Resilience of heterogeneous aquifers evaluated from different dose-response models of Bisphenol A

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1. Introduction

Under the circumstance of the growing attention on the indirect potable reuse application which reuses treated wastewater utilizing an aquifer as an environmental buffer, a concern regarding potential health risks from residual emerging contaminants in groundwater rises (USEPA, 2017). Since Bisphenol A (BPA), one of the emerging contaminants detected in groundwater, is known to cause endocrine-related health effects in a specific low dose range that covers much lower exposure levels than the current regulatory level, it is urged to investigate what potential health effect people have and how long they have from groundwater contamination with BPA (Vandenberg, 2014). To address this concern, human health risk assessment of BPA in groundwater is conducted, and based on that, the aquifer resilience from BPA contamination is estimated.

A challenging issue is the fact that BPA has two types of health effects expressed by different dose-response models: systemic health effects based on a monotonic dose-response model and endocrine-related health effects based on a non-monotonic dose-response model. Together with different DR models, since heterogeneous aquifer structure dictates the groundwater flow and contaminant transport, uncertainty in hydrogeological models will display complex picture of health risks and following aquifer resilience from BPA contamination in groundwater.

2. Objectives

- Investigate the interplay between dose-response models of BPA and natural heterogeneity of the subsurface in determining the aquifer resilience from BPA contamination.
- Provide suggestions on how to improve water resources management in BPA contaminated sites.

4. Results & Discussion

To examine the behavior of BPA plumes in aquifers, residential concentrations of BPA in groundwater on the x-y plane are investigated by averaged along the z-axis. One realization from each level of the aquifer heterogeneity with different time moments are plotted in Fig. 3. As the level of the aquifer heterogeneity increases, BPA plumes are more dispersed along the flow direction as a result of the interaction with the heterogeneous aquifer structure. This dispersion of BPA plumes is displayed in breakthrough curves at the control plane as well (Fig. 4). Following the increase of the aquifer heterogeneity, the variability among breakthrough curves increases as well.

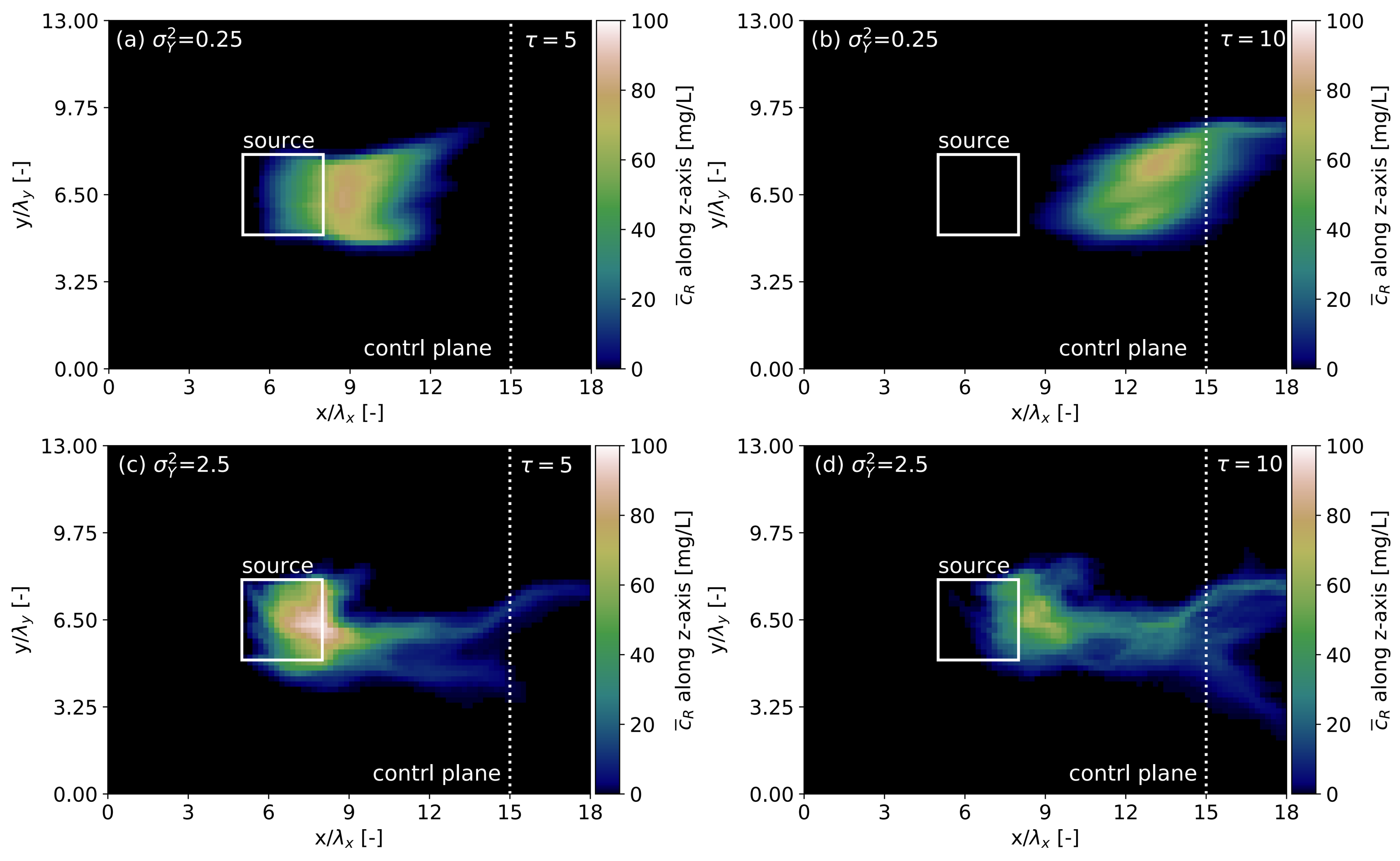

Figure 3: Concentration profiles averaged along the z-axis on the x-y plane; (a) σ_Y^2 = 0.25 at τ = 5 (b) σ_Y^2 = 0.25 at τ = 10 (c) σ_Y^2 = 2.5 at τ = 5 (d) σ_Y^2 = 2.5 at τ = 10

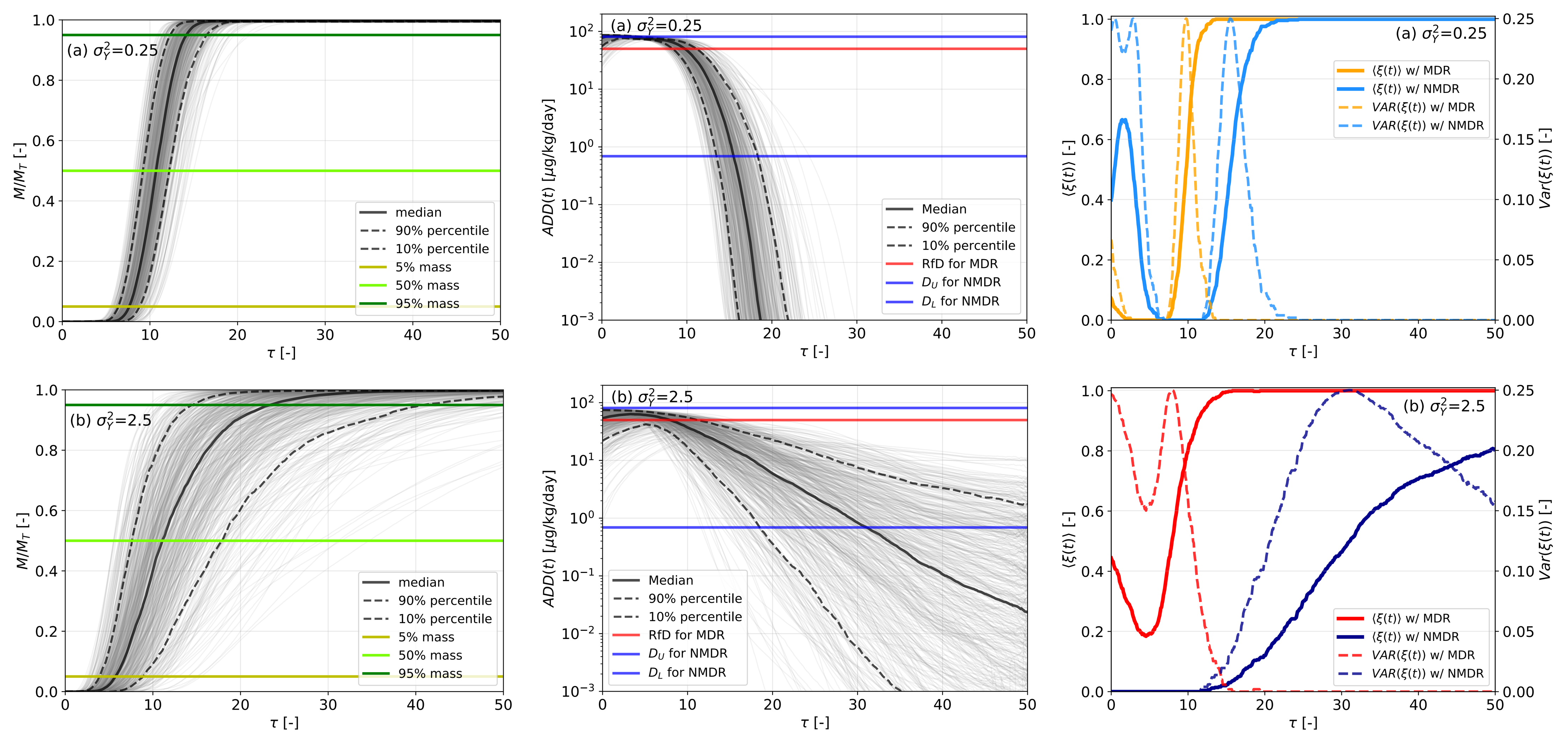

Figure 4 (left): Breakthrough curves of BPA at the control plane depending on the level of aquifer heterogeneity; (a) σ_Y^2 = 0.25 (b) σ_Y^2 = 2.5; Figure 5 (center): Average daily dose as a function of exposure starting time depending on the level of aquifer heterogeneity; (a) σ_Y^2 = 0.25 (b) σ_Y^2 = 2.5; Figure 6 (right): Aquifer reliability as a potable water source depending on the level of aquifer heterogeneity; (a) σ_Y^2 = 0.25 (b) σ_Y^2 = 2.5

Time-profile of Average Daily Dose (ADD) from all realizations with medians and 10 and 90 percentiles are plotted along with the reference dose (RfD) (red line) and the upper/lower bounds of the low dose range (blue lines) in Fig.5. As the level of the aquifer heterogeneity increases, the ADD curves become stretched and flattened with an increased variability, corresponding the dispersion of BPA plumes as shown in Fig.4. This change leads to the less chance of the ADD going over the RfD and the longer periods staying within the low dose range. As a result, the aquifer reliability as a potable water source based on the Monotonic Dose-Response (MDR) model increases in an early period when aquifers become more heterogeneous, while the one based on the Non-Monotonic Dose-Response (NMDR) model decreases in a later period. In the end, the increased level of the aquifer heterogeneity improves the aquifer resilience from the MNR model ($\langle R_L \rangle$ from 9.8 to 6.7) and significantly deteriorates the one from the NMDR model ($\langle R_L \rangle$ from 13.5 to 33.1).

3. Problem Statement & Methodology

Numerical simulation is conducted for a possible BPA contamination scenario in a three-dimensional aquifer. Random log hydraulic conductivity ($Y = \log K$) fields from the same statistics (i.e., $\langle Y \rangle$ = 0 (cm/s) and σ_Y^2 = 0.25 and 2) are generated using SGeMS in a Monte Carlo framework (Remy et al., 2009). For each aquifer, flow and transport problems are solved numerically by MODFLOW and MT3DMS (Harbaugh, 2005; Zheng and Wang, 1999). At the control plane where exposure of BPA to environmentally sensitive targets (i.e., pregnant/ lactating women) occurs through direct ingestion of groundwater, health risks and the aquifer resilience are estimated as follows:

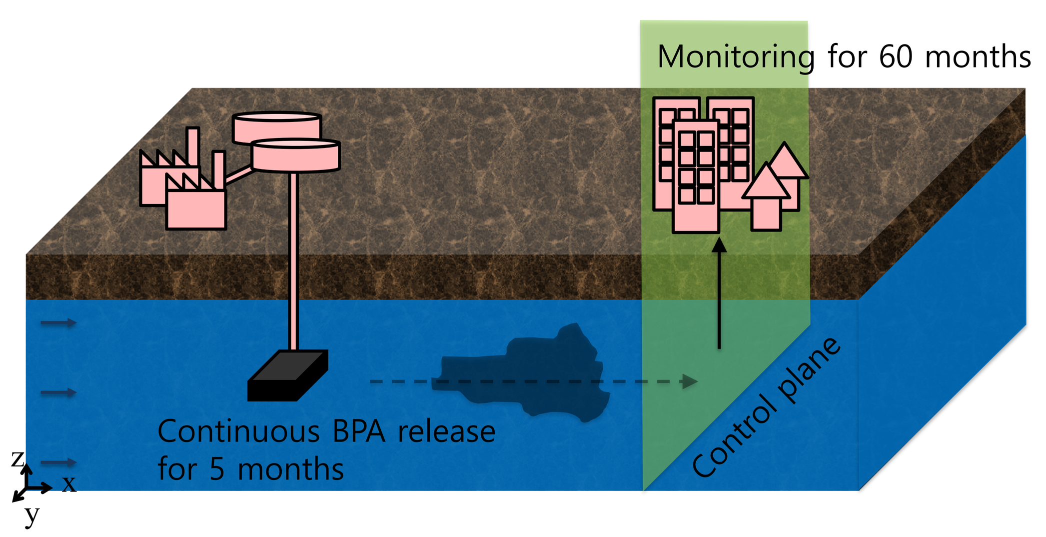

Figure 1: Contamination scenario for this study

Flux-averaged Concentration, C_F(t)

- Steady state groundwater flow toward the x-direction is set with no flow on the rest of boundaries.
- Linear sorption and no biodegradation of BPA are assumed.
- Governing equations consist of Darcy's law, advection-dispersion equation with retardation.
- Parameters of the model are set to reflect the heterogeneity of an aquifer and properties of BPA.

Average Daily Dose, *ADD*(t)

- Average daily dose is calculated by averaging daily doses during exposure periods(i.e., pregnancy and lactation).

$$ADD(t) = \frac{\bar{C}_F(t; x_{CP}) \times IR \times ED}{BW \times AT},$$

where IR is the ingestion rate, ED is the exposure duration, BW is the body weight, and AT the averaging time

- Exposure factors are following USEPA guidelines (USEPA, 2019).

Aquifer Reliability, ξ(t)

- Aquifer reliability as a potable water source depends on health risks
- **MDR model** for systemic health effects in pregnant/lactating women:

$$\xi(t) = \begin{cases} 1, & ADD(t) < \mathrm{RfD} \\ 0, & \text{otherwise} \end{cases}$$

where RfD is the reference dose (USEPA, 2010)

- **NMDR model** for endocrine-related health effects in male offspring when their mothers are exposed during pregnancy and lactation periods:

$$\xi(t) = \begin{cases} 1, & ADD(t) < D_L \text{ or } > D_U \\ 0 & \text{otherwise} \end{cases}$$

where D_U and D_L is the upper and lower bounds for the low dose range possibly causing endocrine-related health effects (Jones et al., 2011)

Loss of Aquifer Resilience, R_L

- Loss of the aquifer resilience indicates a period when an aquifer is not considered potable within the concerned period of time.

$$R_L = \int_{t_0}^{t_0+t_f} [1 - \xi(t)]\, dt$$

where t_0 is the initial time and t_f is the final concerned time

- Dimensionless Time, τ, is used by normalizing time by the characteristic advective time scale

Figure 2: Estimation process of the aquifer resilience

5. Conclusions

The increased level of aquifer heterogeneity has opposite effects in the aquifer resilience depending on DR models of BPA. It is beneficial to the aquifer resilience from the MDR model for systemic health effects in general population and detrimental to the one from the NMDR model for endocrine-related health effects in the vulnerable population (e.g., male offspring having prenatal/ postnatal exposure). Therefore, a site management strategy for BPA contamination should be established in accordance with land uses and demographics which determine which DR model should be considered.

References

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