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Algebraic Calculation of ERB Dilution, Capture, Retardation, Decay, and Dose

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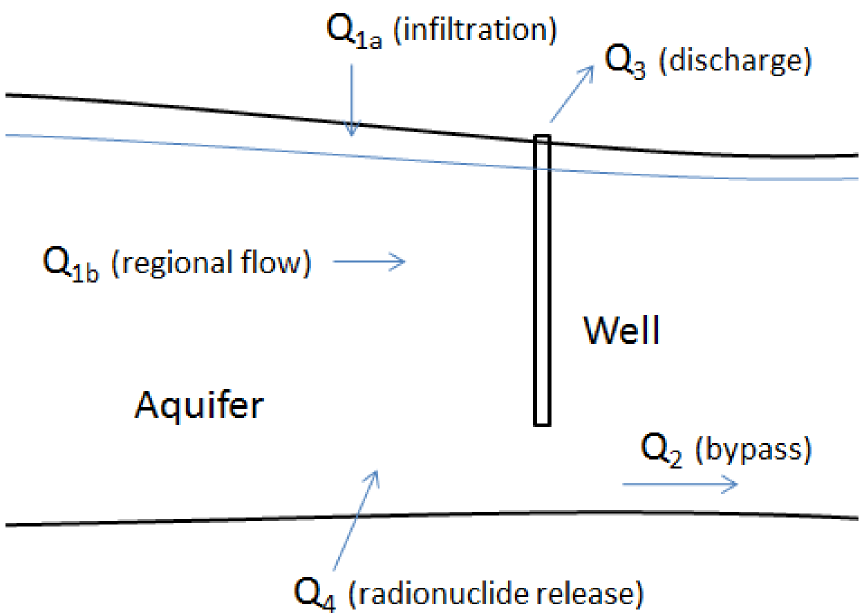
Outline

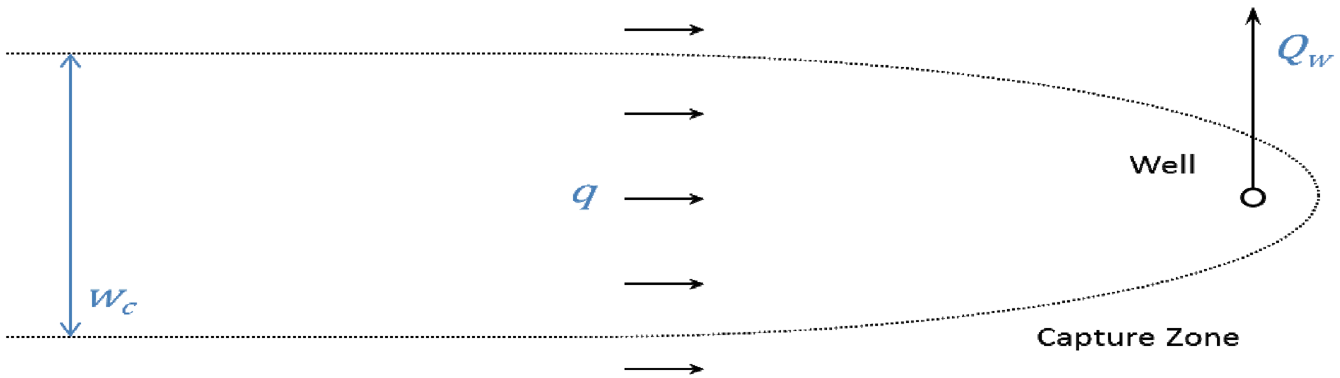
- Review IAEA Example Reference Biosphere (ERB) models
  - Involving groundwater wells (primary exposure pathways)
  - Limitations
    - Must know dilution *a priori*
    - Assume no travel time in aquifer (no sorption, no radioactive decay)
- Show that dilution can be estimated algebraically
  - From the geometries of the plume and well capture zone
- Show that travel time in aquifer can be important
  - Especially for highly sorbed radionuclides
- Present several analytical solutions
  - For different types of releases into a generic aquifer
    - Advective/diffusive
    - Point source/line source/area source

ERB Models

- Example Reference Biospheres (ERBs)
  - Developed in *"Reference Biospheres" for Solid Radioactive Waste Disposal*, IAEA-BIOMASS-6, IAEA (2003)
- ERB 1A and ERB 1B
  - calculate dose rate ($H_{E,i}$) resulting from the concentration of radionuclide i in a well ($C_{3,i}$)
  - $H_{E,i} = C_{3,i} * I * dcf_i$
    - I = individual consumption rate
    - dcf_i = ingestion dose coefficient
- For ERB 1B, dilution in the aquifer and well should not be arbitrarily chosen
  - Can vary from 1 to 10^6 or more
  - Dose rate is highly sensitive to the chosen dilution



Capture Zone



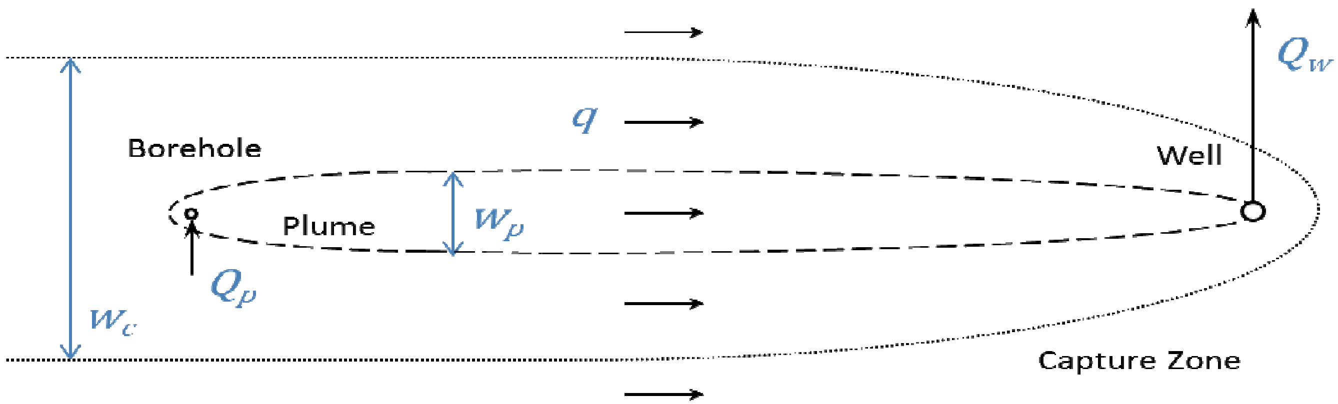
- Analytical solution for generic model aquifer
  - Model aquifer conditions
    - Uniform saturated thickness b [m]
    - Uniform regional specific discharge (darcy velocity) q [m yr^{-1}]
    - Fully penetrating, fully screened well
  - Width of the well capture zone w [m] is

$$w = \frac{Q_W}{bq} - \frac{Q_W}{\pi bq} \tan^{-1} \frac{w}{2x}$$

(Javandel and Tsang 1986, *Ground Water*, **35**(5) 842-847)

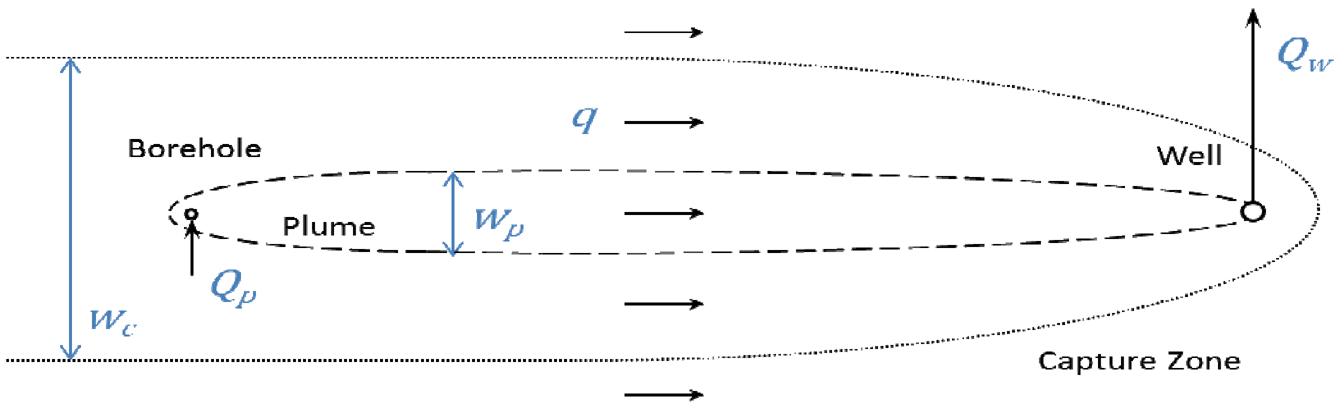
  - Maximum capture zone width w_c [m] (as distance x gets large) is

Plume Width and Dilution



- Advective release from a fully penetrating vertical borehole (VBA) (e.g., abandoned unsealed exploratory borehole)
  - Assume well is on same streamline as borehole
  - Assume large Peclet number in aquifer (negligible dispersion)
    - Negligible transverse dispersion maximizes capture at the well
    - Negligible longitudinal dispersion maximizes peak concentrations at well
  - Maximum plume width w_p [m] is: $w_p = \frac{Q_p}{bq}$
  - Dilution: $D \ldots = \frac{w_c}{\ldots} = \frac{Q_w}{\ldots}$ if $Q \ldots < Q \ldots$

Plume Capture



- Fraction of plume captured, vertical borehole advective (VBA)

$$F_{vba} = 1 \qquad \text{if } Q_p \leq Q_w$$
$$= \frac{w_c}{w_p} = \frac{Q_w}{Q_p} \qquad \text{otherwise}$$

- Travel time in aquifer for radionuclide i

$$T_i = \frac{LnR_{f,i}}{q}$$

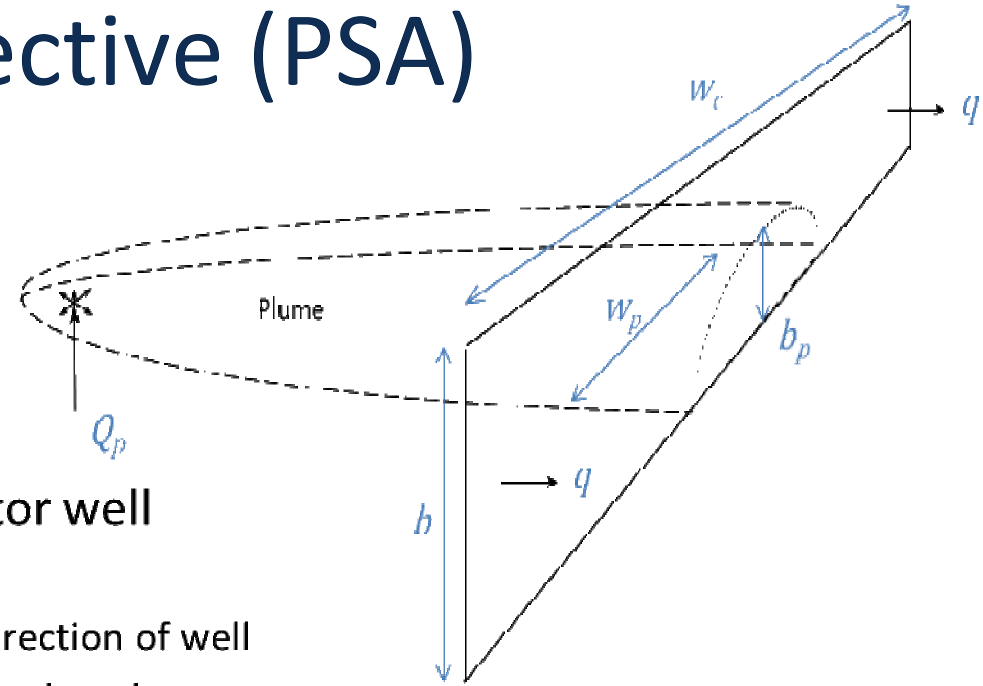
L = distance btn borehole and well
n = porosity
$R_{f,i}$ = retardation factor

- Concentration at well of radionuclide i released from borehole at time $t - T_i$

$$C_{w,i}(t) = \frac{C_{p,i}(t-T_i)e^{-\lambda T_i}}{D_f(t-T_i)}$$

λ = decay constant

Point Source Advective (PSA)



- Point source release
  - Advective (PSA)
  - Top or bottom of aquifer
  - E.g., from unsealed borehole, shaft, fracture zone, etc.
- Same generic aquifer and receptor well
  - Constant saturated thickness
  - Constant regional flow velocity in direction of well
  - Well is fully penetrating, fully screened, and more than 3w down gradient
  - Vertical anisotropy (a) important for point source release

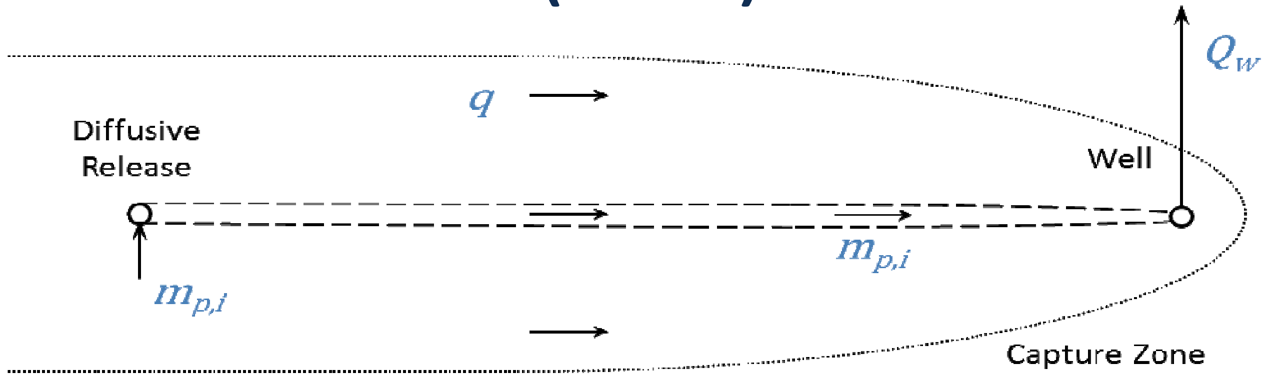
$$a = \left(\frac{K_h}{K_v}\right)^{\frac{1}{2}}$$

- Plume cross-section $\quad w_p = 2\left(\frac{2Q_p a}{\pi q}\right)^{\frac{1}{2}} \qquad b_p = \left(\frac{2Q_p}{\pi q a}\right)^{\frac{1}{2}}$ semi-ellipse, assuming $b_p < b$
- Dilution

$$D_{f,psa} = \frac{w_c b}{A_{psa}} \qquad \text{where} \qquad A_{psa} = \frac{\pi}{4} w_p b_p \qquad \text{if } w_p \le w_c$$

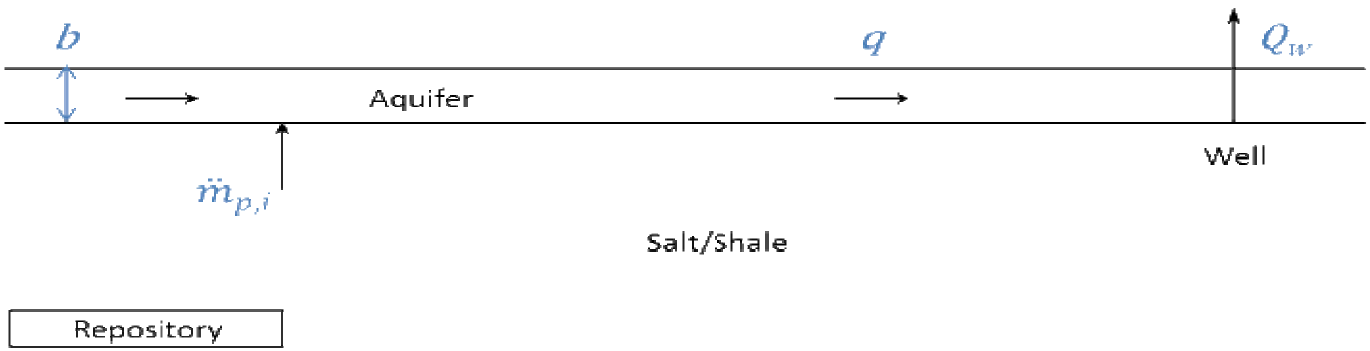
$$= 2\int_0^{\frac{w_c}{2}} \left(\frac{b_p}{\frac{1}{2}w_p}\sqrt{\left(\tfrac{1}{2}w_p\right)^2 - y^2}\right) dy \qquad \text{otherwise}$$

Diffusive Release (PSD)



- Point source diffusive (PSD) release (e.g., from sealed borehole or shaft)
- Same generic aquifer and fully-penetrating, fully-screened receptor well
  - Narrow plume width, so no bypassing and no minimum distance requirement
- Mass flux of radionuclide i : $m_{p,i}(t)$ [g yr^{-1}]
- Dilution occurs, but no dilution factor can be calculated
  - A diffusive flux is not volume-based
- Travel time, retardation (same): $T_i = \frac{LnR_{f,i}}{q}$
- Concentration at well : $C_{w,i}(t) = \frac{m_{p,i}(t-T_i)e^{-\lambda T_i}}{Q_w}$
- Dose at well (same): $H_{E,i}(t) = C_{w,i}(t) * I * dcf_i$

Broad Diffusive (BD) Release



- Broad diffusive (BD) release (e.g., from low permeability formation)
- Same generic aquifer and fully-penetrating, fully-screened receptor well
- Plume width assumed to be larger than capture zone
- Mass flux to bottom (or top) of aquifer: $\ddot{m}_{p,i}(t)$ [g yr^{-1} m^{-1}]
  - Units are mass flux per unit lateral width of aquifer perpendicular to flow
- No lateral dilution, only dilution from vertical mixing
  - Again, no dilution factor can be calculated
- Travel time, retardation in aquifer, calculated as before
- Concentration at well : $$C_{w,i}(t) = \frac{\ddot{m}_{p,i}(t - T_i)e^{-\lambda T_i}}{qb}$$
  - Not a function of well discharge

Example Applications

- Example applications presented in paper
  - Vertical borehole advective (VBA)
    - Variable release rate
  - Point source advective (PSA)
    - Bypassing (plume width sometimes greater than capture zone)
  - Point source diffusive (PSD)
  - Broad diffusive (BD)
- Constants for each example
  - Aquifer and well properties
    - q = 8 m yr^{-1}, b = 15 m, a^2 = 10, n = 0.4, L = 5 km, Q_w = 10,000 m^3 yr^{-1}
  - Travel time in aquifer, $T_i =$ 1,000 yr (consistent with a K_d of 0.76 mL g^{-1})
  - Radionuclide half life = 1,000 yr
    - Implies 50% of radionuclide mass will decay during travel time

VBA Example

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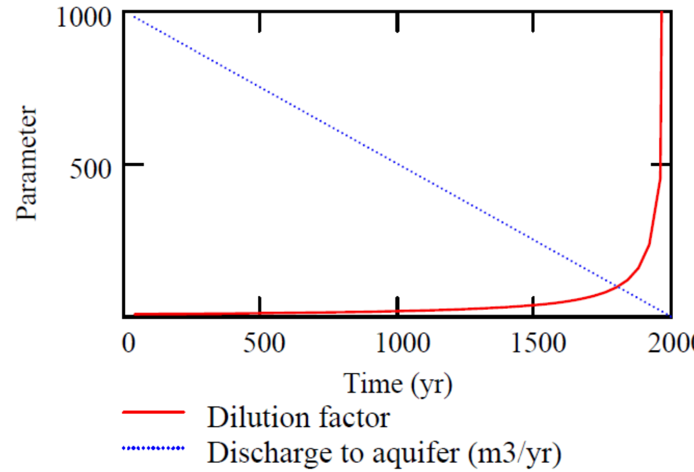
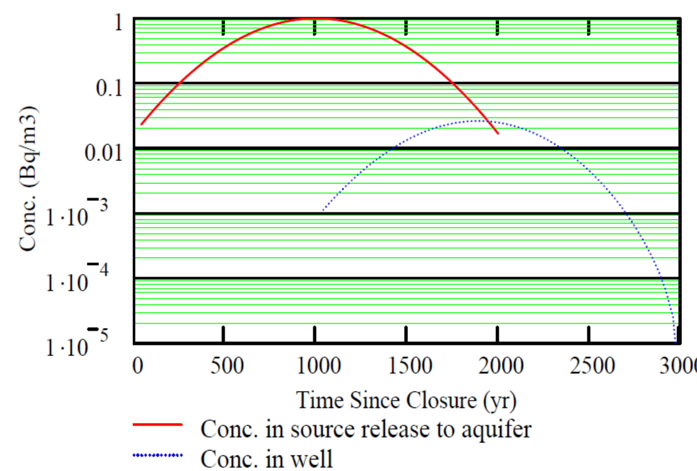
- Vertical borehole advective (VBA)
  - Variable release rate, $Q_p(t)$
  - Constant well discharge, Q_w
- Dilution factor changes with t

$$D_{f,vba}(t) = \frac{w_c}{w_p(t)} = \frac{Q_w}{Q_p(t)} \quad \text{for } Q_p(t) \le Q_w$$

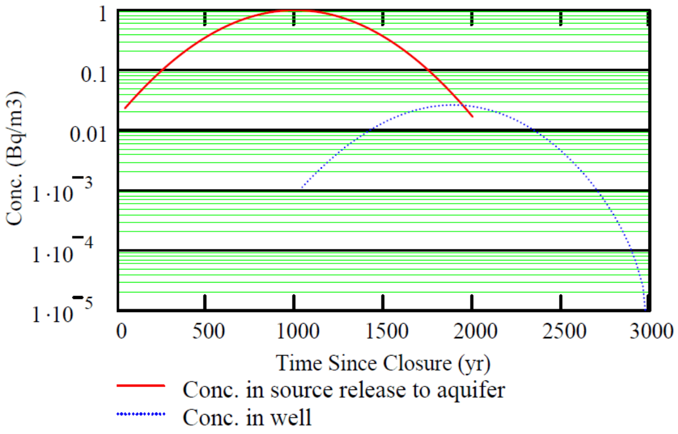
  - As $Q_p(t)$ goes from 1,000 to 1 $m^3\ yr^{-1}$ $D_{f,vba}(t)$ goes from 10 to 10,000
- Concentration at well
  - Peak arrives at well 1,000 yr after peak release
  - Peak concentration at well is 40-fold lower than peak concentration released
    - 20-fold decrease due to dilution
    - 2-fold decrease due to decay



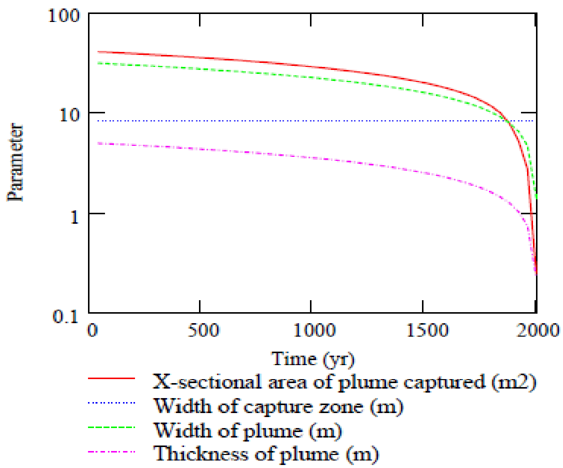


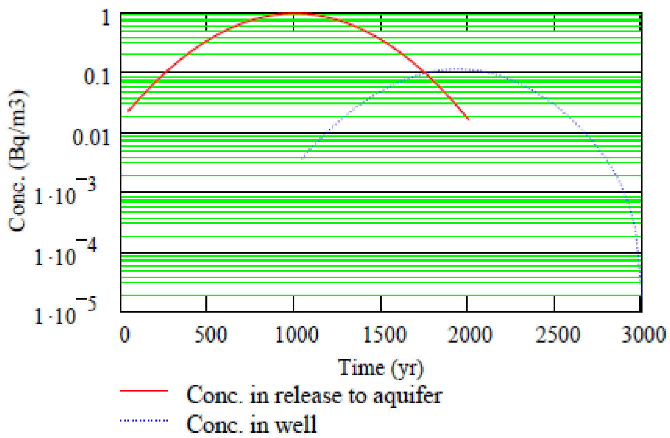
PSA Examples

- Point source advective (PSA) example 1
  - Same $Q_p(t)$ and Q_w as VBA example
  - Same dilution factor, $D_f(t)$
    - Width of plume remains within capture zone
  - Same concentrations at well



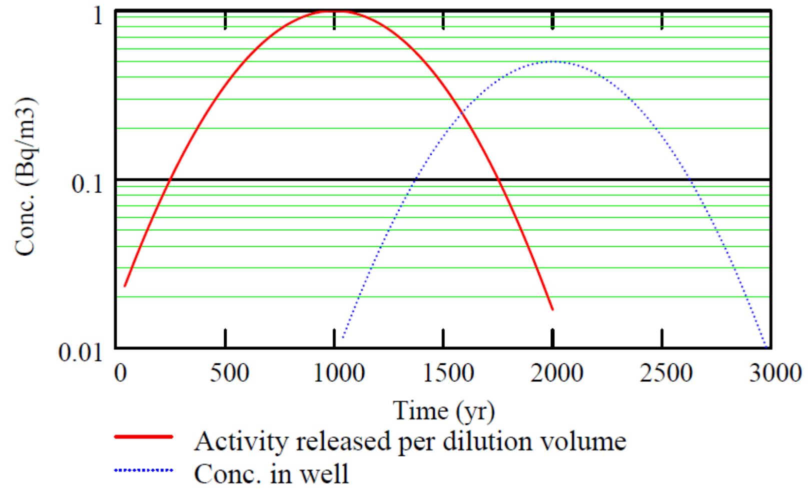
- PSA example 2 with reduced well discharge
  - Same as PSA example 1, but Q_w fixed at 1,000 m^3 yr^{-1} instead of 10,000 m^3 yr^{-1}
  - Width of plume exceeds width of capture zone for first ~1,800 yr
  - Much of plume bypasses well
  - Dilution of peak is much lower
  - Peak concentration is much higher





Diffusive Release Examples

- Point source diffusive (PSD) example
  - The release concentration is represented by normalizing the mass flux release by the well discharge rate, called hereafter the activity released per dilution volume: $C_{p,i}(t) = \frac{m_{p,i}(t)}{Q_w}$
  - Reduced concentrations at the well are due only to decay



- Broad diffusive (BD) example
  - The activity released per dilution volume for the BD example is: $$C_{p,i}(t) = \frac{\ddot{m}_{p,i}(t)}{qb}$$
  - Dilution is built into the source breakthrough curve (as in PSD example)
    - Less dilution is expected for the BD model versus the PSD model because PSD dilution is due to vertical and lateral mixing; only vertical mixing for BD model
  - The same breakthrough curves at the well are obtained because

Model Summary

- Simple algebraic analytical solutions
- Dilution factors
  - Calculated from inputs
    - Ensures consistency
  - Vary over time when volumetric fluxes change
- Bypassing included
  - When plume width exceeds capture zone
- Travel time and decay included
  - Especially important for highly sorbed Rn's

TABLE I. Factors Affecting Dose Rate Calculations in the Aquifer Release Models

Parameter	VBA	PSA	PSD	BD
Pump rate, $Q_w(t)$	✓	✓	✓	
Release rate, $Q_p(t)$	✓	✓		
Diffusive flux, $m_{p,i}(t)$			✓	
Diffusive flux, $\ddot{m}_{p,i}(t)$				✓
Saturated thickness, b		✓		✓
Specific discharge, q	✓	✓		✓
Capture zone width, w_c	✓	✓		
Dilution factor, $D_f(t)$	✓	✓		
Anisotropy, a		✓		
Fraction captured, F		✓		
Well distance, L	✓	✓	✓	✓
Retardation factor, $R_{f,i}$	✓	✓	✓	✓
Decay rate, λ	✓	✓	✓	✓
Porosity, n	✓	✓	✓	✓
Travel time, T_i	✓	✓	✓	✓
Indiv. consump. rate, I	✓	✓	✓	✓
Ingest. dose coeff., dcf_i	✓	✓	✓	✓

Next Steps

- Consider additional release scenarios
  - E.g., release from multiple fractures
- Include in-growth
- Sensitivity analyses
  - Identify important parameters for various release scenarios and radionuclides