A new risk and stochastic analysis of monitoring and remediation in subsurface contamination

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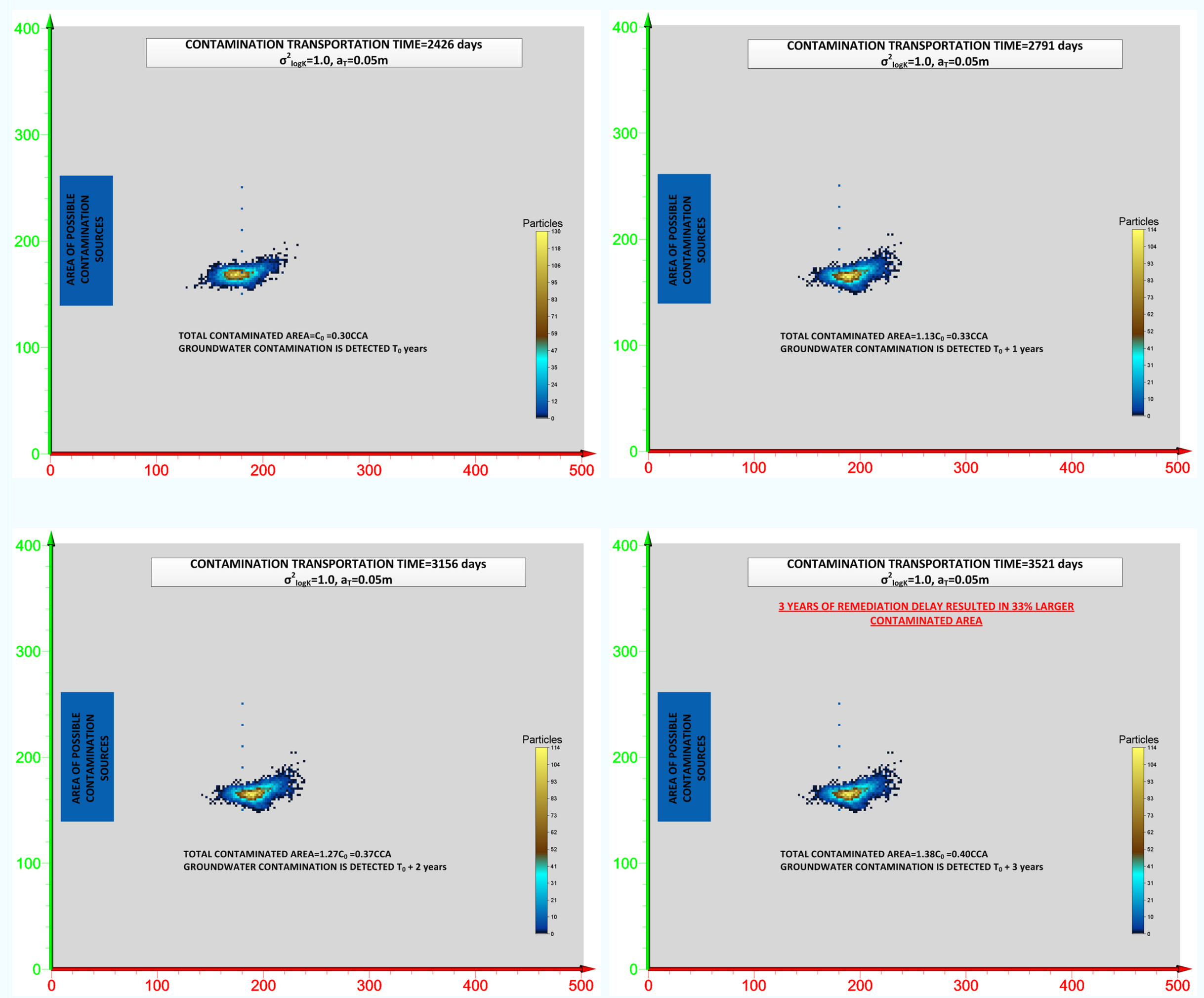
1. Introduction

Aquifer contamination from waste disposal facilities has been seen to occur with a significant likelihood, despite the mandated U.S. or E.U. measures.

Successful detection of groundwater contamination via monitoring wells is of value if remedial actions follow as soon as possible.

Contemporary risk analyses consider the cost of alternative remediation procedures by assuming that the contamination area to be remediated coincides with the area calculated at the time of detection.



Contamination plume is transporting and dispersing 3 years after its detection, resulting in a 30% larger contaminated area

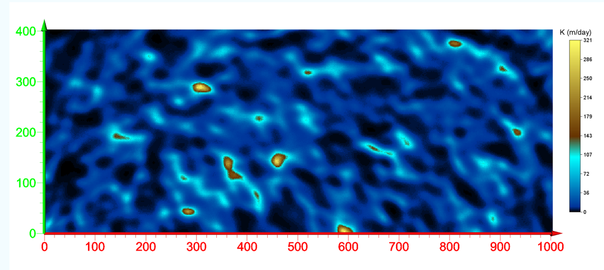
Practically, there is always a considerable lag between the time that a plume is detected and the time when remediation commences, resulting in a larger contaminated volume. This time lag constitutes a random variable that depends on available resources and technologies, as well as efficiency of administration decision-making.

2. Objective

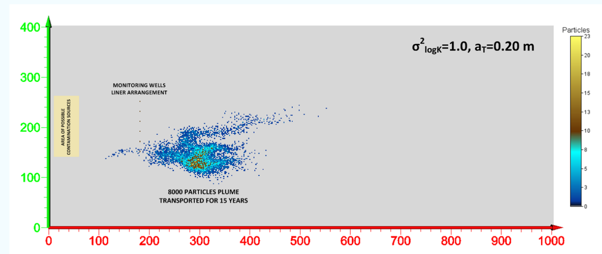
An expression is proposed that accounts for the delay between detection and remedial action in order to provide a correction to decision analyses that evaluate the economic worth of well monitoring. In this context, new corrected detection probabilities of groundwater contamination for various linear arrangements of monitoring wells are numerically calculated and sensitivity analysis is performed to investigate how field heterogeneity and contamination dispersion affect the results.

3. Model Development

A model was developed (*Papapetridis and Paleologos*, 2011) where high-resolution numerical Monte Carlo realizations were utilized to calculate the probabilities of detection P_d by a linear arrangement of monitoring wells that are sampled every day.

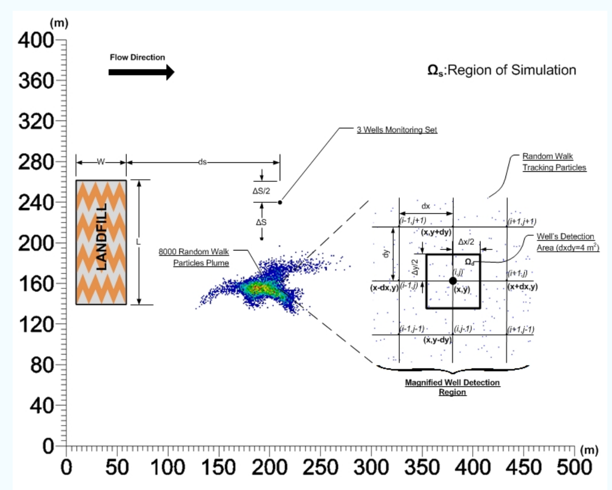


The heterogeneity of the geologic environment was addressed through the hydraulic conductivity, which was simulated with the Spectral Turning Bands Algorithm. (Picture : exampe of a heterogeneous field with σ^2_{logK}=1.0)



Random Walk Tracking Particle algorithm was used to simulate the 2-D plume's advective and dispersive movement. (Picture: An 8000 particles plume transported for 15 years)

Steady state groundwater flow in an isotropic, heterogeneous porous medium, with a fixed depth of aquifer was considered with a hydraulic gradient of 0.001 m, between the nodes lying perpendicular to the direction of flow, and no-flow conditions at the lower and upper boundaries of the flow domain. The simulated region was 1000 m long and 400 m wide, and it was discretized by 2x2 m² cells creating a 500x200 grid.



It was assumed that any point within a cell of a landfill was an equal-probable source of leakage, taking place once as a single failure event at zero time (when the simulation began) and resulting in an instantaneous ejection of contaminants into the aquifer.

MODEL'S INPUT PARAMETERS	VALUES					
Landfill's lenght, L	50 m					
Landfill's width, W	120 m					
Total mass of contaminant	1000 gr (8000 particles)					
Initial concentration	4000 mgr/lt					
Variation Y, σ_{logK}^2	0.00	0.50	1.00	2		
Longitudinal dispersion coefficient, α_L	0.10 m	0.50 m	2.00 m	5.00 m		
Transversal dispersion coefficient, α_T	0.01 m	0.05 m	0.20 m	0.50 m		
Total time of simulation	10950 days (30 years)					
Time step, Δt	1 day					
Remediation delay (in months)	3	6	12	24	36	
Number of monitoring wells	20	12	8	6	4	3
Threshold concentration of detectable contamination, C_{TH}	0.35% x C_0 =14 mg/lt or 112 particles per grid cell					

During Monte Carlo simulations the distance of monitoring wells arrangements was selected so that their performance would be maximized.

4. Results

Decision analysis aims at determining a particular well arrangement that maximizes the detection probability while minimizing the contaminated area, or equivalently minimizing the remediation cost in conjuction with the capital cost of operating the facility.

Implicit in the decision analysis framework is the assumption that remediation takes place immediately after detection occurs. In our work we consider that there is a delay in the remediation response and we address this issue using the ratio of A_t/A_{t+dt} to correct this remedial action delay, where A_t is the contaminated area in the 2-D case at time t of detection, and A_{t+dt} is the contaminated area at time t+dt when remediation might take place.

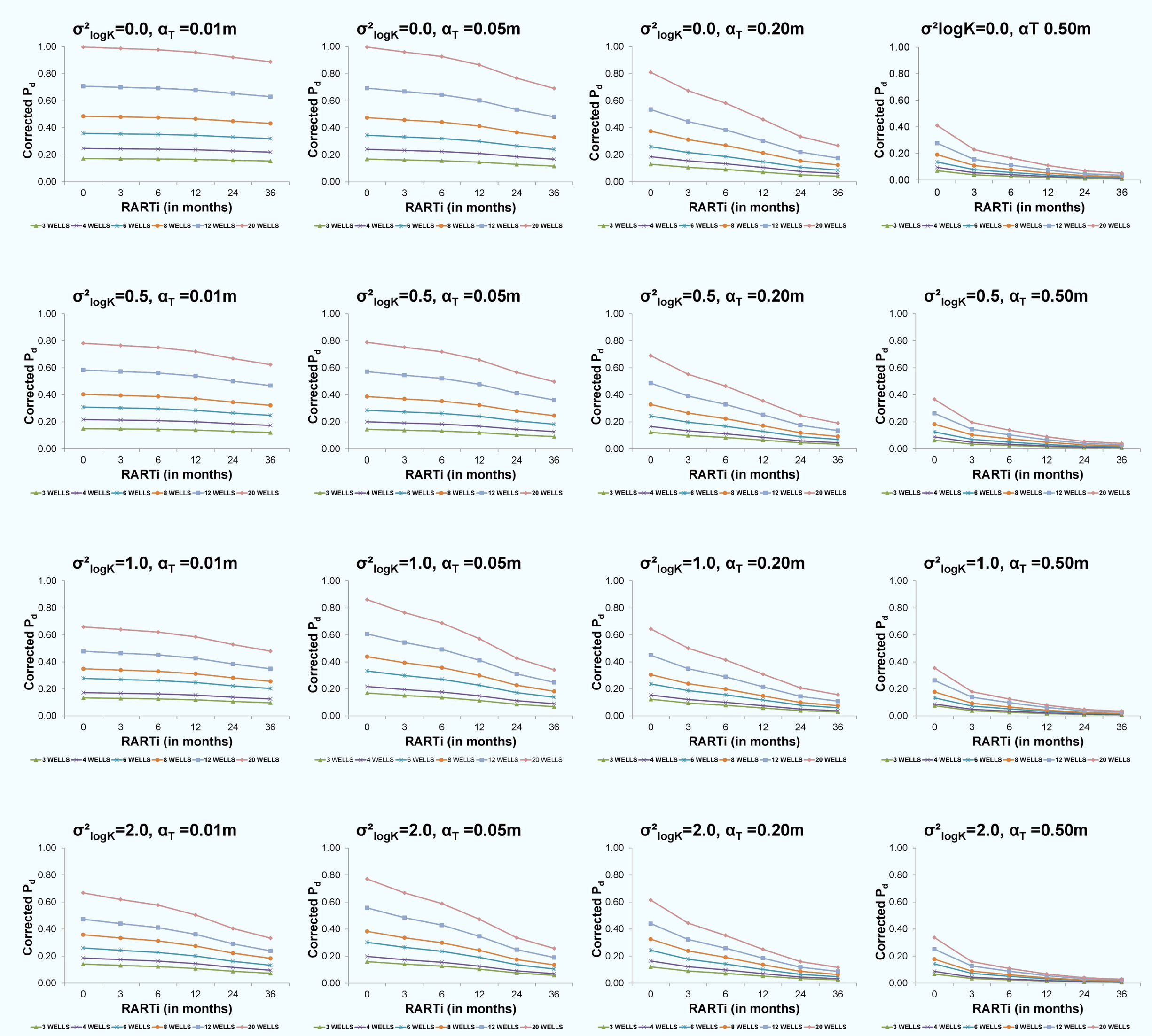
Multiplying this ratio by P_d results in a reduced detection probability P_d^{cor},where an increased delay in the response to remediate can be considered, in terms of economic outcome, as equivalent to a monitoring arrangement with a decreased efficiency to detect.

This procedure is summarized in an equation, equivalent to that of *Yenigul et al.* (2006) yielding a corrected risk R^{cor} that accounts for the remedial action response delay:

$$R^{cor} = P_d^{cor}\ C_d + P_f^{cor}\ C_f$$

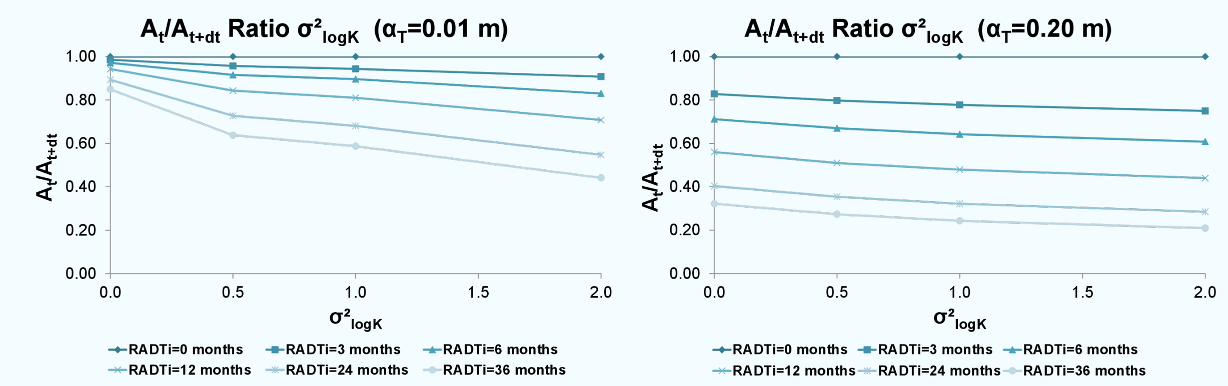
$$\text{where}\ \ P_d^{cor} = P_d\left(\frac{A_t}{A_{t+dt}}\right)\ \text{and}\ \ P_f^{cor} = 1 - P_d^{cor}$$

Numerical experiment results showed that P^{cor}_d heavily decreases as Remedial Action Response Time (RARTi) is increased beyond 6 months (*Papapetridis and Paleologos*, 2012). Our expression allows us to estimate that, for a heterogeneous field where i.e. 12 monitoring wells are operating, a remediation delay of 36 months is equivalent to reducing the P_d from 59% to 22%, or increasing the failure probability from 41% to 78%, almost doubling the failure cost entering risk calculations.

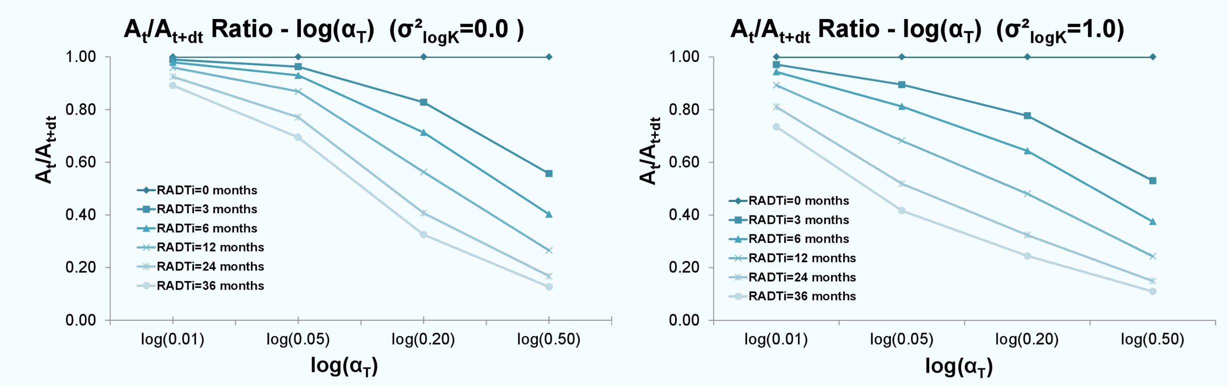


3000 repetitions per case Monte Carlo simulation results, corrected P_d vs RARTi. From left to right dispersion is increased, top to bottom heterogeneity is increased. Detection at RARTi=0 indicates native capability P_d of every monitoring installation if no delay is assumed.

Sensitivity analysis illustrated that between heterogeneity and contaminant dispersion into groundwater, it is the influence of the latter that mostly affects the corrected P_d.



In low dispersion environment there is an average 35% decrease in A_t/A_{t+dt} ratio when RARTi is bigger than 6 months, while in a high dispersion environment heterogeneity seems not to alter the ratio significantly.



Dispersion is the main reason for RARTi to cause similar decrease of the A_t/A_{t+dt} ratio, independently from field's heterogeneity. In case of 36 months,i.e., delay causes in both cases an 85% A_t/A_{t+dt} ratio decrease.

5. Conclusions

- Based on a correction presented by Papapetridis and Paleologos (2011) for remedial response delays, the current study demonstrates that in highly dispersive environments the remediation response must be of the order of a few months if one does not wish the contaminated areas and remediation costs to grow significantly.
- While detection probability P_d contains information about the degree of our knowledge of the event detection, corrected detection probability P_d^{cor} can be considered as a measure of the utility of P_d.
- Our expression allows us to numerically estimate how P_d changes, for a heterogeneous field where dispersion of contamination into groundwater takes place, as remedial action response time (RARTi) is increased.

References

Papapetridis, K., and E.K. Paleologos (2011), *Contaminant Detection Probability in Heterogeneous Aquifers and Corrected Risk Analysis for Remedial Response Delay,* Water Resour. Res., 47, W10518, doi:10.1029/2011WR010652

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