The Relationship Between Partial DNAPL Source Zone Remediation and Groundwater Plume Attenuation

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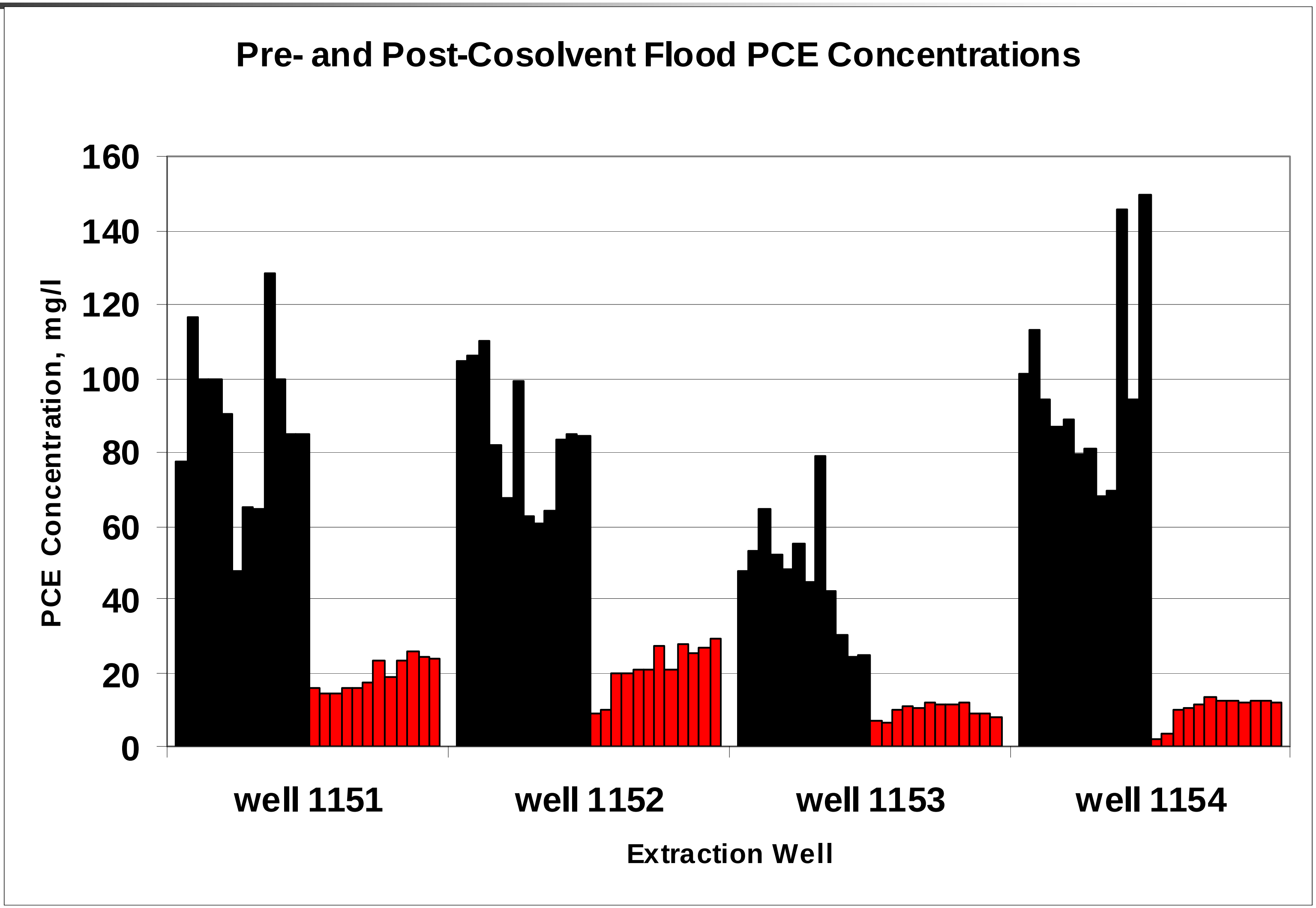
Basic Premise:

- We cannot “restore” a DNAPL source zone, but we can remove much of the DNAPL mass (~60% to >90%)
- Removing DNAPL mass will reduce the contaminant discharge or flux to groundwater
- This can result in reduced plume size, mass, longevity, and health risk
- Overall project involves field, laboratory, and modeling studies
- My talk focuses on plume behavior using simplified analytical modeling approaches

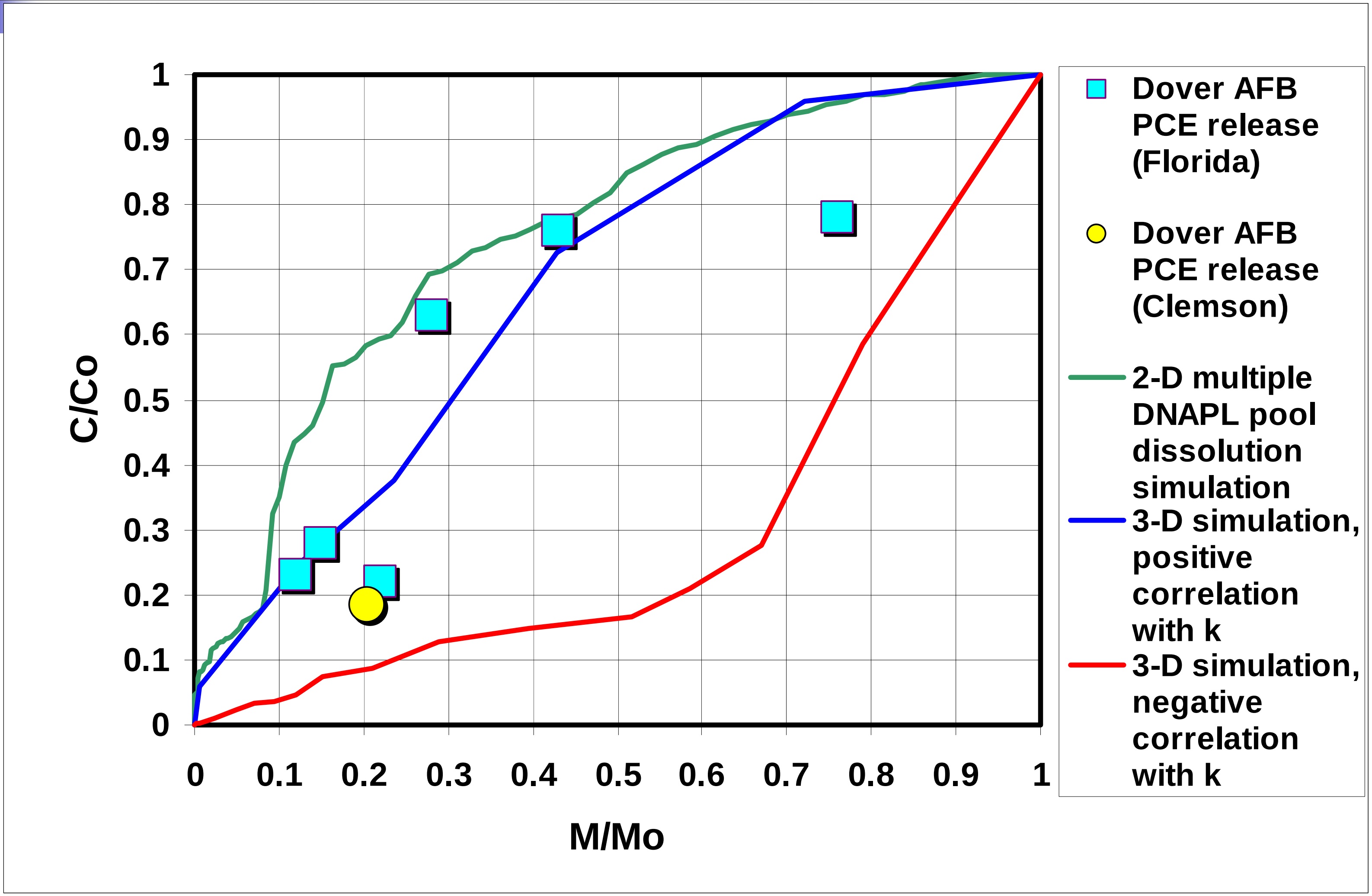
Example of Source Remediation: SERDP / EPA / Clemson Field Test of DNAPL Removal by Alcohol Flooding, Dover AFB

EPA released 92 kg of pure PCE into the test cell at a depth of 35’ below the ground surface. A total of 73.5 kg was removed during a 40 day alcohol flood

80% source removal resulted in 81% reduction in groundwater concentration

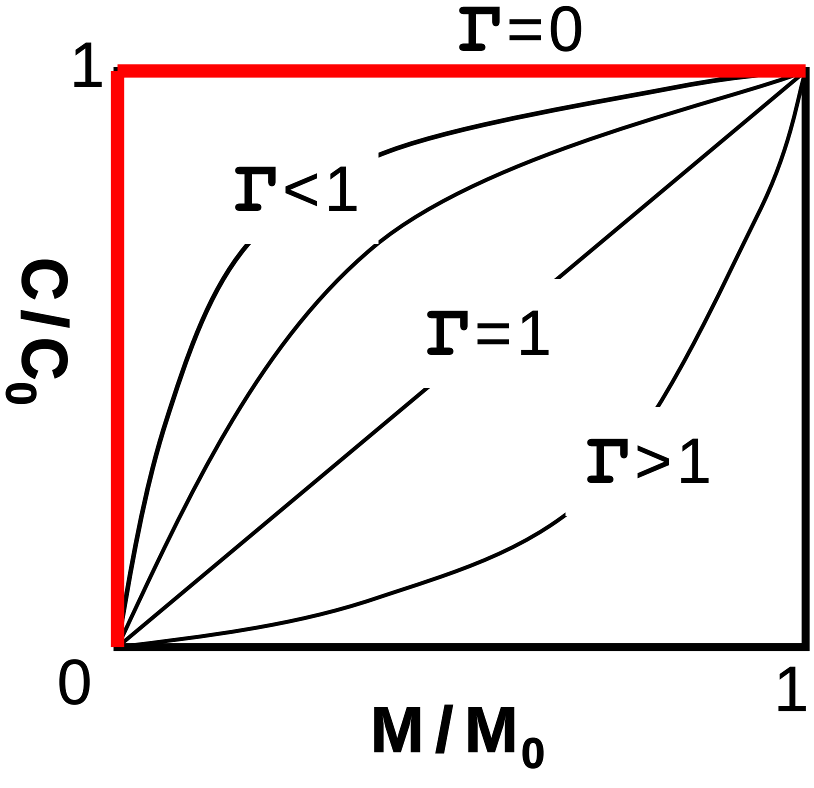


Relationship between source mass and discharge (flow averaged concentration)

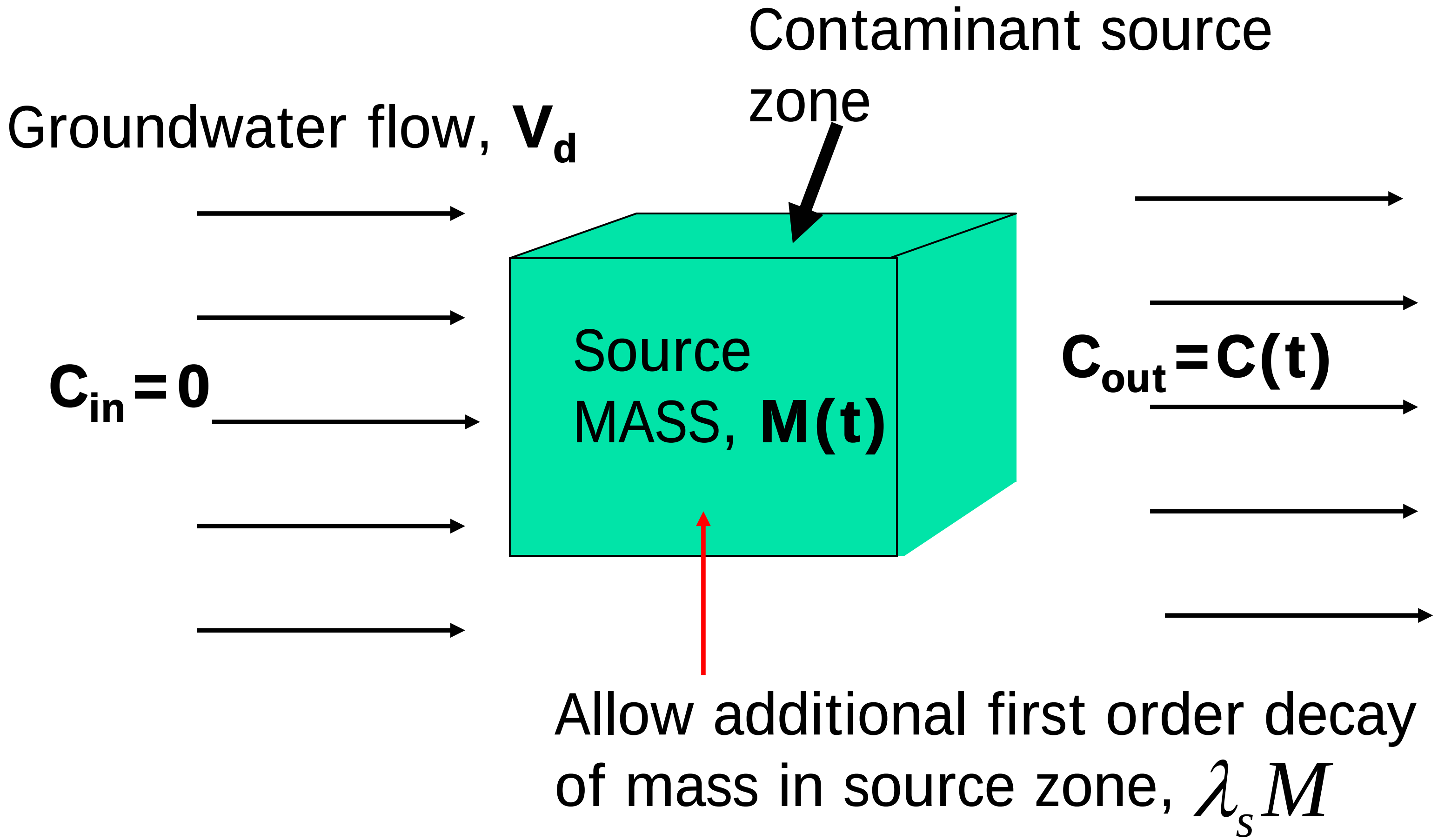


DNAPL Source Model: Approximate these curves as a power function [Rao et al., 2001; Parker and Park, 2004; Zhu and Sykes, 2004]

$$\frac{C}{C_0} = \left(\frac{M}{M_0} \right)^{\Gamma}$$



Source zone conceptual model: Mass is mainly removed from source zone by flushing, with some additional source decay



Source Zone Solutions

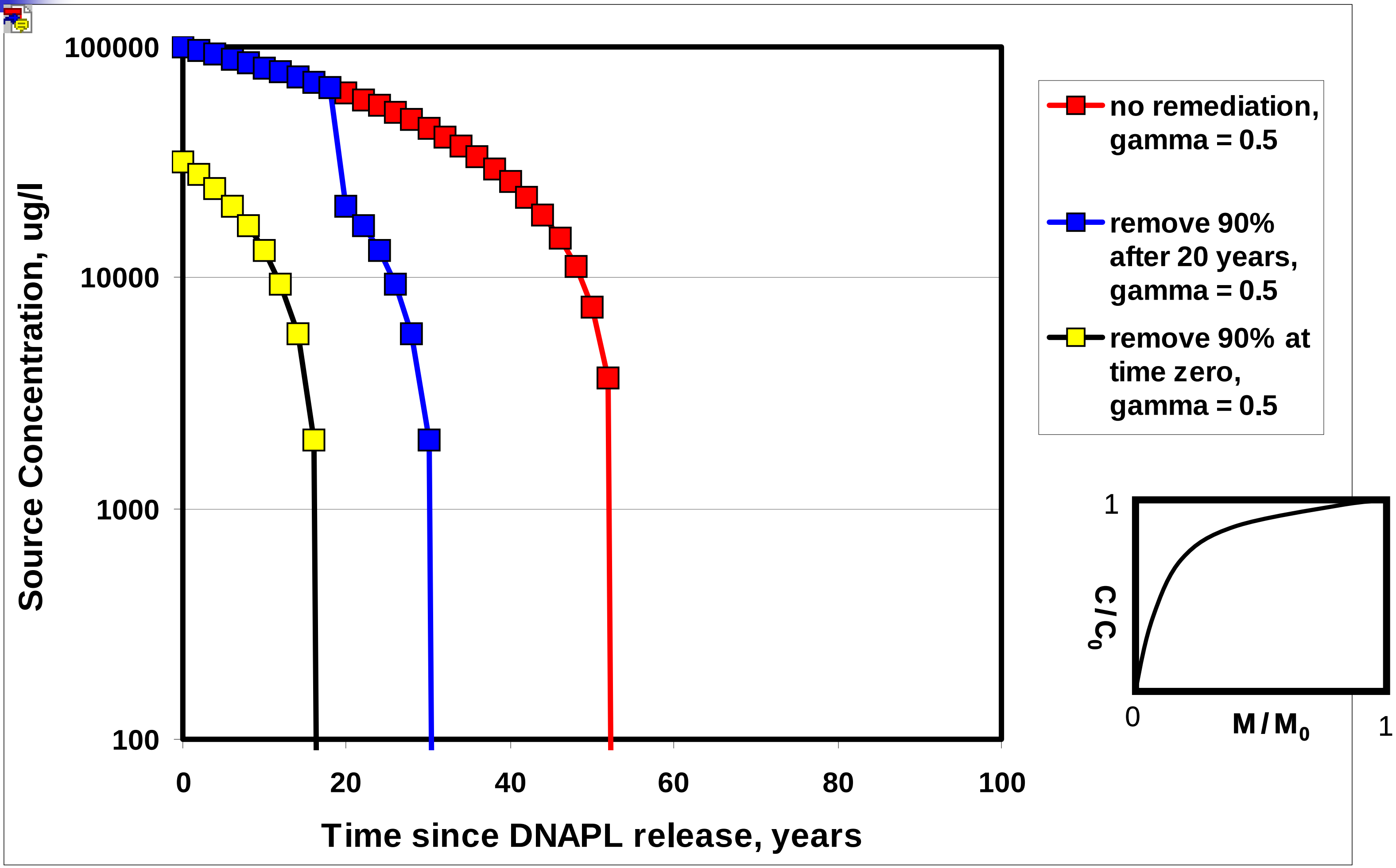
General Solution

$$M(t) = \left\{ -\frac{V_d A C_0}{\lambda_s M_0^{\Gamma}} + \left(M_0^{1-\Gamma} + \frac{V_d A C_0}{\lambda_s M_0^{\Gamma}} \right) e^{(\Gamma-1)\lambda_s t} \right\}^{\frac{1}{1-\Gamma}}$$

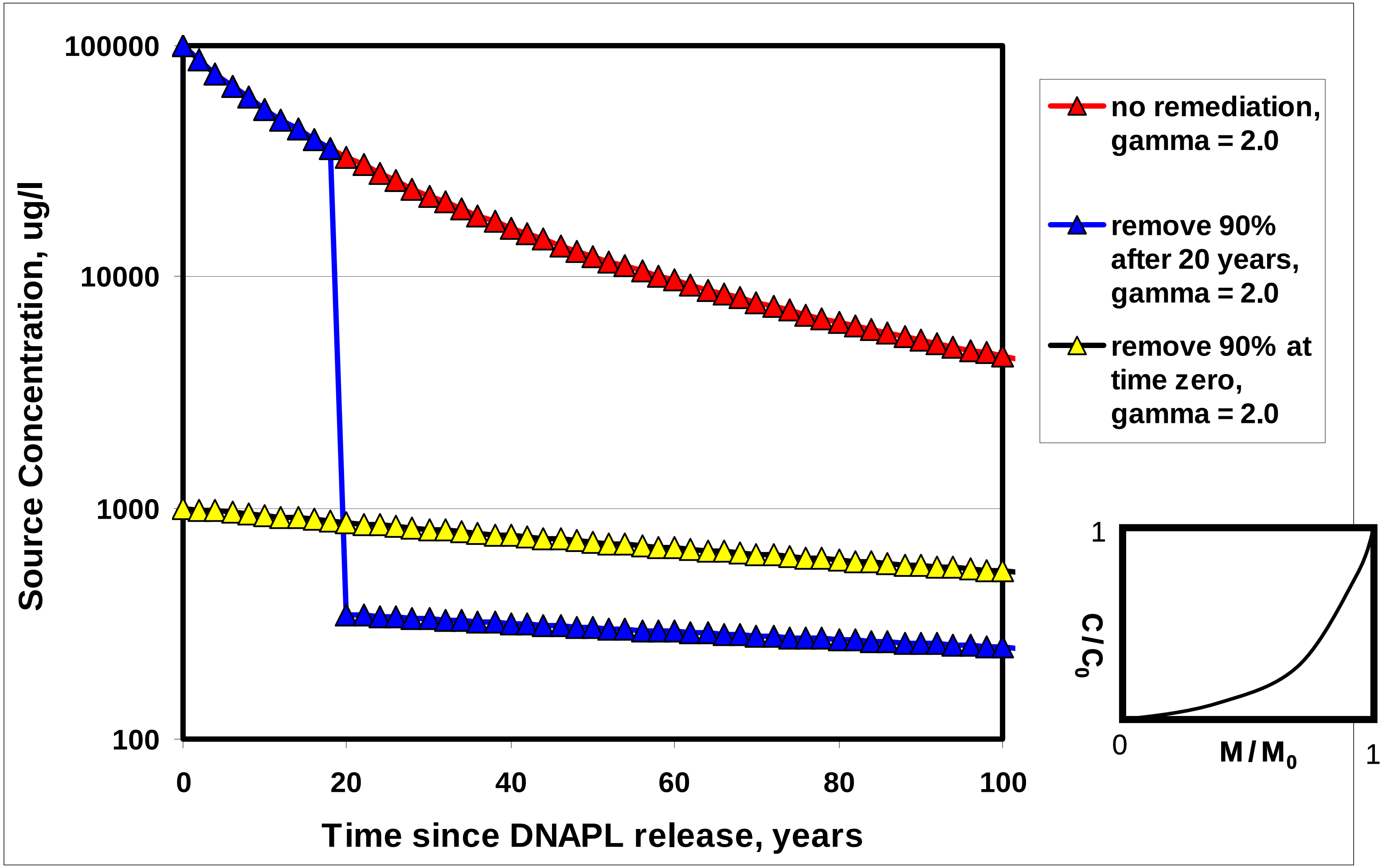
For partial DNAPL remediation of "**X**" of the source mass,

$$M(t) = \left\{ \frac{-V_d A C_0 (1-X)^{\Gamma}}{\lambda_s \left[(1-X)M_0\right]^{\Gamma}} + \left(\left[(1-X)M_0\right]^{1-\Gamma} + \frac{V_d A C_0 (1-X)^{\Gamma}}{\lambda_s \left[(1-X)M_0\right]^{\Gamma}} \right) \exp\left[(\Gamma-1)\lambda_s t\right] \right\}^{\frac{1}{1-\Gamma}}$$

Source Behavior: Γ=0.5, M_0= 1620 kg, V=20 m/yr, A=10m x 3m, C_0=100 mg/l



Source Behavior: Γ =2.0, M_0= 1620 kg, V=20 m/yr, A=10m x 3m, C_0=100 mg/l



Modified Domenico/Sun et al. (Biochlor/Bioscreen) transport solution with the new source function

Use the new source function as the boundary condition In a 3-D advection dispersion differential equation:

$$R\frac{\partial C}{\partial t} = -v\frac{\partial C}{\partial x} + \alpha_x v\frac{\partial^2 C}{\partial x^2} + \alpha_y v\frac{\partial^2 C}{\partial y^2} + \alpha_z v\frac{\partial^2 C}{\partial z^2} - \lambda_p C$$

Use a flux-based, mixed boundary condition at x=0:

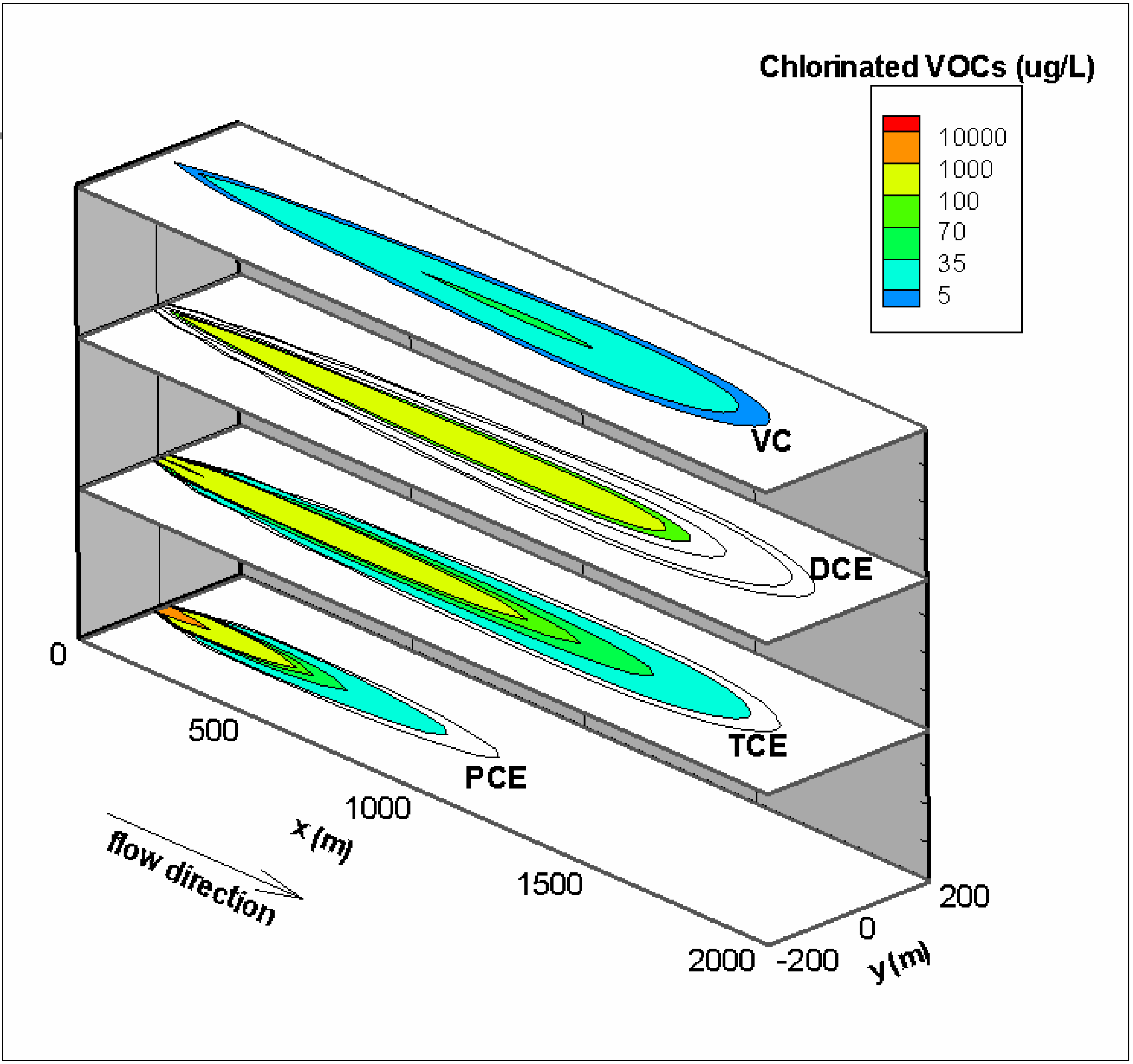
$$mass\ \ flux = V_d C_s(t) = \left[V_d C - \phi \alpha_x v \frac{\partial C}{\partial x} \right]_{x=0}$$

Where (for remediation at t=0; delayed case is similar)

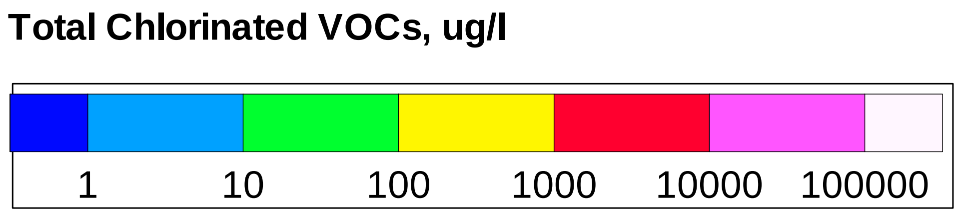
$$C_s(t) = \frac{(C_0(1-X)^{\Gamma})}{\left[(1-X)M_0\right]^{\Gamma}} \left\{ \frac{-V_d A C_0 (1-X)^{\Gamma}}{\lambda_s \left[(1-X)M_0\right]^{\Gamma}} + \left(\left[(1-X)M_0\right]^{1-\Gamma} + \frac{V_d A C_0 (1-X)^{\Gamma}}{\lambda_s \left[(1-X)M_0\right]^{\Gamma}} \right) \exp\left[(\Gamma-1)\lambda_s t\right] \right\}^{\frac{\Gamma}{1-\Gamma}}$$

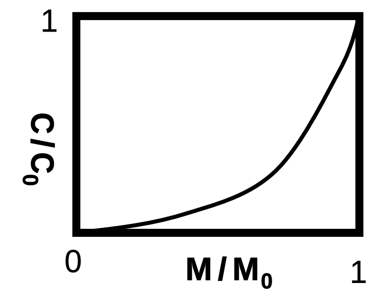
Example model results: Γ=1, no remediation, plume after 50 years. Contours above MCLs are colored

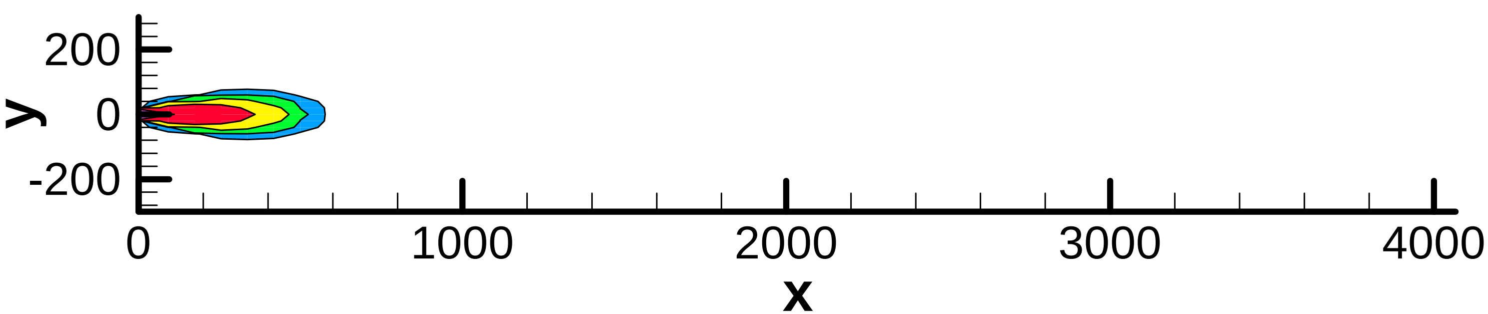
- Source zone 10mx10mx3m, darcy velocity = 20 m/yr; S_n=.01; 1620 kg DNAPL
- C_0=100 mg/l leaving source zone, initial discharge = 60kg/yr
- Pore velocity=60 m/yr, R=2, dissolved (plume) rate constants λ_{pce}=0.4/yr, λ_{tce} =0.15, λ_{dce} =0.1, λ_{vc} =0.2
- Longitudinal dispersivity=10m, transverse dispersivity=0.5m, vertical dispersivity=0.1



Example: Gamma=2, remove 90% of source after 20 years







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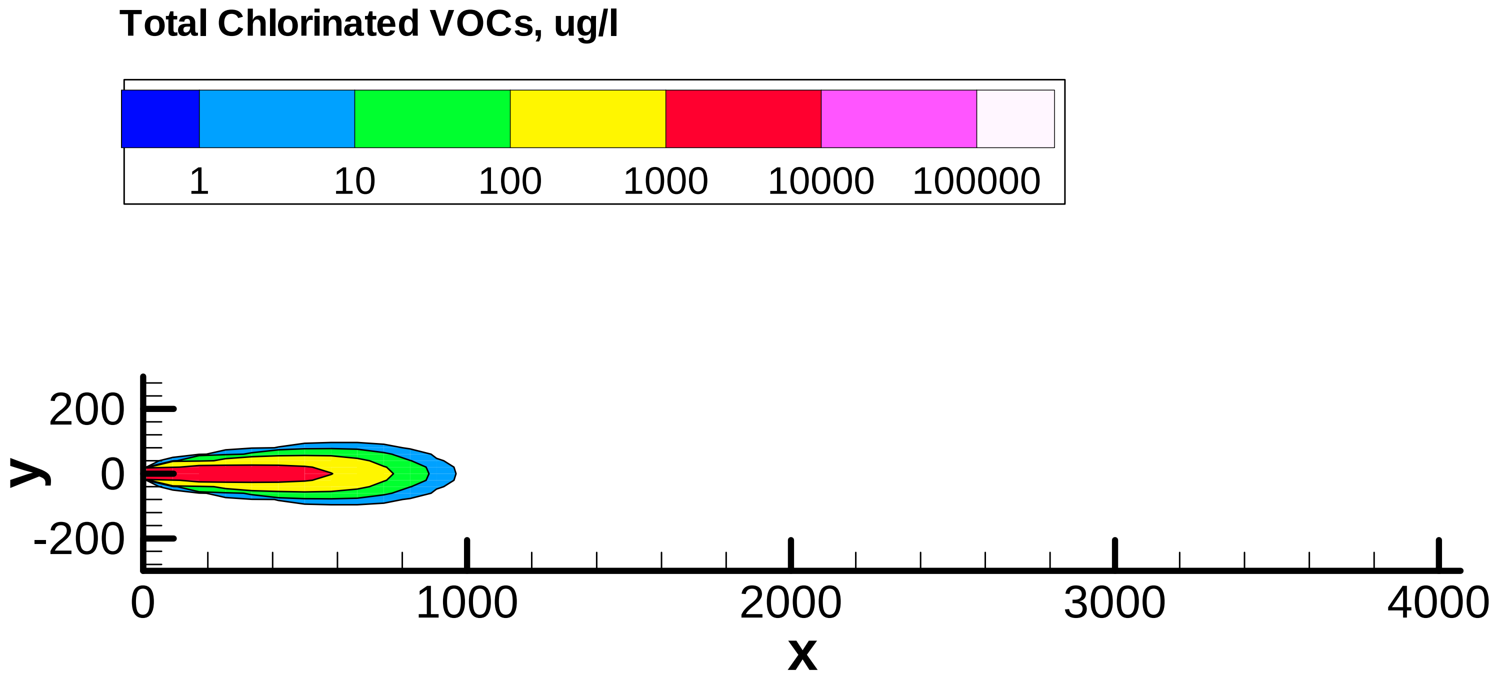

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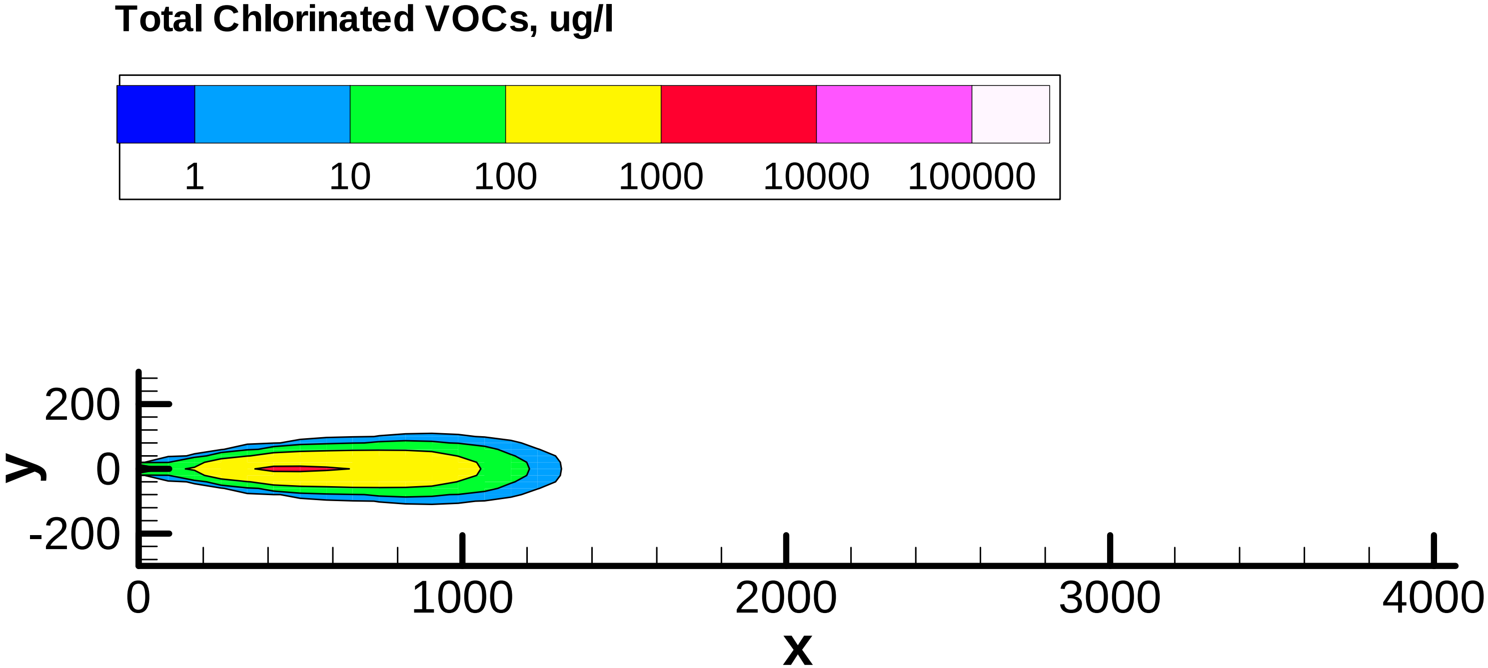

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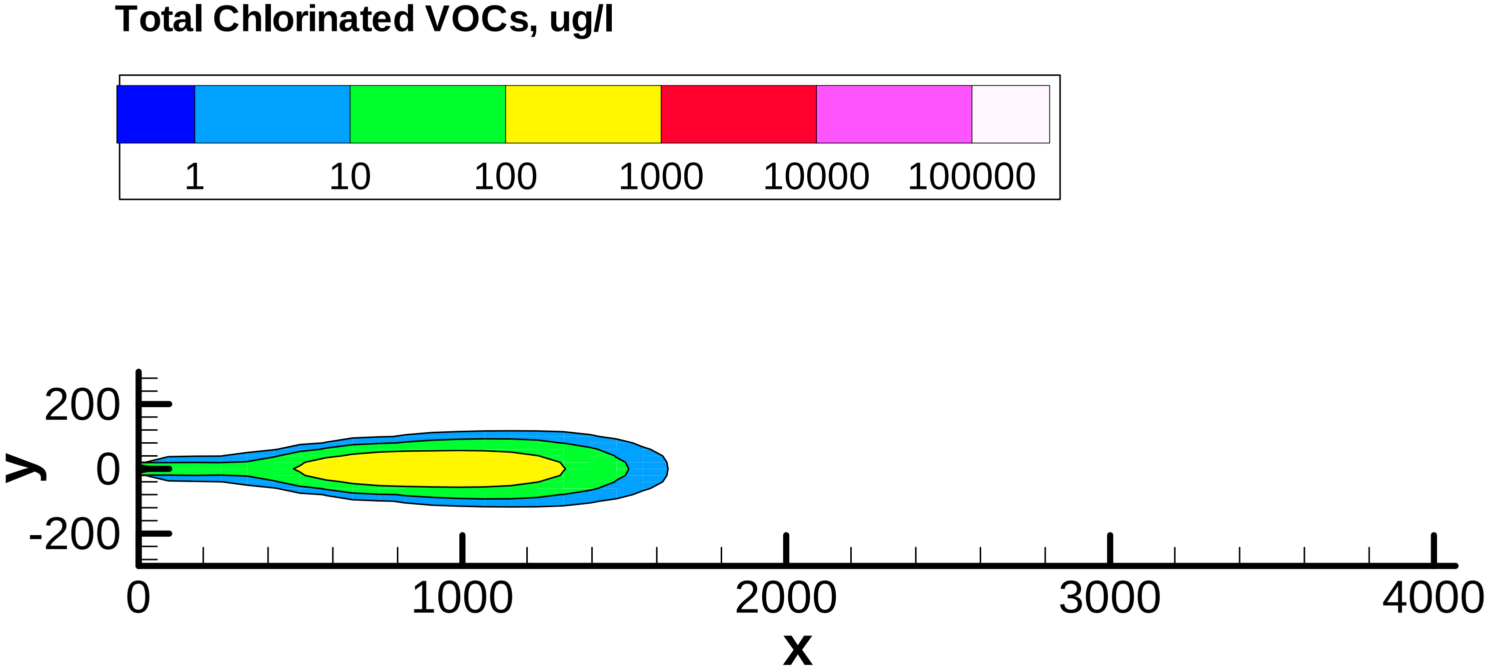

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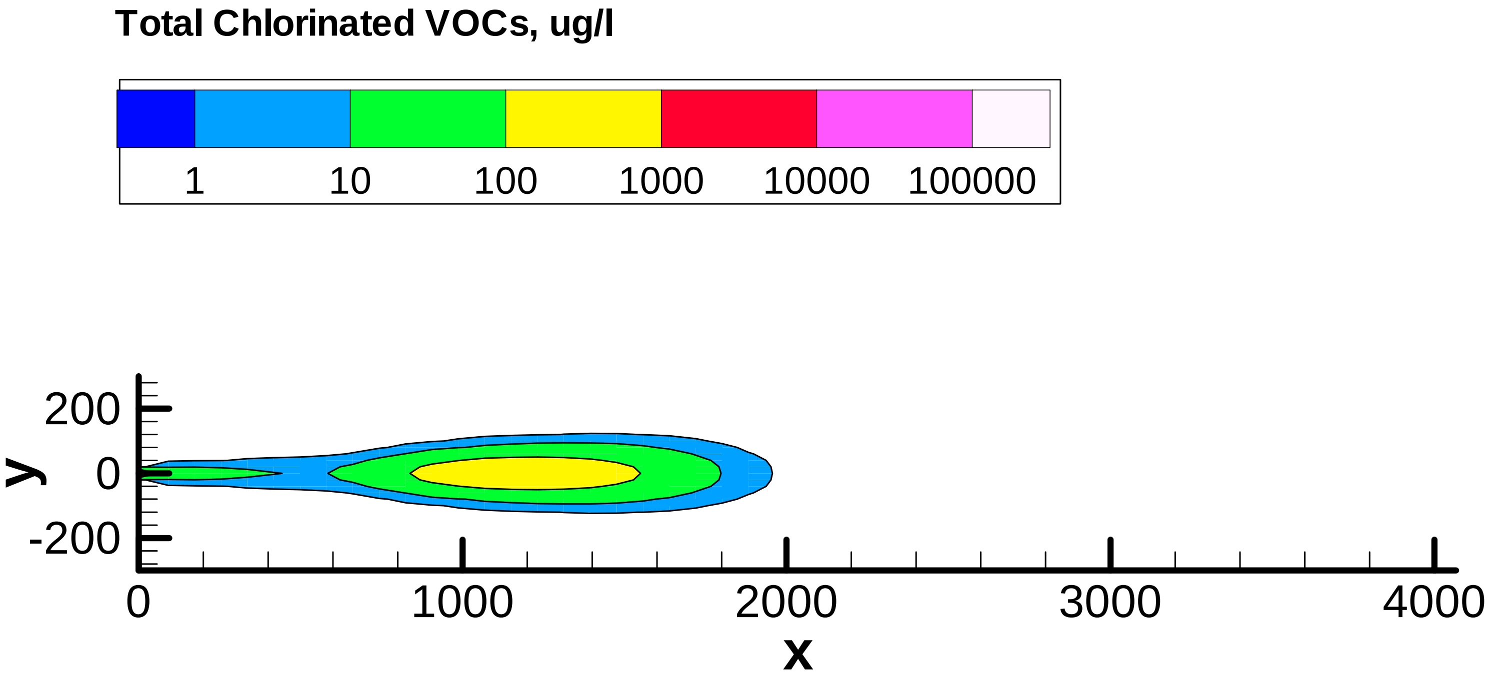

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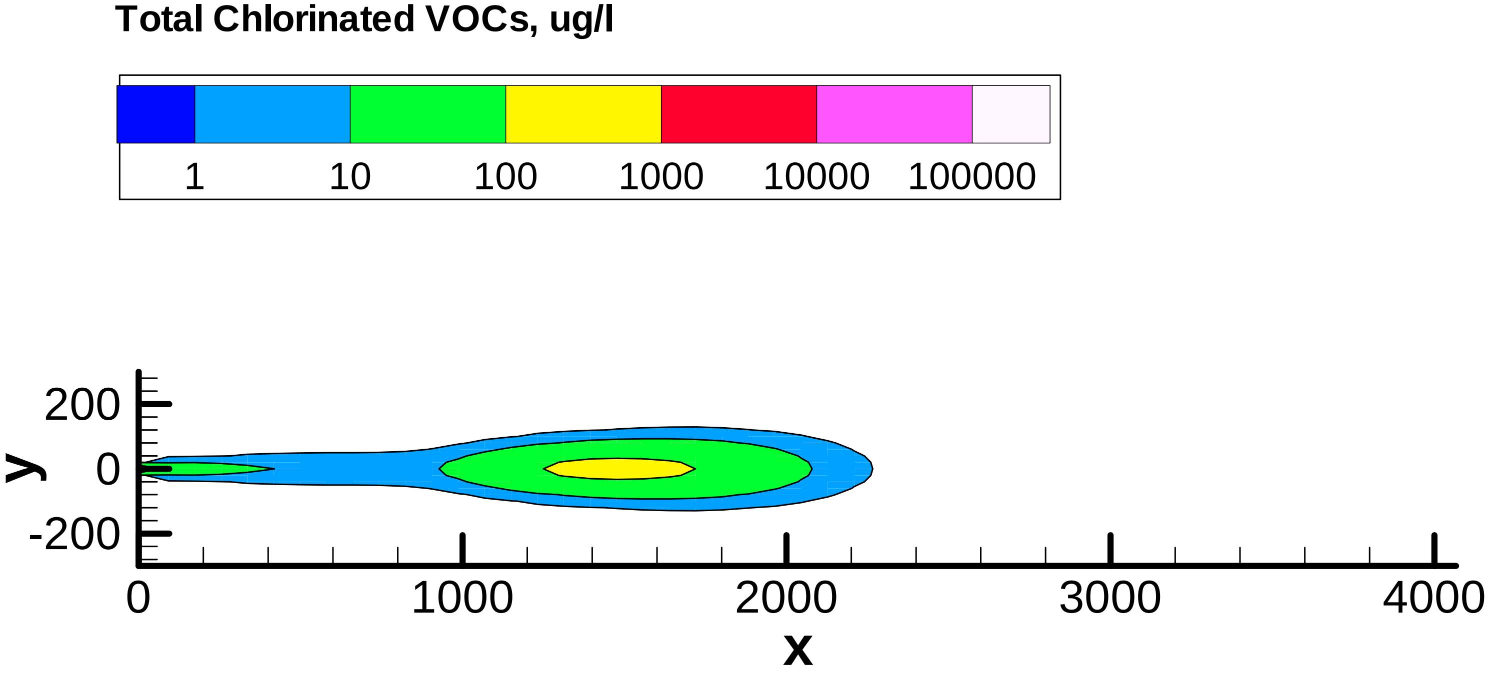

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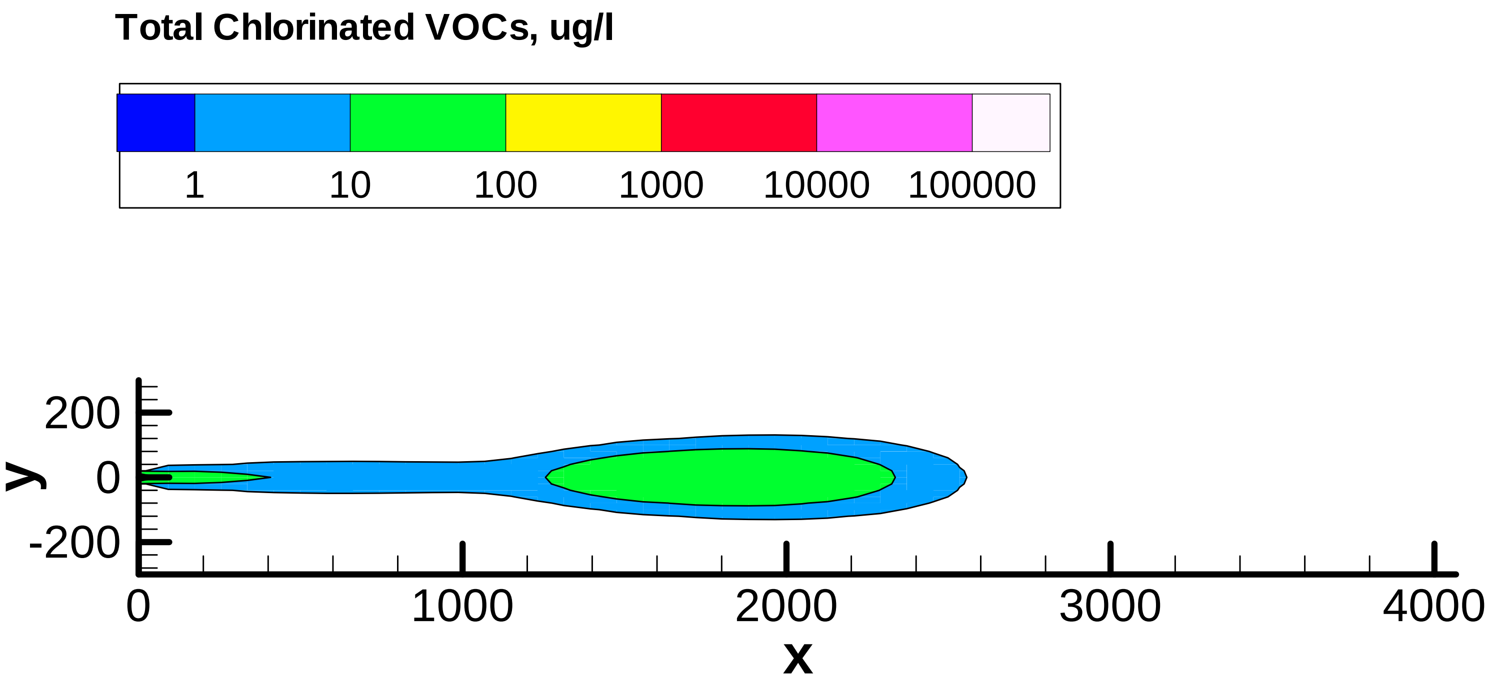

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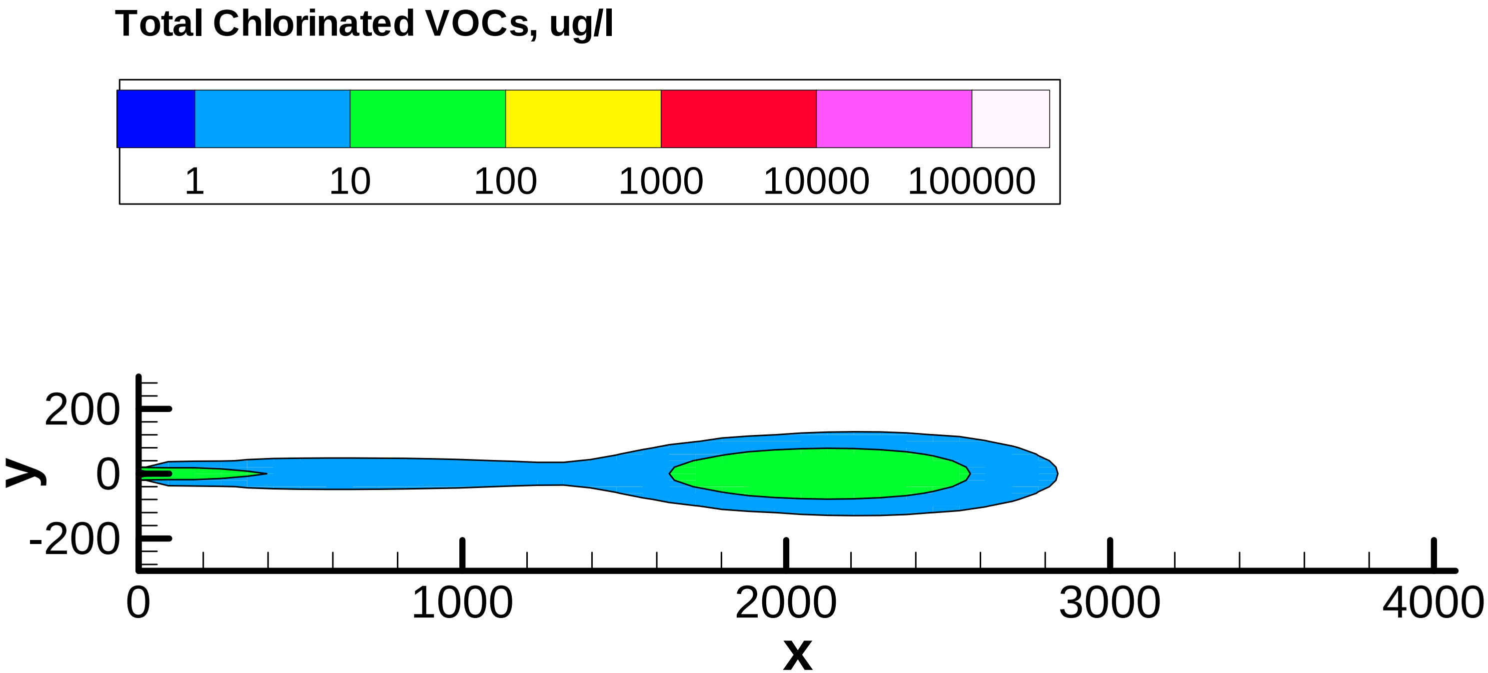

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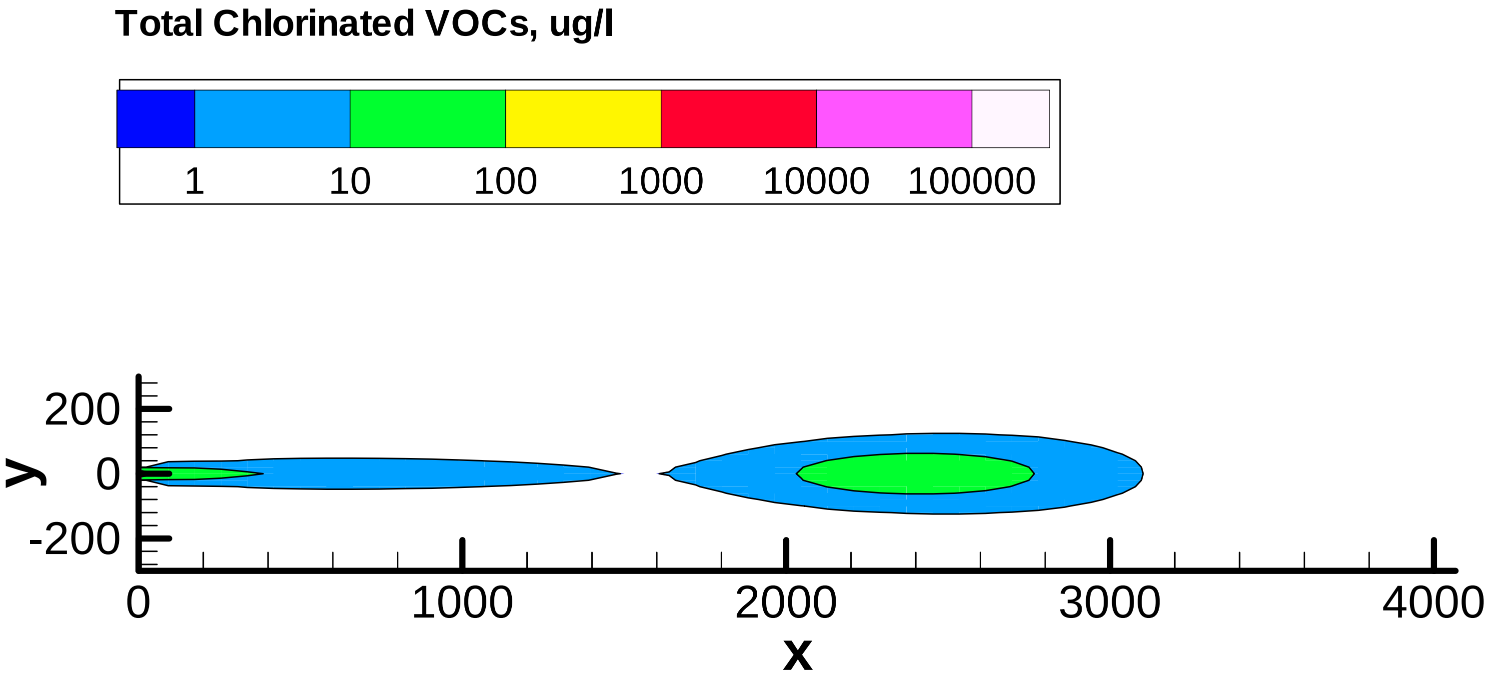

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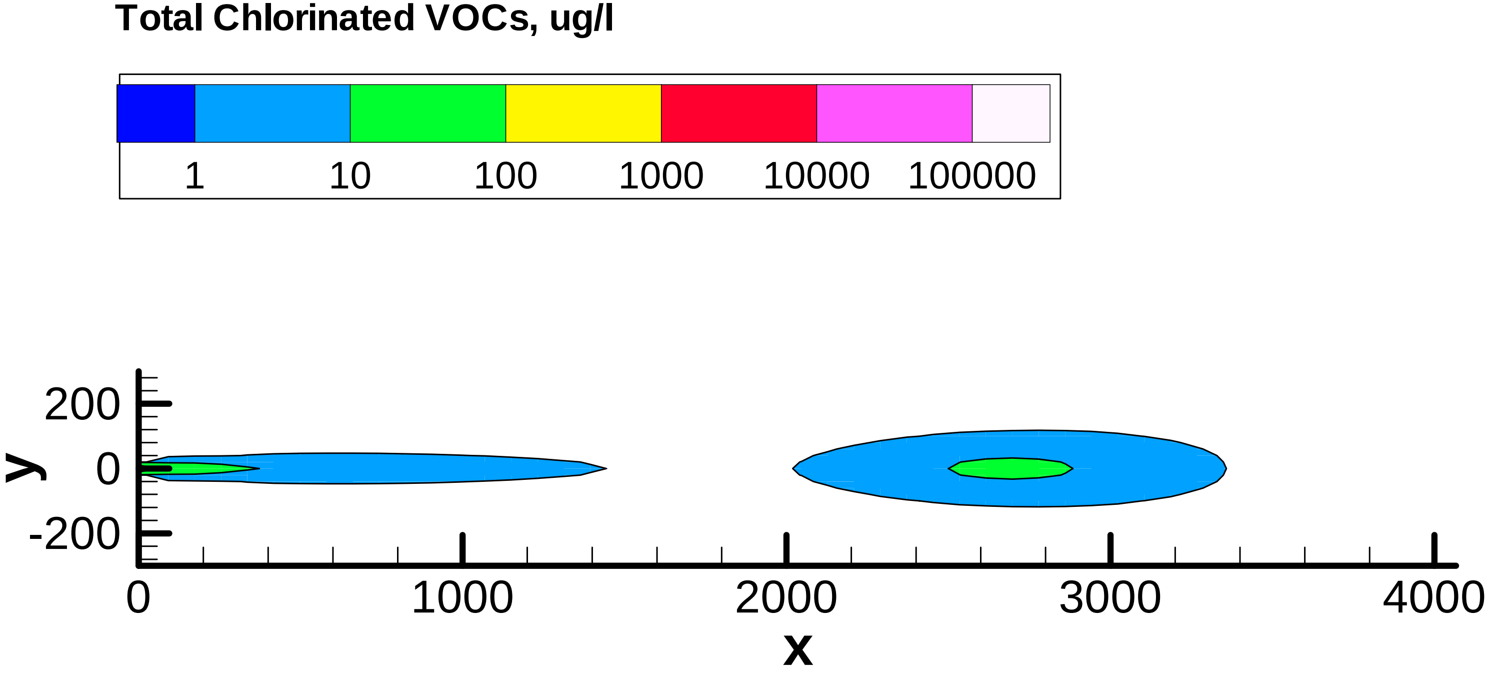
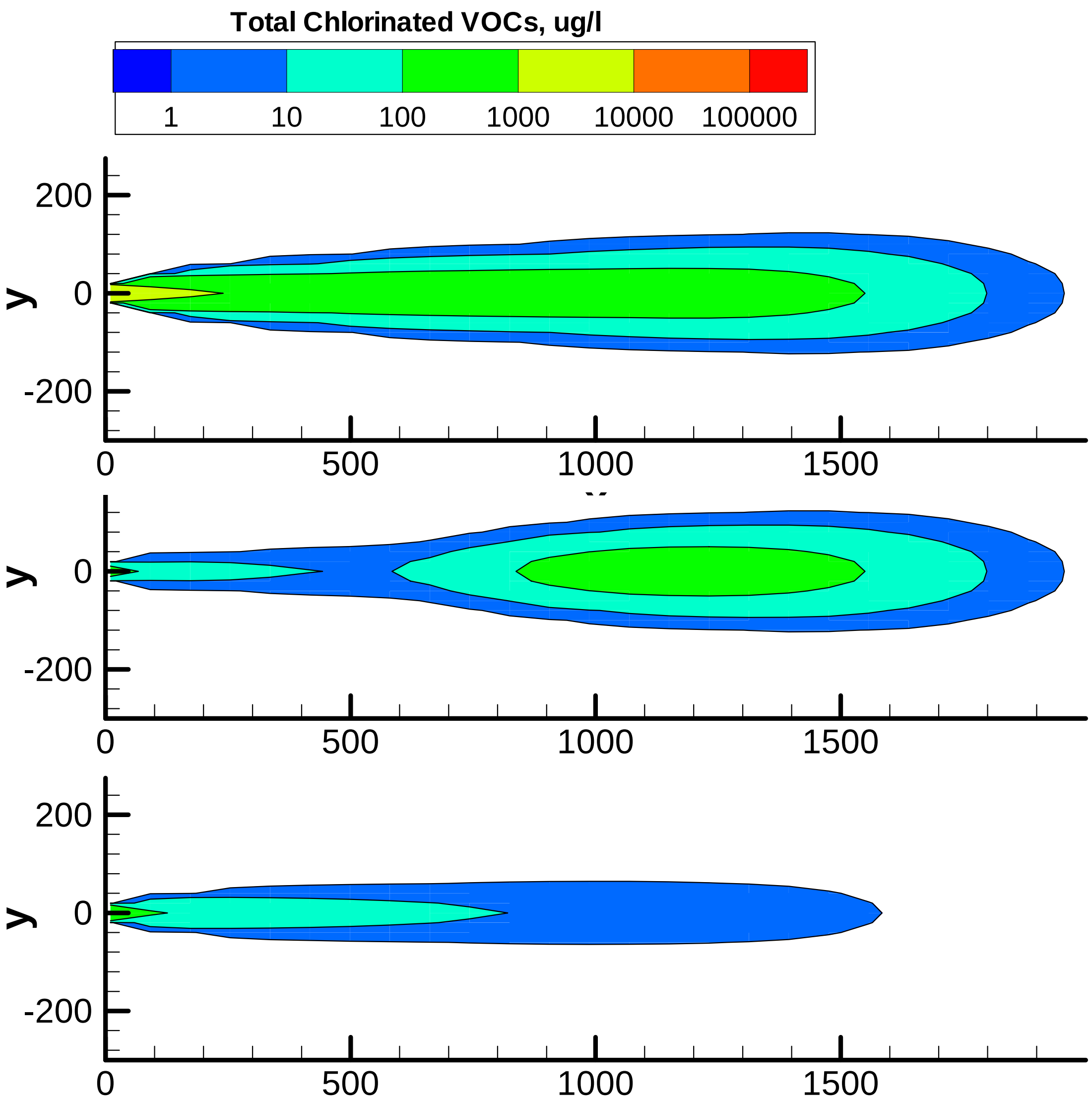
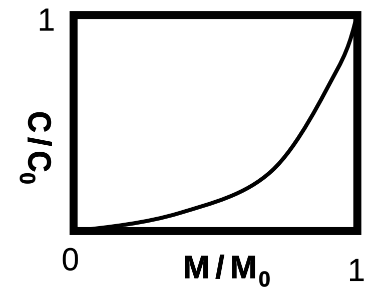
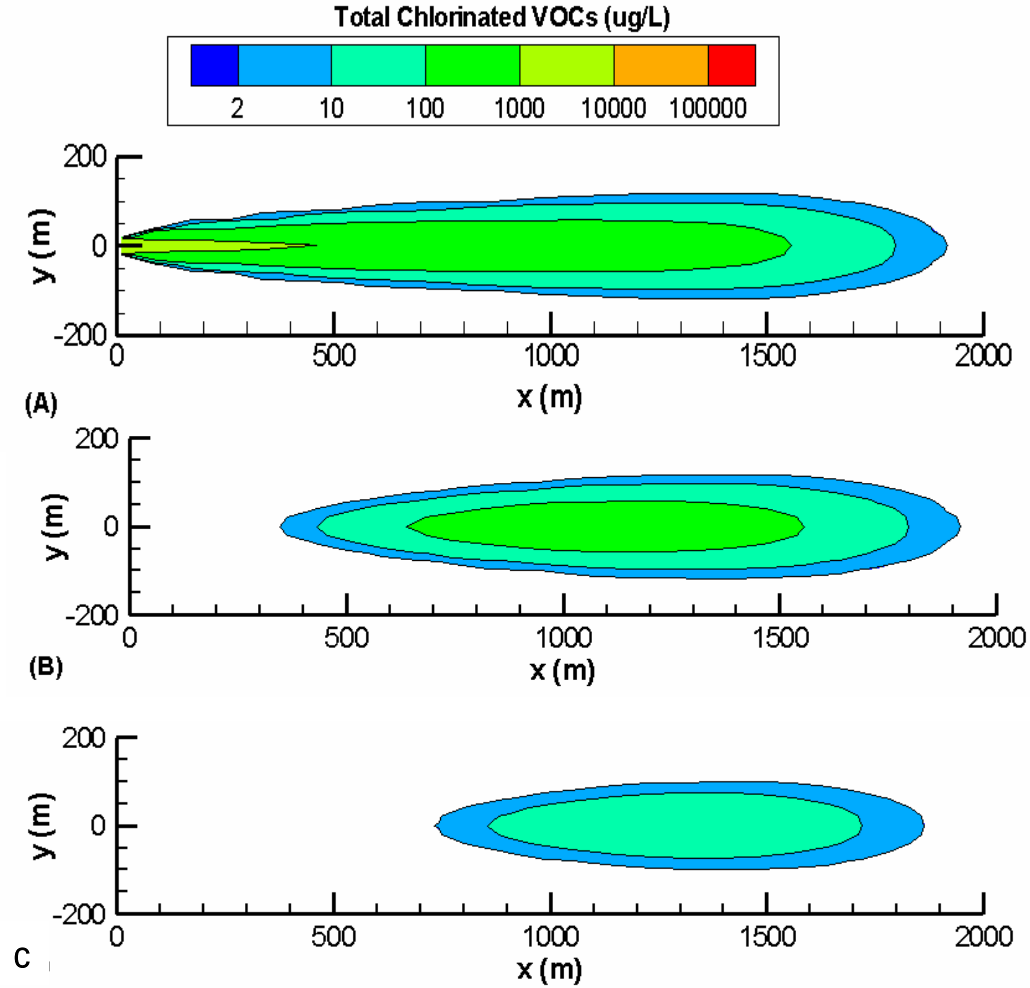


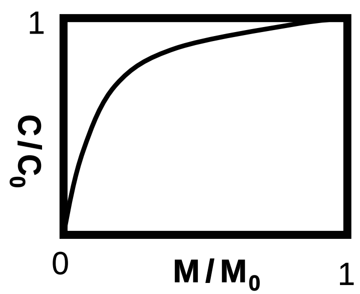
Dissolved plume concentrations of total chlorinated VOCs 50 years after DNAPL release for $\Gamma=2.0$. (A) No source remediation; (B) Removal of 90% of source mass 20 years after the spill; (C) Removal of 90% of source mass immediately after the spill





Dissolved plume concentrations of total chlorinated VOCs 50 years after DNAPL release for **Γ=0.5.** (A) No source remediation; (B) Removal of 90% of source mass 20 years after the spill; (C) Removal of 90% of source mass immediately after the spill





Cancer risk from drinking water at a given location over time

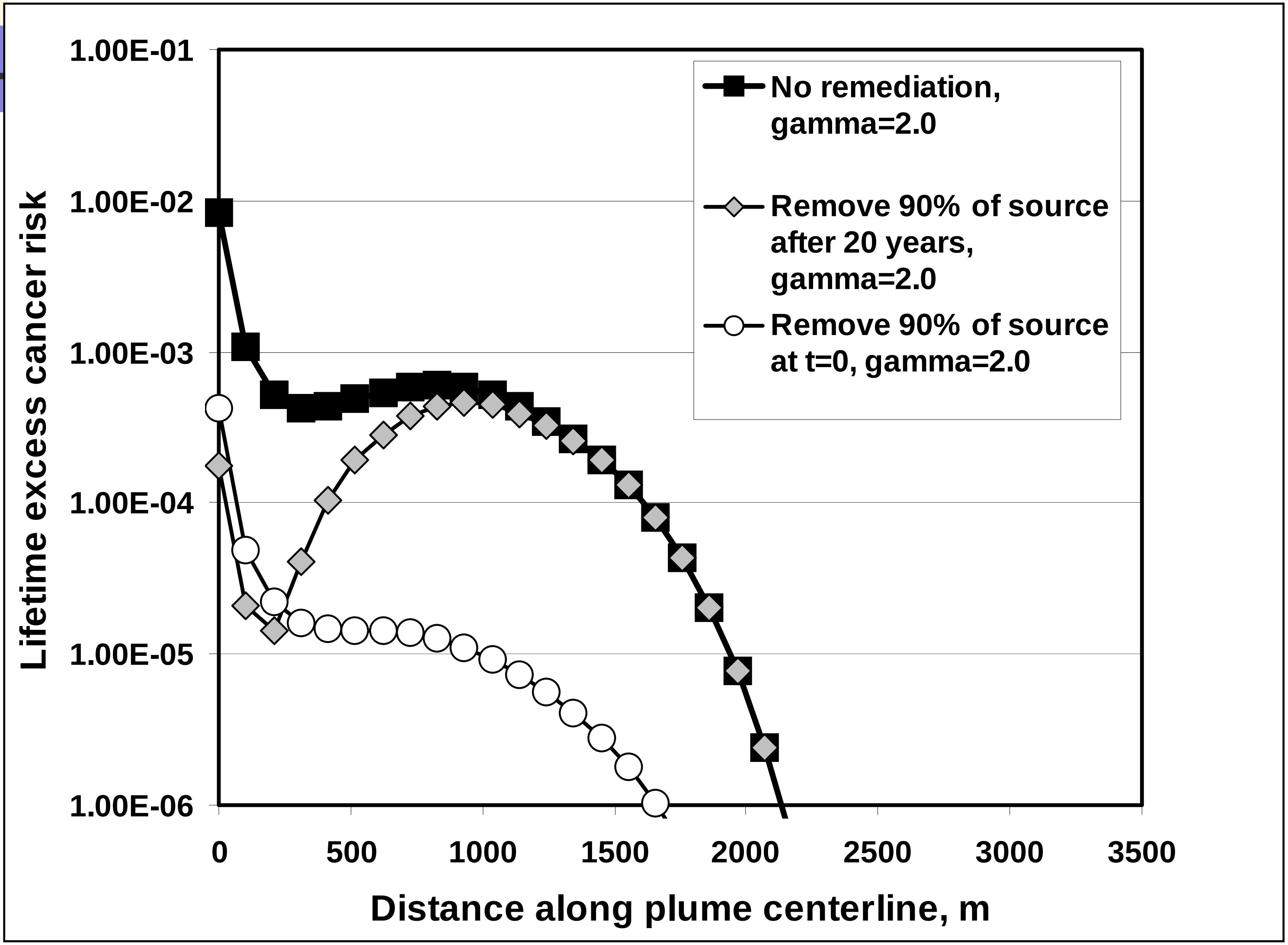
Compute chronic daily intake (CDI) of each carcinogen:

$$CDI_i = \frac{q_w}{mT_{life}} \int_{\max(0,t-T_{ex})}^{t} C_w^i(t)dt$$

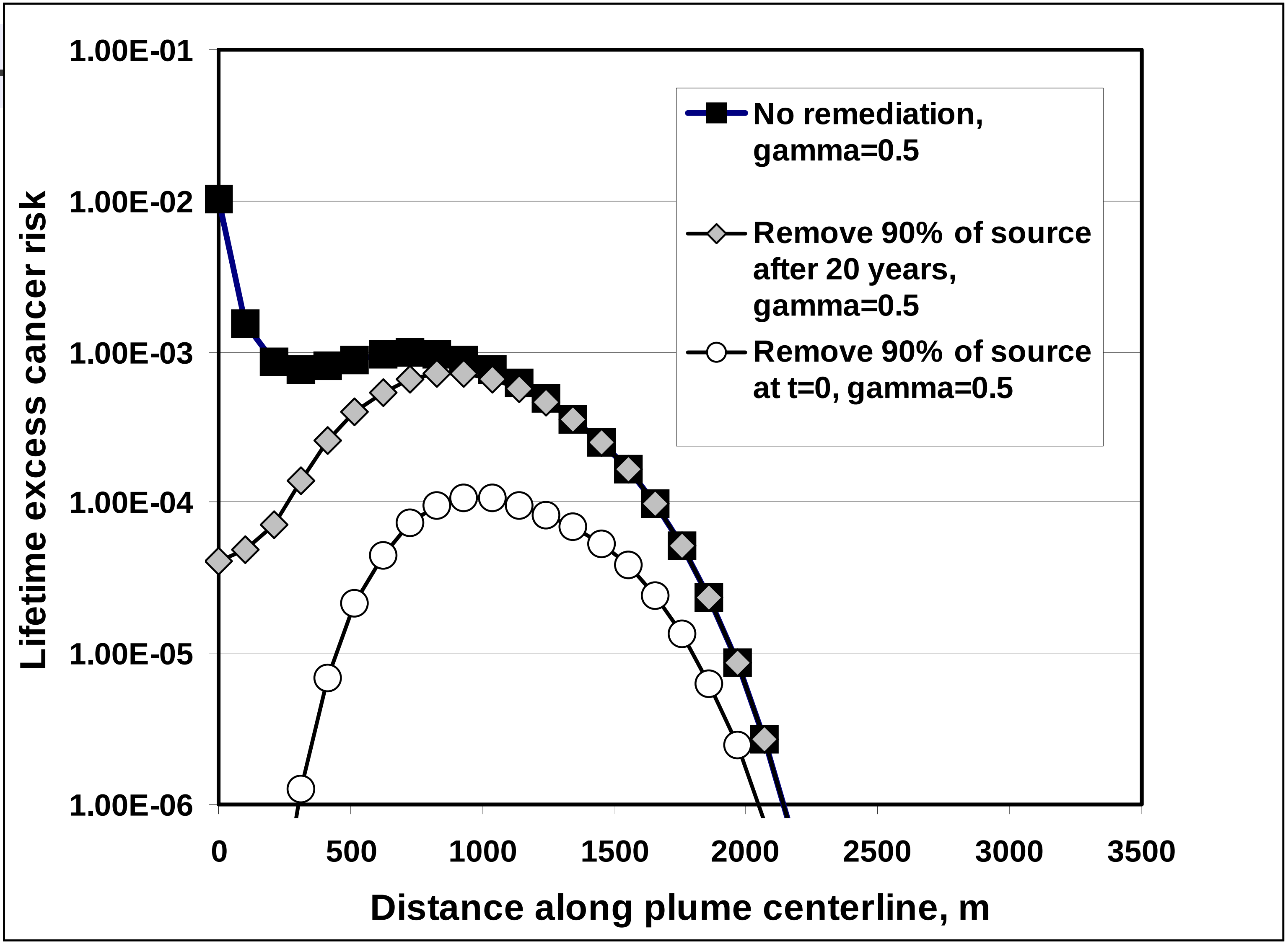
Where q_w is the daily water intake (2 l/d), m is the body mass (70 kg), T_{life} is the 70 year lifetime averaging period, t is the Time, T_{ex} is the length of the exposure period (30 years), and C_w is the concentration of the carcinogen in the well. The CDI is essentially the cumulative dose of carcinogen. With a cancer risk slope factor, SF, the cancer risk is then:

$$Risk_i = CDI_i \, x \, SF_i \qquad Risk_T = \sum Risk_i$$

Γ= 2 case, t=60 years. Cancer risk is dominated by vinyl chloride except near source where PCE dominates



Γ= 0.5 case, t=60 years. Cancer risk is dominated by vinyl chloride except near source where PCE dominates



Summary

- New analytical model shows impact of partial DNAPL source remediation. This is a screening-level model intended to show the leading order behavior
- Partial source remediation has a limited effect on plume length and longevity (as defined by a low MCL value)
- Partial source remediation has a large effect on the plume mass, especially if remediation occurs promptly after the release
- If the source remediation effort is prompt, potential health risks in the plume area are reduced by a large amount.
- If the source remediation effort is substantially delayed, the main health risk reduction occurs near the source, with little or no effect at the leading edge of the plume