# CONTAMINANT TRANSPORT

## MECHANICAL ASPECTS

### ADVECTION

$$\bar{v} = \frac{Kdh}{\phi_e dl} = \text{average linear velocity}$$

### DISPERSION/DIFFUSION

due to variable advection
that occurs in the transition zone between
two domains of the fluid with different compositions
(diffusion is caused by chemical gradients)

Later we will look at some fundamental
Some NONMECHANICAL ASPECTS : Decay & Sorption

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If we only consider advection and
start with a "point" of material with $C_o$=1000mg/l

A point has no volume so can it have a concentration? So why do we say a “point”?

K = 0.1 cm/sec
dh = 10 cm
dl = 100 cm
$\phi$ = 0.2

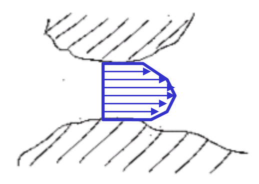
How long will it take for the material to move 50cm?
What will the concentration be at that location at that time?

## However concentration will decreasse due to DIFFUSION and DISPERSION

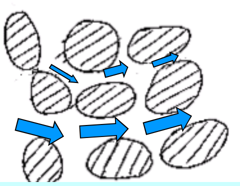
In the direction of flow we consider

**LONGITUDINAL DISPERSION:**

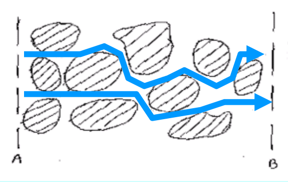
Velocity variation within pores:



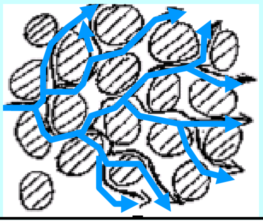
Velocity variation between pores:



Variation of flow path lengths



**TRANSVERSE DISPERSION (normal to the flow path):**



Splitting of flow paths

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These physical mixing processes are combined and referred to as **"Mechanical Dispersion"**

Mechanical dispersion is related to average pore velocity by **dispersivity ($\alpha$)**

$$\text{Mechanical Dispersion} = D = \alpha\bar{v}$$

**dispersivity ($\alpha$)**

units of length

increases with increased heterogeneity

and thus with travel distance

## Diffusion:

**Movement of dissolved species from areas of high concentration to low concentration**

## Fick's Law:

$$\mathbf{Flux} = \mathbf{F} = -\mathbf{D}\frac{\partial \mathbf{C}}{\partial \mathbf{l}}$$

**D in open water for common groundwater ions**
**~1x10$^{-9}$ to 2x10$^{-9}$ m$^2$/sec**

**D* represents D in porous media, and is reduced due to tortuosity and effective porosity**

**D* ~ 2x10$^{-11}$ to 5x10$^{-10}$ m$^2$/sec**

$$\text{some suggest } D^* = D\frac{\phi_e}{\tau}$$

$$\tau = \frac{\text{actual path}}{\text{direct path}}$$

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## Transport Equations

**The combined mechanical and chemical diffusion process is treated with a Fick's Law approach**

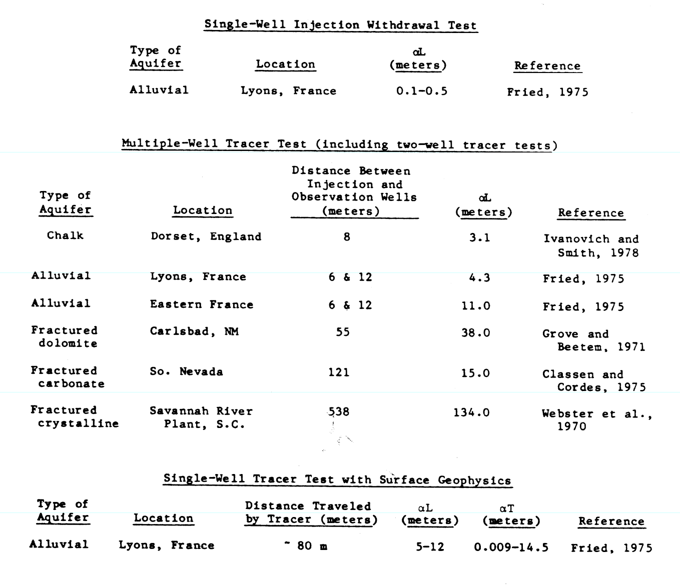
$$\mathbf{F} = -\mathbf{D}_l \frac{\partial \mathbf{C}}{\partial \mathbf{l}}$$

**But here D is**
**Hydrodynamic Dispersion expressed as**

$$\mathbf{D}_l = \alpha_l \overline{\mathbf{v}_l} + \mathbf{D}^*$$

**Studies indicate scale dependence of dispersivity, $\alpha$**

# Dispersivities at various scales & measured by various methods as compiled by Stan Davis et al. Table B1 in the book, "Ground Water Tracers"



### Single-Well Injection Withdrawal Test

| Type of Aquifer | Location | αL (meters) | Reference |
|---|---|---|---|
| Alluvial | Lyons, France | 0.1-0.5 | Fried, 1975 |

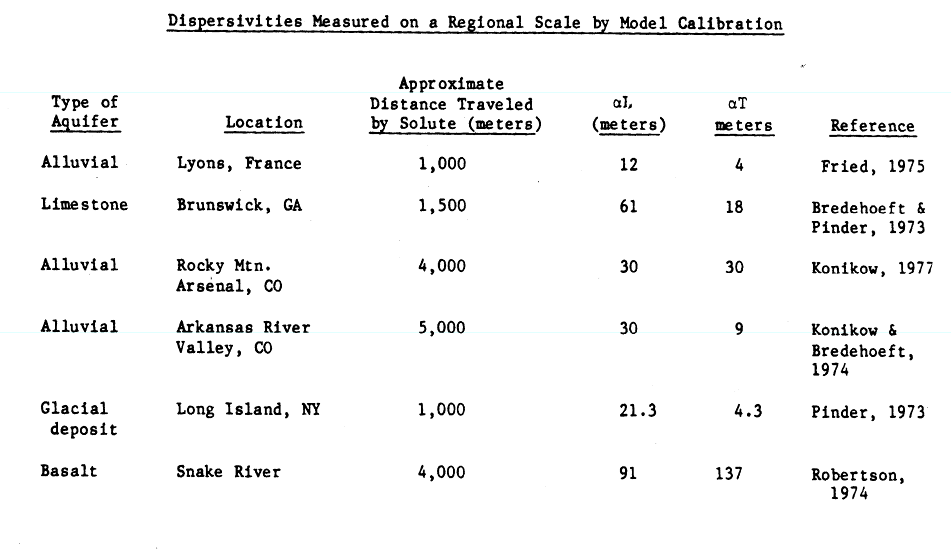
### Multiple-Well Tracer Test (including two-well tracer tests)

| Type of Aquifer | Location | Distance Between Injection and Observation Wells (meters) | αL (meters) | Reference |
|---|---|---|---|---|
| Chalk | Dorset, England | 8 | 3.1 | Ivanovich and Smith, 1978 |
| Alluvial | Lyons, France | 6 & 12 | 4.3 | Fried, 1975 |
| Alluvial | Eastern France | 6 & 12 | 11.0 | Fried, 1975 |
| Fractured dolomite | Carlsbad, NM | 55 | 38.0 | Grove and Beetem, 1971 |
| Fractured carbonate | So. Nevada | 121 | 15.0 | Classen and Cordes, 1975 |
| Fractured crystalline | Savannah River Plant, S.C. | 538 | 134.0 | Webster et al., 1970 |

### Single-Well Tracer Test with Surface Geophysics

| Type of Aquifer | Location | Distance Traveled by Tracer (meters) | αL (meters) | αT (meters) | Reference |
|---|---|---|---|---|---|
| Alluvial | Lyons, France | ~ 80 m | 5-12 | 0.009-14.5 | Fried, 1975 |

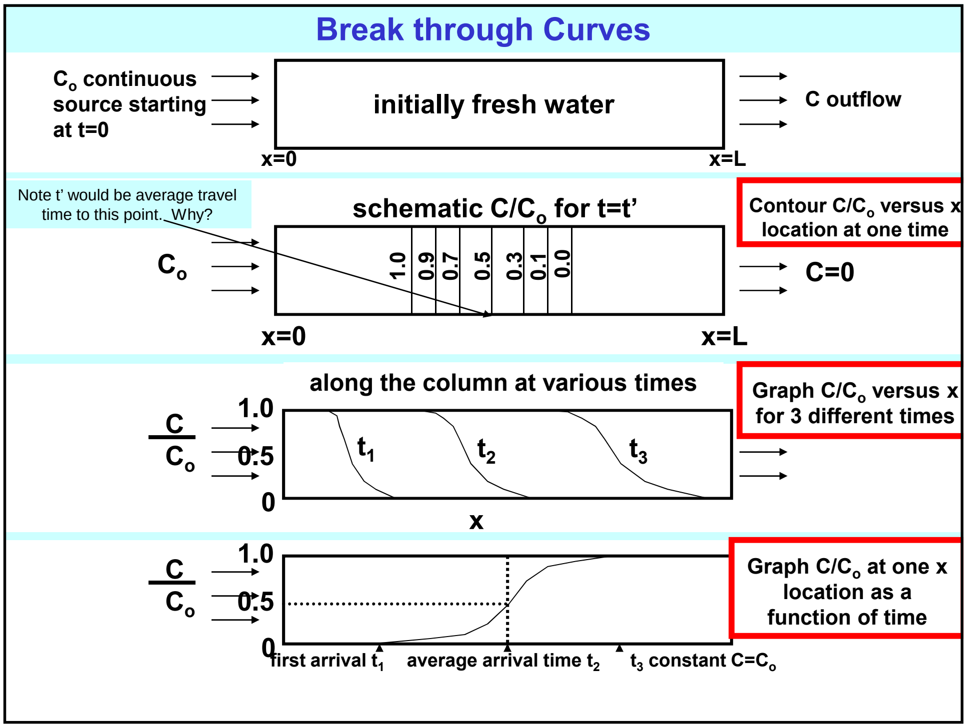
# Table B1 CONTINUED Dispersivities at various scales & measured by various methods from "Ground Water Tracers"



### Dispersivities Measured on a Regional Scale by Model Calibration

| Type of Aquifer | Location | Approximate Distance Traveled by Solute (meters) | αL (meters) | αT meters | Reference |
|---|---|---|---|---|---|
| Alluvial | Lyons, France | 1,000 | 12 | 4 | Fried, 1975 |
| Limestone | Brunswick, GA | 1,500 | 61 | 18 | Bredehoeft & Pinder, 1973 |
| Alluvial | Rocky Mtn. Arsenal, CO | 4,000 | 30 | 30 | Konikow, 1977 |
| Alluvial | Arkansas River Valley, CO | 5,000 | 30 | 9 | Konikow & Bredehoeft, 1974 |
| Glacial deposit | Long Island, NY | 1,000 | 21.3 | 4.3 | Pinder, 1973 |
| Basalt | Snake River | 4,000 | 91 | 137 | Robertson, 1974 |

## Break through Curves



Note t' would be average travel time to this point. Why?

schematic $C/C_o$ for t=t'

**Contour $C/C_o$ versus x location at one time**

along the column at various times

**Graph $C/C_o$ versus x for 3 different times**

**Graph $C/C_o$ at one x location as a function of time**

first arrival $t_1$ average arrival time $t_2$ $t_3$ constant $C=C_o$

## Mechanical Transport Equations can be derived by considering an elemental volume as we did for the flow equations

**We leave the derivation to a later course & consider the practical analytical forms**

$$\frac{\partial C}{\partial t} = D_l \frac{\partial^2 C}{\partial {l_l}^2} + D_t \frac{\partial^2 C}{\partial {l_t}^2} + D_v \frac{\partial^2 C}{\partial {l_v}^2} - \overline{v}_l \frac{\partial C}{\partial l}$$

| | |
|---|---|
| **C** | **concentration in fluid** |
| **t** | **time** |
| **l** | **spatial coordinate** |
| $\underline{\mathbf{D}}$ | **dispersion tensor** |
| $\overline{\mathbf{v}}$ | **interstitial velocity** |
| $l_l$ | **reflects the flow direction** |
| $l_t$ | **reflects the direction transverse laterally to flow** |
| $l_v$ | **reflects the direction transverse vertically to flow** |

Note differing form of flow equations

$$\frac{\partial h}{\partial t} = \frac{T}{S}\left[\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2}\right]$$

## Equation for mechanical transport in 1-D

$$\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial x^2} - \overline{v}_x \frac{\partial C}{\partial x}$$

| | |
|---|---|
| C | concentration in fluid |
| t | time |
| x | spatial coordinate |
| D | dispersion tensor |
| $\overline{v}$ | interstitial velocity |

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## Analytical Solution for transport in 1-D flow field
## continuous source
## 1D spreading
## without chemical reaction

This is an appropriate model for transport along a sand column
It will over estimate C at x if applied to a case with spreading in the transverse lateral or vertical directions

It will predict the break through curves we looked at earlier

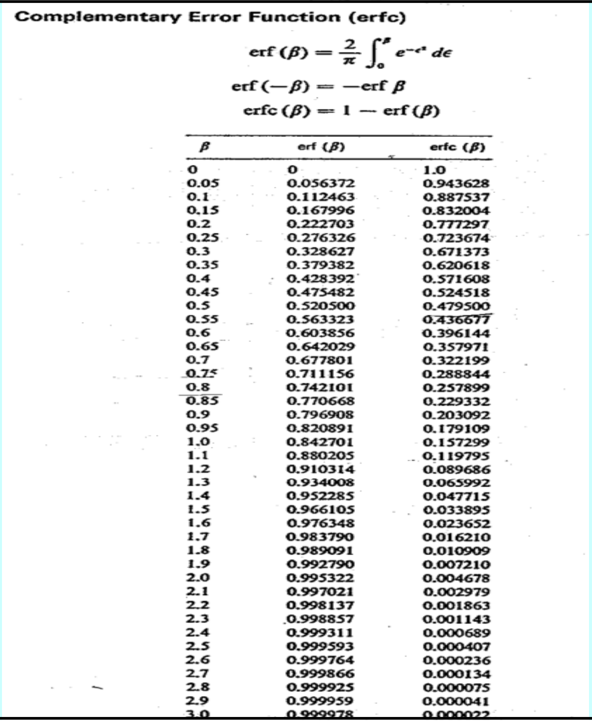
$$C = \frac{C_o}{2}\left( \operatorname{erfc}\left( \frac{x - \overline{v}_x t}{2\sqrt{D_x t}} \right) + \exp\left( \frac{\overline{v}_x x}{D_x} \right) \operatorname{erfc}\left( \frac{x + \overline{v}_x t}{2\sqrt{D_x t}} \right) \right)$$

erfc is the complimentary error function

**Error Function**

**Tables are listed in the back of ground water hydrology books**

**WARNING EXCEL DOES NOT APPROXIMATE THIS ACCURATELY AT EXTREME VALUES OF BETA**



**Complementary Error Function (erfc)**

$$\mathrm{erf}(\beta) = \frac{2}{\pi}\int_0^\beta e^{-\epsilon^2}\,d\epsilon$$

$$\mathrm{erf}(-\beta) = -\mathrm{erf}\,\beta$$

$$\mathrm{erfc}(\beta) = 1 - \mathrm{erf}(\beta)$$

| $\beta$ | erf ($\beta$) | erfc ($\beta$) |
|---|---|---|
| 0 | 0 | 1.0 |
| 0.05 | 0.056372 | 0.943628 |
| 0.1 | 0.112463 | 0.887537 |
| 0.15 | 0.167996 | 0.832004 |
| 0.2 | 0.222703 | 0.777297 |
| 0.25 | 0.276326 | 0.723674 |
| 0.3 | 0.328627 | 0.671373 |
| 0.35 | 0.379382 | 0.620618 |
| 0.4 | 0.428392 | 0.571608 |
| 0.45 | 0.475482 | 0.524518 |
| 0.5 | 0.520500 | 0.479500 |
| 0.55 | 0.563323 | 0.436677 |
| 0.6 | 0.603856 | 0.396144 |
| 0.65 | 0.642029 | 0.357971 |
| 0.7 | 0.677801 | 0.322199 |
| 0.75 | 0.711156 | 0.288844 |
| 0.8 | 0.742101 | 0.257899 |
| 0.85 | 0.770668 | 0.229332 |
| 0.9 | 0.796908 | 0.203092 |
| 0.95 | 0.820891 | 0.179109 |
| 1.0 | 0.842701 | 0.157299 |
| 1.1 | 0.880205 | 0.119795 |
| 1.2 | 0.910314 | 0.089686 |
| 1.3 | 0.934008 | 0.065992 |
| 1.4 | 0.952285 | 0.047715 |
| 1.5 | 0.966105 | 0.033895 |
| 1.6 | 0.976348 | 0.023652 |
| 1.7 | 0.983790 | 0.016210 |
| 1.8 | 0.989091 | 0.010909 |
| 1.9 | 0.992790 | 0.007210 |
| 2.0 | 0.995322 | 0.004678 |
| 2.1 | 0.997021 | 0.002979 |
| 2.2 | 0.998137 | 0.001863 |
| 2.3 | 0.998857 | 0.001143 |
| 2.4 | 0.999311 | 0.000689 |
| 2.5 | 0.999593 | 0.000407 |
| 2.6 | 0.999764 | 0.000236 |
| 2.7 | 0.999866 | 0.000134 |
| 2.8 | 0.999925 | 0.000075 |
| 2.9 | 0.999959 | 0.000041 |
| 3.0 | 0.999978 | 0.000022 |

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**Suppose that source enters the up gradient end of a column**
**At a continuous concentration of $C_o$=1000mg/l**
**K = 0.1 cm/sec**
**dh = 10 cm**
**dl = 100 cm**
**$\phi$ = 0.2**
**Dispersivity $\alpha_x$ = 5 cm**
**What will the concentration be at 50 cm after 1000sec?**

**average linear velocity**

$$\bar{v} = \frac{Kdh}{\phi dl} = \frac{0.1\frac{cm}{\sec}}{0.2}\frac{10cm}{100cm} = 0.05\frac{cm}{\sec}$$

**distance traveled in 1000sec?**

$$d = \bar{v}t = 0.05\frac{cm}{\sec}1000\sec = 50cm$$

**By inspection we know that the concentration should be 0.5*$C_o$=500mg/l**
**But let's carry out the calculation**

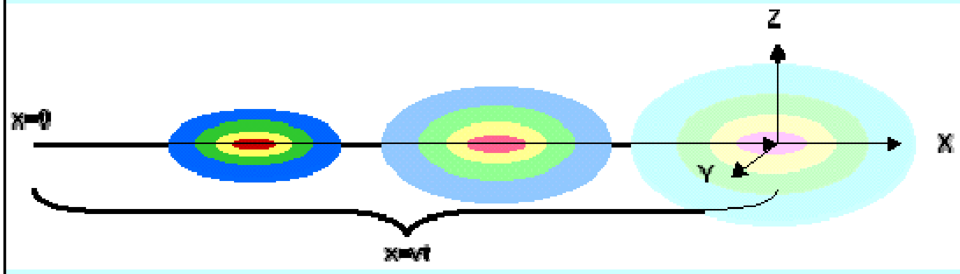
## Experiment with the spreadsheet

http://inside.mines.edu/~epoeter/_GW/22ContamTrans/C1d.xls

Note the values of C using only the first term and then both terms at times and locations where your intutition allows you to know the concentration.

When is use of the second term important?  When does excel cause it to be in error?

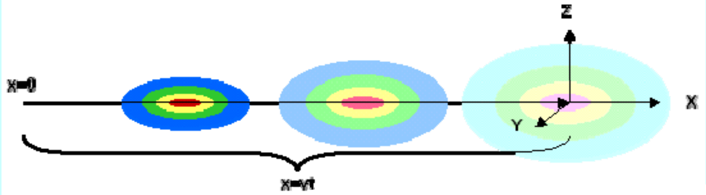
## Analytical Solution for transport in 1-D flow field
## slug source
## 3D spreading
## without chemical reaction



## Analytical Solution for transport in 1-D flow field
slug source
3D spreading
without chemical reaction

$$C(x = vt + X, y = Y, z = Z) = \frac{M}{8(\pi t)^{\frac{3}{2}}\sqrt{D_x D_y D_z}} \exp^{\left(-\frac{X^2}{4D_x t}-\frac{Y^2}{4D_y t}-\frac{Z^2}{4D_z t}\right)}$$

IMPORTANT! X Y Z = distance from center of mass



Maximum concentration will occur at
the center of mass
Where X=Y=Z=0

$$C_{max} = \frac{M}{8(\pi t)^{\frac{3}{2}}\sqrt{D_x D_y D_z}}$$

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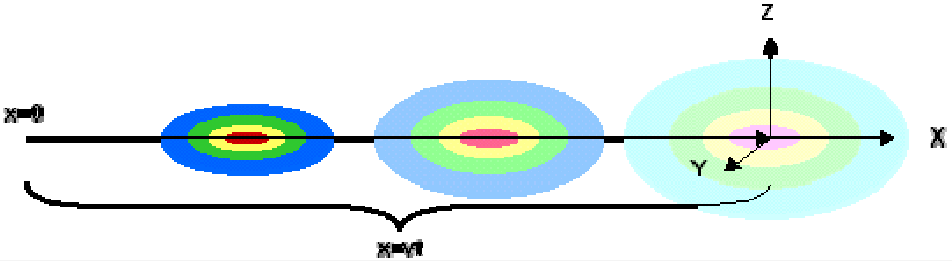
Suppose a slug source
enters a uniform flow field
With an initial mass of $M_o$=1000mg
K = 0.1 cm/sec
dh = 10 cm
dl = 100 cm
$\phi$ = 0.2
dispersivity $\alpha_x$ = 5 cm
dispersivity $\alpha_y$ = 1/5 $\alpha_x$
dispersivity $\alpha_z$ = 1/10 $\alpha_x$
What will the concentration be at 50 cm
directly down gradient after 1000sec?

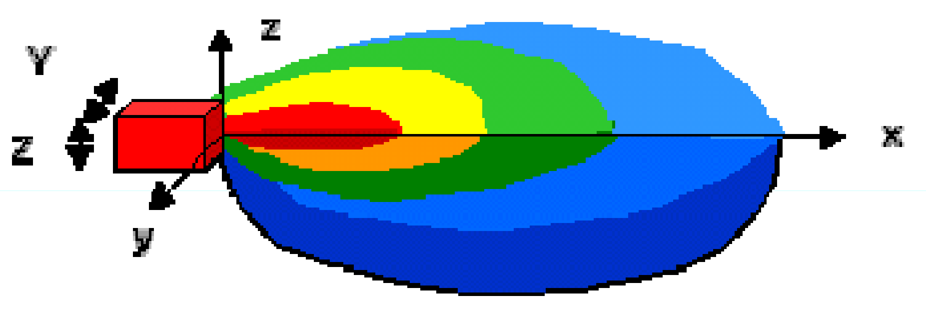
So we just considered an Analytical Solution for transport in
1-D flow field
slug source
3D spreading
without chemical reaction

$$C\left(x = vt + X, y = Y, z = Z\right) = \frac{M}{8(\pi t)^{\frac{3}{2}}\sqrt{D_x D_y D_z}} \exp\left(-\frac{X^2}{4D_x t}-\frac{Y^2}{4D_y t}-\frac{Z^2}{4D_z t}\right)$$

X Y Z = distance from center of mass in each direction



NEXT Analytical Solution for transport in
1D flow field
continuous source
3D spreading
without chemical reaction



Analytical Solution
for transport in

uniform 1D flow
continuous source

3D spreading

without chemical
reaction

see previous
graphic

Upper case
Y and Z
Are the source
width and height

$$C(x,y,z,t)=\frac{C_o}{8}\left(\operatorname{erfc}\left(\frac{x-\bar{v}_x t}{2\sqrt{D_x t}}\right)\right)\left(\operatorname{erf}\left(\frac{y+\frac{Y}{2}}{2\sqrt{D_y\frac{x}{\bar{v}}}}\right)-\operatorname{erf}\left(\frac{y-\frac{Y}{2}}{2\sqrt{D_y\frac{x}{\bar{v}}}}\right)\right)\left(\operatorname{erf}\left(\frac{z+\frac{Z}{2}}{2\sqrt{D_z\frac{x}{\bar{v}}}}\right)-\operatorname{erf}\left(\frac{z-\frac{Z}{2}}{2\sqrt{D_z\frac{x}{\bar{v}}}}\right)\right)$$

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Analytical Solution
for transport in
uniform 1D flow
continuous source
3D spreading
without chemical
reaction

If source is on the
water table such that
spreading is only
downward

Omit (/2) on Z terms

$$C(x,y,z,t)=\frac{C_o}{8}\left(\operatorname{erfc}\left(\frac{x-\bar{v}_x t}{2\sqrt{D_x t}}\right)\right)\left(\operatorname{erf}\left(\frac{y+\frac{Y}{2}}{2\sqrt{D_y\frac{x}{\bar{v}}}}\right)-\operatorname{erf}\left(\frac{y-\frac{Y}{2}}{2\sqrt{D_y\frac{x}{\bar{v}}}}\right)\right)\left(\operatorname{erf}\left(\frac{z+Z}{2\sqrt{D_z\frac{x}{\bar{v}}}}\right)-\operatorname{erf}\left(\frac{z-Z}{2\sqrt{D_z\frac{x}{\bar{v}}}}\right)\right)$$

Analytical Solution
for transport in
uniform 1D flow
continuous source
3D spreading
without chemical
reaction

If source is of full
vertical extent in a
confined aquifer
OR
if you are far from a
limited extent
source in a confined
aquifer

Change Co/8 to Co/4
Omit z terms

$$C(x,y,z,t) = \frac{C_o}{4}\left(\operatorname{erfc}\left(\frac{x-\overline{v}_x t}{2\sqrt{D_x t}}\right)\right)$$

$$\left(\operatorname{erf}\left(\frac{y+\frac{Y}{2}}{2\sqrt{D_y\frac{x}{\overline{v}}}}\right)-\operatorname{erf}\left(\frac{y-\frac{Y}{2}}{2\sqrt{D_y\frac{x}{\overline{v}}}}\right)\right)$$

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Suppose a source continuously enters that uniform flow field
With an initial concentration of $C_o$=1,000mg/l

pause to consider relationship of mass and concentration
Mass = Conc * Volume
Mass/Time = Conc * Velocity * Area = Conc * Q (Q is discharge)
Mass = Conc * Q * Time

Envision the source is submerged and
emanates from a 0.5cm high x 1cm wide zone
pause to consider the character of the source geometry

v = 0.05 cm/sec
dispersivity $\alpha_x$ = 5 cm
dispersivity $\alpha_y$ = 1/5 $\alpha_x$
dispersivity $\alpha_z$ = 1/10 $\alpha_x$

What will the concentration be at 50 cm
directly down gradient after 1000sec?
pause to consider the coordinate system

**What do you make of the concentration relative to the C we obtained for the slug source?**

**How much mass enters the system in 1000sec?** $M = CQT = CAV_DT$

**How would you go about developing a contour map of the plume?**

**If you did not know the dispersivities, how could you use this equation to estimate them?**

**How might you set up the problem if 8g/d arrived at the water table over a 1m$^2$ area in an aquifer with the properties and conditions used for the example?**

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**Analytical Solutions for transport provide smoothed representations of plumes**
**Be sure to practice using this topic's exercises**

**View an animation of contaminant transport**

**Consider how what you see will affect:**

**1) the predictions you make using the analytical solutions**

**2) the concentrations you obtain in samples from field sites**

**View DVD**

**NOW CONSIDER THE NON-MECHANICAL ASPECTS OF CONTAMINANT TRANSPORT**

## Decay

$$\frac{dN}{dt} = -\lambda N$$

$$\text{or} \quad N = N_o e^{(-\lambda t)}$$

$$\text{where} \quad \lambda = \frac{0.693}{T_{\frac{1}{2}}}$$

decay constant

0.693 is the natural log of 0.5

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## For a material with a half-life of 12 yrs, how much is left after 40 yrs? (Hint figure it as a % of initial mass)

$$N = N_o e^{(-\lambda t)} \quad \lambda = \frac{0.693}{T_{\frac{1}{2}}}$$

## It is often said that material is essentially gone after 7 half-lives. How much is left then?

$$N = N_o e^{(-\lambda t)} \qquad \lambda = \frac{0.693}{T_{\frac{1}{2}}}$$

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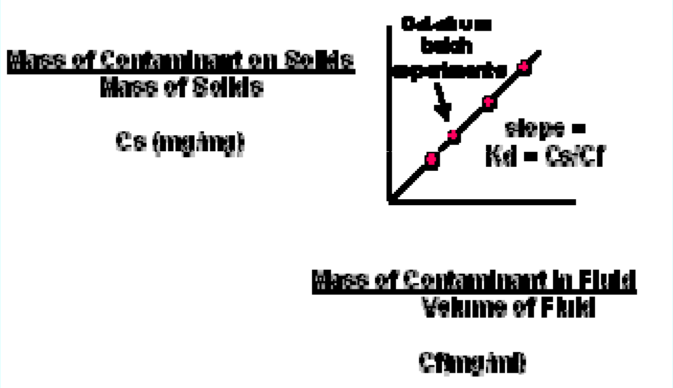
## Retardation - Adsorption



**Units**
$K_d$

$\frac{\text{ml}}{\text{mg}}$

$$R = \frac{V_{water}}{V_{contaminant}} = \left(1 + \frac{\rho_b}{\phi_e} K_d\right)$$

## What is the Retardation Coefficient for a site with

**$K_d = 0.01\frac{\text{ml}}{\text{mg}}$**

**effective porosity of 0.3**

**particle density of 2.65 g/cc**

$$R = \frac{V_{water}}{V_{\text{contaminant}}} = \left(1 + \frac{\rho_b}{\phi_e} K_d\right)$$

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## What is the Retardation Coefficient for a site with

**Ground water velocity = 0.05 cm/sec**

**Contaminant velocity = 0.0009 cm/sec**

$$R = \frac{V_{water}}{V_{\text{contaminant}}} = \left(1 + \frac{\rho_b}{\phi_e} K_d\right)$$

## Equation for transport in 1-D with Decay, Retardation, Reaction, Source

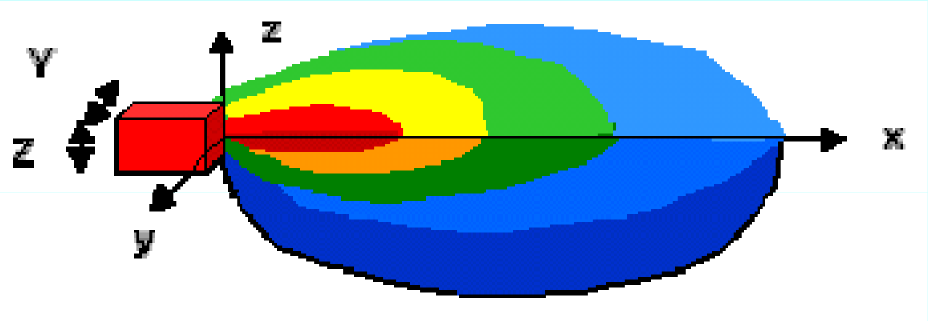
Divide D's and V's by R

$$\frac{\partial C}{\partial t} = \frac{D_x}{R}\frac{\partial^2 C}{\partial x^2} - \frac{\bar{v}_x}{R}\frac{\partial C}{\partial x} + \frac{W(C-C')}{R\phi b} + \frac{CHEM}{\phi} - \lambda C$$

| | |
|---|---|
| C | concentration in fluid |
| t | time |
| b | aquifer thickness |
| x | spatial coordinate |
| D | dispersion tensor |
| R | retardation coefficient |
| $\bar{v}$ | interstitial velocity |
| W | source fluid flux |
| $\phi$ | porosity |
| C' | concentration of source fluid |
| CHEM | chemical reaction source/sink per unit volume of aquifer |
| lambda | decay constant |

## Analytical Solution for transport in uniform 1D flow continuous source 3D spreading

With Decay



**Analytical Solution for transport in uniform 1D flow continuous source 3D spreading with Decay**

**Upper case Y and Z Are the source width and height**

**Same modifications apply for downward & no vertical spreading**

$$C(x,y,z,t)=\frac{C_o}{8}\exp\left(\frac{x}{2\alpha_x}\left(1-\sqrt{1+\frac{4\lambda\alpha_x}{\bar{v}}}\right)\right)$$

$$\left(erfc\left(\frac{x-\bar{v}t\left(1+\sqrt{\frac{4\lambda\alpha_x}{\bar{v}}}\right)}{2\sqrt{\alpha_x\bar{v}t}}\right)\right)$$

$$\left(erf\left(\frac{y+\frac{Y}{2}}{2\sqrt{\alpha_y x}}\right)-erf\left(\frac{y-\frac{Y}{2}}{2\sqrt{\alpha_y x}}\right)\right)$$

$$\left(erf\left(\frac{z+\frac{Z}{2}}{2\sqrt{\alpha_z x}}\right)-erf\left(\frac{z-\frac{Z}{2}}{2\sqrt{\alpha_z x}}\right)\right)$$

**If R>1 Divide $\bar{v}$ by R**

**Note this includes a simplification of D=α$\bar{v}$**

$D_y\frac{x}{\bar{v}}$ if $D^*$ is ignored then equivalent to $\alpha_y\bar{v}\frac{x}{\bar{v}}$ which $=\alpha_y x$

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**Analytical Solution for transport in uniform 1D flow continuous source 3D spreading with Decay**

**Upper case Y and Z Are the source width and height**

**ON THE CENTER LINE**

$$C(x,y,z,t)=$$

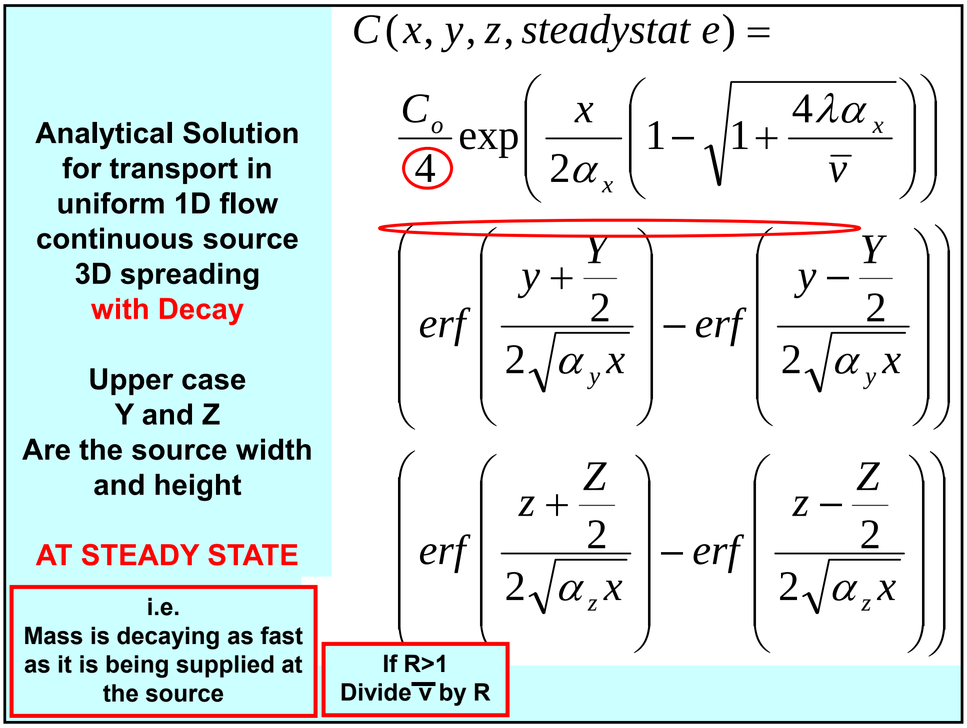
$$\frac{C_o}{2}\exp\left(\frac{x}{2\alpha_x}\left(1-\sqrt{1+\frac{4\lambda\alpha_x}{\bar{v}}}\right)\right)$$

$$\left(erfc\left(\frac{x-\bar{v}t\left(1+\sqrt{\frac{4\lambda\alpha_x}{\bar{v}}}\right)}{2\sqrt{\alpha_x\bar{v}t}}\right)\right)$$

$$\left(erf\left(\frac{Y}{2\sqrt{\alpha_y x}}\right)\right)\left(erf\left(\frac{Z}{2\sqrt{\alpha_z x}}\right)\right)$$

**i.e. y = z = 0**

**If R>1 Divide $\bar{v}$ by R**



Analytical Solution for transport in uniform 1D flow continuous source 3D spreading **with Decay**

Upper case Y and Z Are the source width and height

**AT STEADY STATE**

$$C(x,y,z,steadystat\ e)=$$

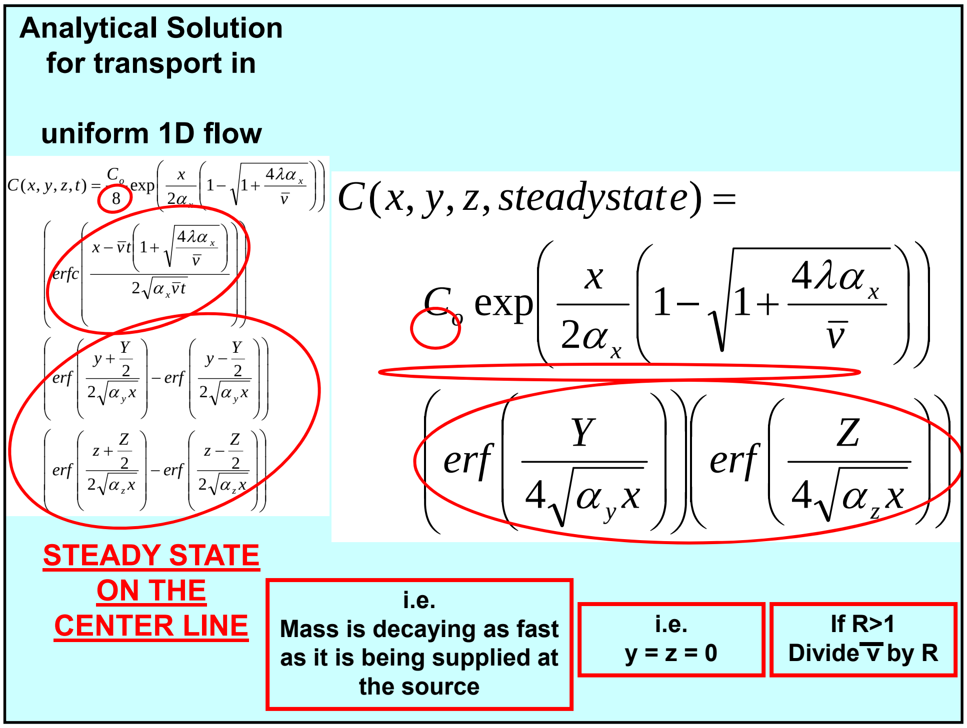
$$\frac{C_o}{\textcircled{4}}\exp\left(\frac{x}{2\alpha_x}\left(1-\sqrt{1+\frac{4\lambda\alpha_x}{\bar{v}}}\right)\right)$$

$$\left(erf\left(\frac{y+\frac{Y}{2}}{2\sqrt{\alpha_y x}}\right)-erf\left(\frac{y-\frac{Y}{2}}{2\sqrt{\alpha_y x}}\right)\right)$$

$$\left(erf\left(\frac{z+\frac{Z}{2}}{2\sqrt{\alpha_z x}}\right)-erf\left(\frac{z-\frac{Z}{2}}{2\sqrt{\alpha_z x}}\right)\right)$$

i.e.
Mass is decaying as fast as it is being supplied at the source

If R>1
Divide $\bar{v}$ by R



Analytical Solution for transport in

uniform 1D flow

$$C(x,y,z,t)=\frac{C_o}{\textcircled{8}}\exp\left(\frac{x}{2\alpha_x}\left(1-\sqrt{1+\frac{4\lambda\alpha_x}{\bar{v}}}\right)\right)$$

$$\left(erfc\left(\frac{x-\bar{v}t\left(1+\sqrt{\frac{4\lambda\alpha_x}{\bar{v}}}\right)}{2\sqrt{\alpha_x\bar{v}t}}\right)\right)$$

$$\left(erf\left(\frac{y+\frac{Y}{2}}{2\sqrt{\alpha_y x}}\right)-erf\left(\frac{y-\frac{Y}{2}}{2\sqrt{\alpha_y x}}\right)\right)$$

$$\left(erf\left(\frac{z+\frac{Z}{2}}{2\sqrt{\alpha_z x}}\right)-erf\left(\frac{z-\frac{Z}{2}}{2\sqrt{\alpha_z x}}\right)\right)$$

$$C(x,y,z,steadystate)=$$

$$C_o\exp\left(\frac{x}{2\alpha_x}\left(1-\sqrt{1+\frac{4\lambda\alpha_x}{\bar{v}}}\right)\right)$$

$$\left(erf\left(\frac{Y}{4\sqrt{\alpha_y x}}\right)\right)\left(erf\left(\frac{Z}{4\sqrt{\alpha_z x}}\right)\right)$$

**STEADY STATE ON THE CENTER LINE**

i.e.
Mass is decaying as fast as it is being supplied at the source

i.e.
y = z = 0

If R>1
Divide $\bar{v}$ by R

THINK IN TERMS OF ORGANIZING THE ANALYTICAL SOLUTIONS IN TERMS OF

THE TYPE OF SOURCE:

SLUG OR CONTINUOUS

TYPE OF SPREADING:

1D, 2D, 3D

TYPE OF CONTAMINANT BEHAVIOR:

DECAYING, ADSORPING

(and if so steady-state? center-line?)

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## A transport model for your exploration:

http://inside.mines.edu/~epoeter/_GW/22ContamTrans/TransportModel/tdpf1.0web/pflow/pflow.html

Explore plume spreading as a function of heterogeneity as represented by K variation AND local heterogeneity as represented by the input dispersivity

Create grid. Make sure you understand the size of the system you are working with.

Properties: Run at least 1 homogeneous and 1 heterogeneous model

Calculate heads

Choose particle movement for flow (this is by random walk … advecting based on Ks and gradient then randomly displacing each particle based on dispersivity)

Be aware of the number of particles you use given spacing, grid size and your drawn area

Use the same particles for the above comparison of 1 homogeneous and 1 heterogeneous model

Choose # days per second such that you will get transport across your grid in a matter of a minute or so (make a rough estimate of travel time given gradient, K, porosity and distance)

Always choose to show center of mass, std deviation bars of particles and plot the variance of particle locations.

Run both your homogeneous and heterogeneous models with and without local dispersion. When you use local dispersion make sure it is a reasonable value. Try varying the value.

For all cases note the spatial variance of the particles. Explain the results.

When does it stop plotting spatial variance? Why?