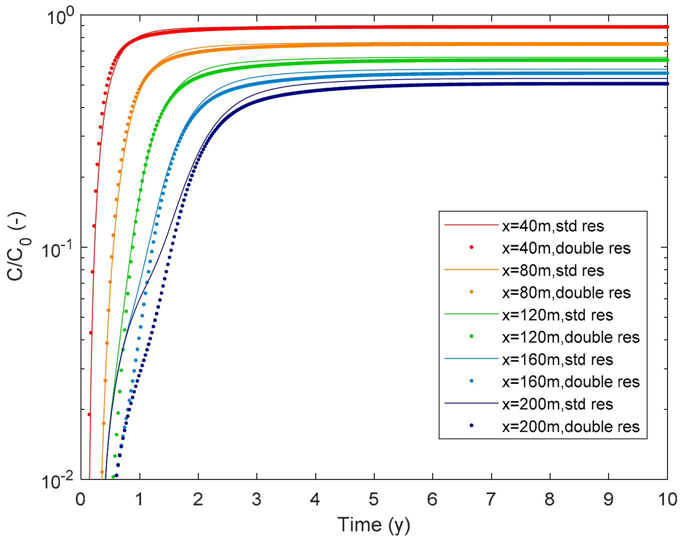

Figure 3. Effect of vertical resolution: comparison of the time series of contaminant concentrations at different distances downstream the borehole outlet (40,80,120,160 and 200 m) with the "standard" resolution (layer thickness of 5 m for aquifers and 1 m for the aquitard) and the doubled resolution (layer thickness of 2.5 m for aquifers and 0.5 m for the aquitard).

4. Hydraulic head differences between shallow and deep aquifer

The hydrogeological setup hypothesized in the paper, i.e. a shallow aquifer with a higher hydraulic head compared to the deep aquifer, may occur especially in foothill areas or in the case the deep aquifer is exploited for pumping. We report an example from Piemonte (NW Italy), where hydraulic head difference of about 6 m is observed between two monitoring wells in Ciriè, near to Turin, installed at a depth of 20 m and 50 m respectively and managed by the local environmental protection agency (ARPA Piemonte).

Error! Reference source not found. reports the time series of years 2014-2017 of hydraulic heads in the shallow aquifer (source: https://bit.ly/34rL0BP) and in the deep aquifer (source: https://bit.ly/3edIdRa).

Figure 4. Position of Ciriè, the location of the two monitored wells examined, in North-Western Italy.

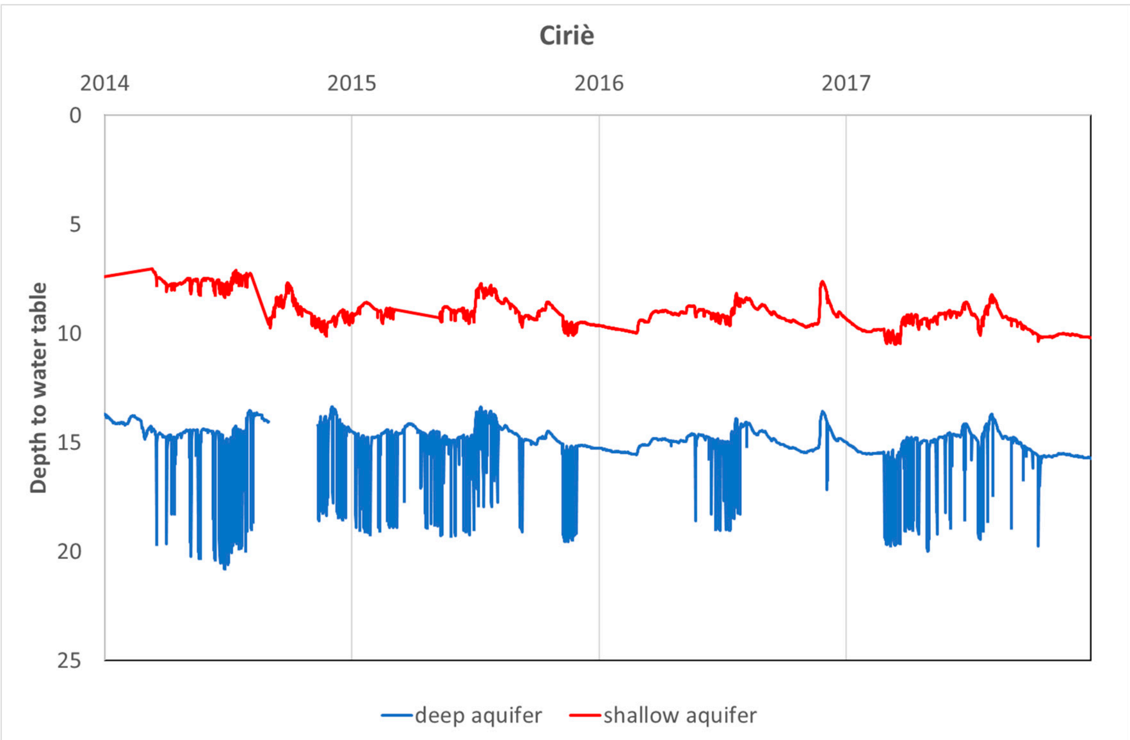

Figure 5. Monitoring wells in Ciriè, screened in the shallow aquifer (red line) and in the deep aquifer (light blue line).

References

1. Sethi, R.; Di Molfetta, A. *Groundwater Engineering: A Technical Approach to Hydrogeology, Contaminant Transport and Groundwater Remediation*; 2019; ISBN 978-3-030-20516-4.