# An Introduction to Groundwater Issues at Mine Sites


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# Topic 7:
# Contaminant Migration in Groundwater Systems

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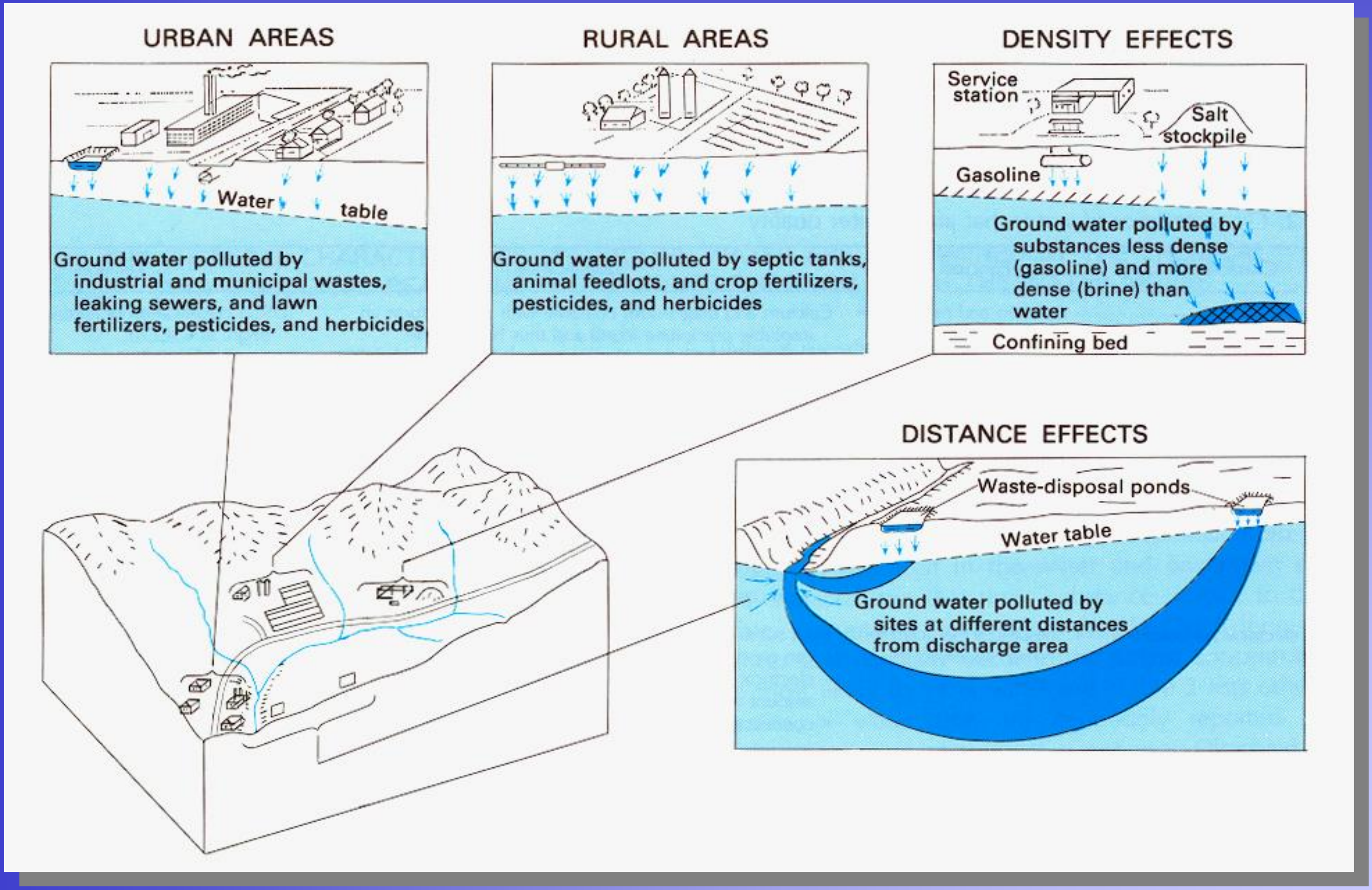
# Contamination Migration in Groundwater Systems



# Example Sources of Contamination

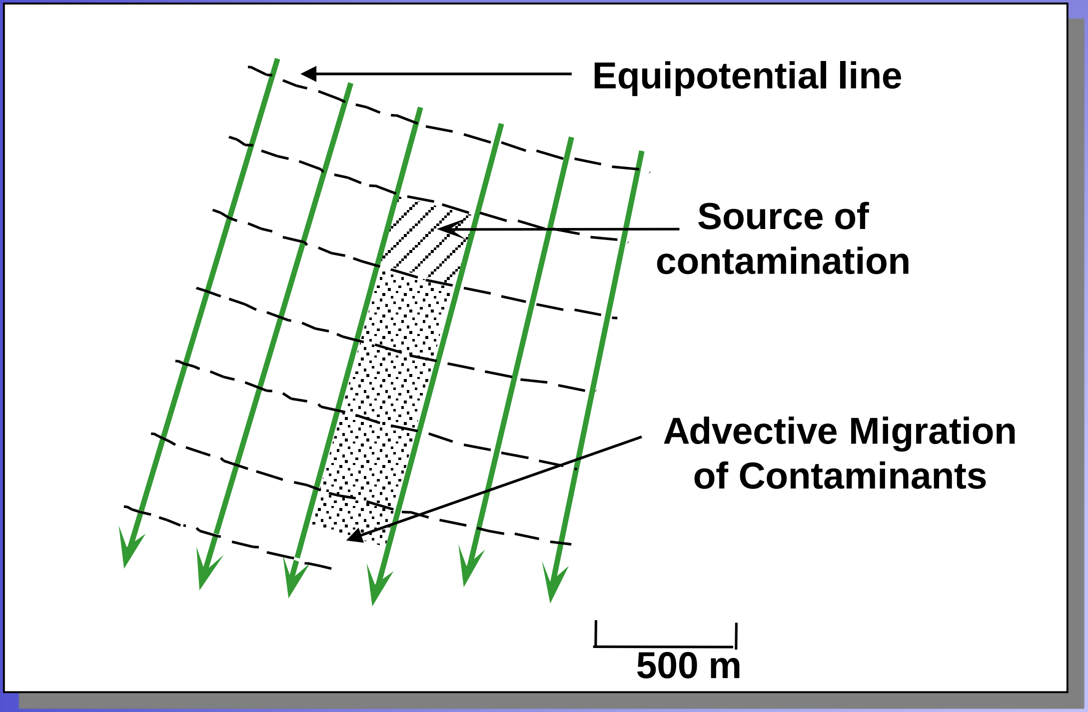
- Holding ponds (unlined / leaky)
- Tailings (with process water / other lechate)
- Waste rock (reactive – eg. acidity)
- Fuel spills
- Process chemical spills
- Smelter gases (outfall as particulate / in precipitation)

# Process Contributing to Transport

- Advection
  - migration with water flow
- Dispersion
  - mixing and dilution during flow
- Diffusion
  - slow, random concentration driven migration

# Advection

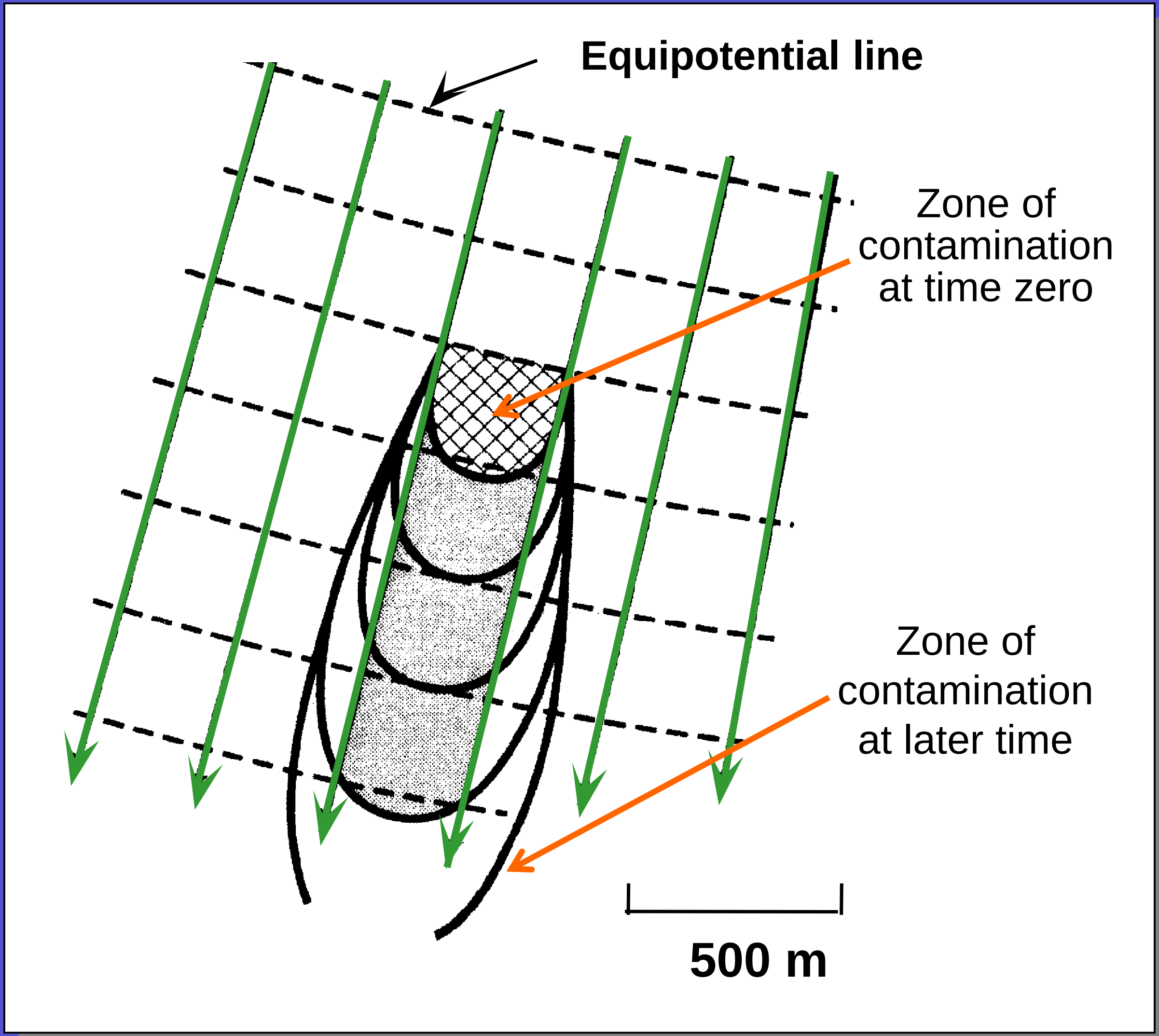
- Depends on velocity
  - $\overline{v} = q/n = k/n \, dh/dl$
  - Distance = $\overline{v} * t$



# Dispersion

- Mixing at boundaries of plume
- Due to
  - Microscopic effect – flow around grains
  - Macroscopic effects – variation in flow rates in layers etc.
- Causes contaminations to travel "faster" (at more dilute concentrations) and linger longer when rehabilitation is applied

# Dispersion


Equipotential line
Zone of contamination at time zero
Zone of contamination at later time
500 m

# Diffusion

## Fick's Law

- $F = -D\, dc/dx$

Where:

F is flux [$M\ L^{-2}\ T^{-1}$]

C is concentration [$M\ L^{-3}$]

x is distance [L]

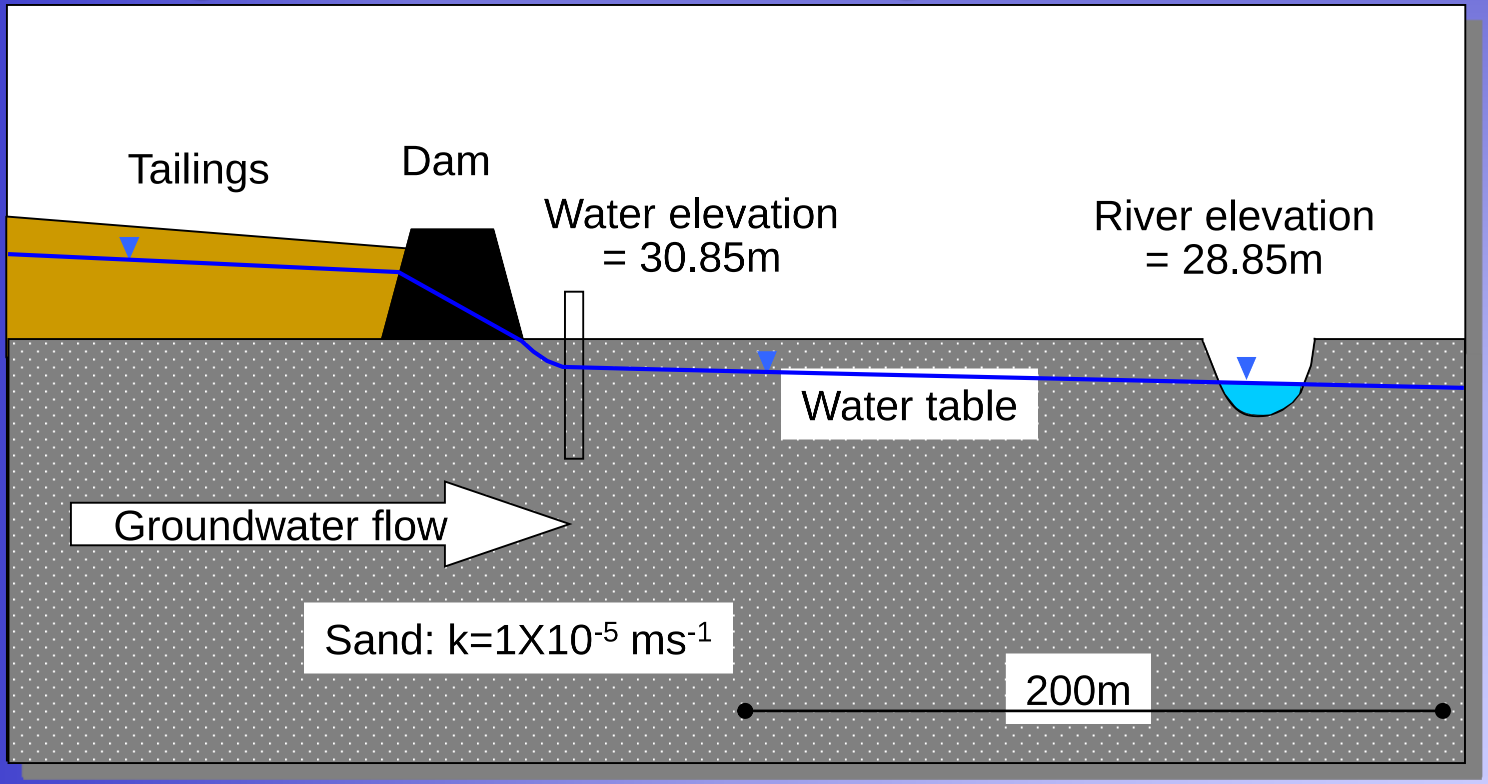
D is proportionality constant called the Diffusion Coefficient [ $L^2\ T^{-1}$]

# Comparing Effects of Advection, Dispersion and Diffusion

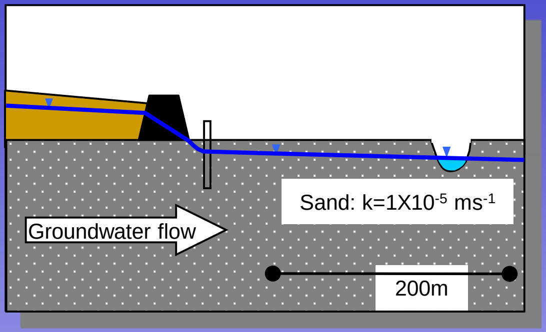
- In high K systems (sands and gravels) advection dominates
- In low K systems (clay) diffusion dominates
- At screening level calculations it is convenient to select one OR the other condition

# Example: Estimating Travel Time

- Estimate the travel time for tailings water to migrate to a river via groundwater



# Example: Estimating Travel Time




## Assume

- Porosity = 0.40
- Steady flow
- Constant hydraulic gradient

## Hydraulic gradient

dh/dl = (30.85-28.85)m/200m = 2/200 = 0.01

## Velocity

V = K/n dh/dl = 1X10$^{-5}$ms$^{-1}$/0.40 * 0.01 = 2.5X10$^{-7}$ms$^{-1}$

= 7.9 ma$^{-1}$

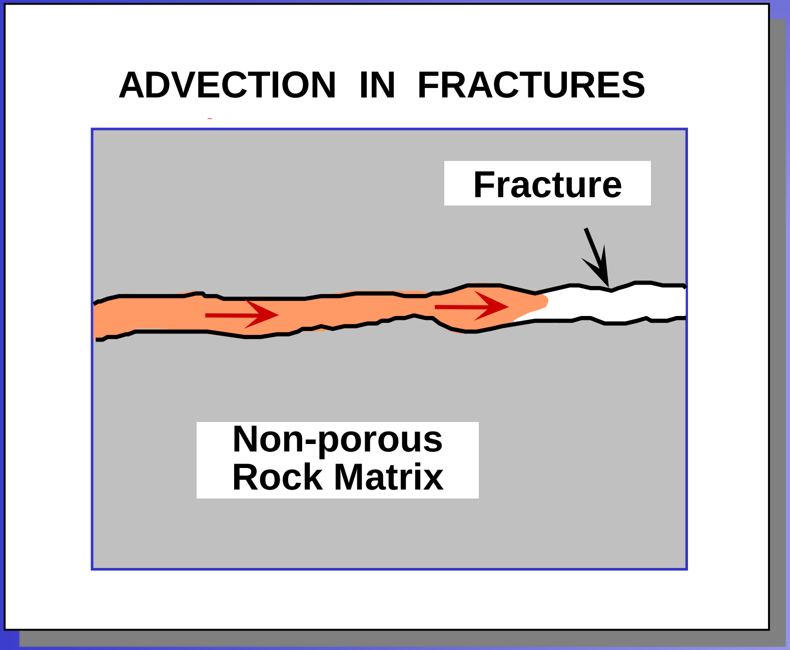
## Time

Time = distance/velocity = 200m/ 7.9 ma$^{-1}$ = ~25a

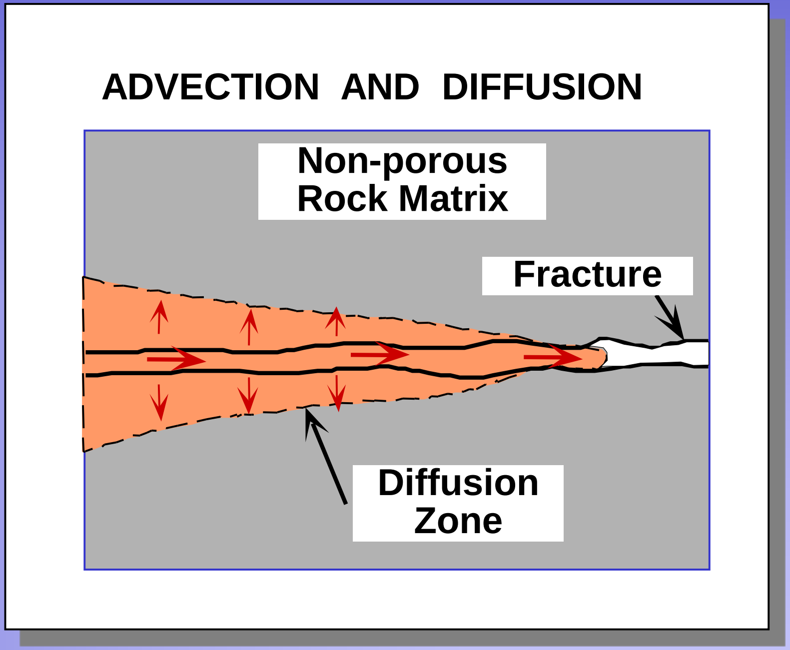
[ if k=1X10$^{-7}$ (silt); Time = 2,500 a for same gradient]

# Flow and Transport in Fractured Rock

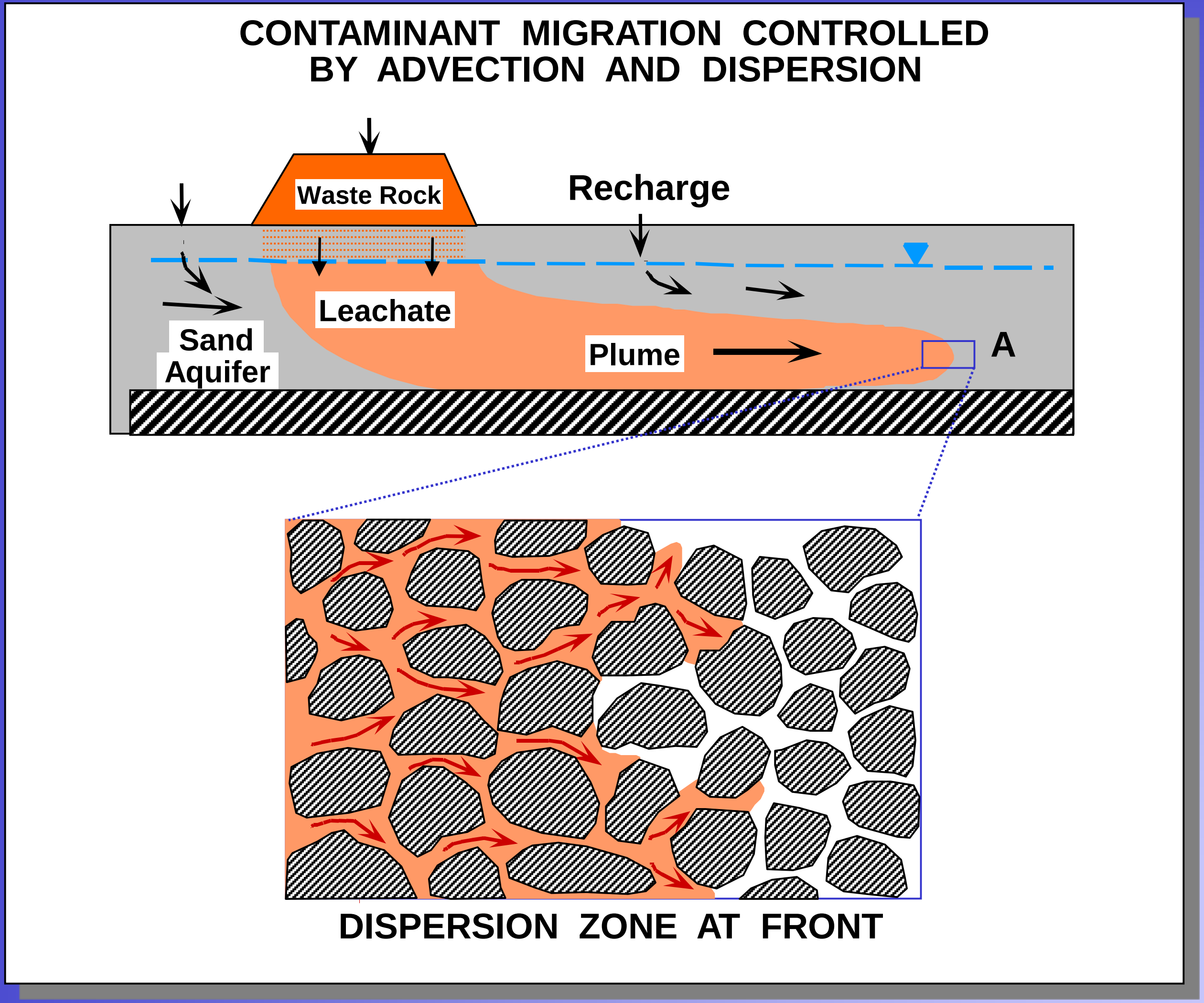
## Non porous



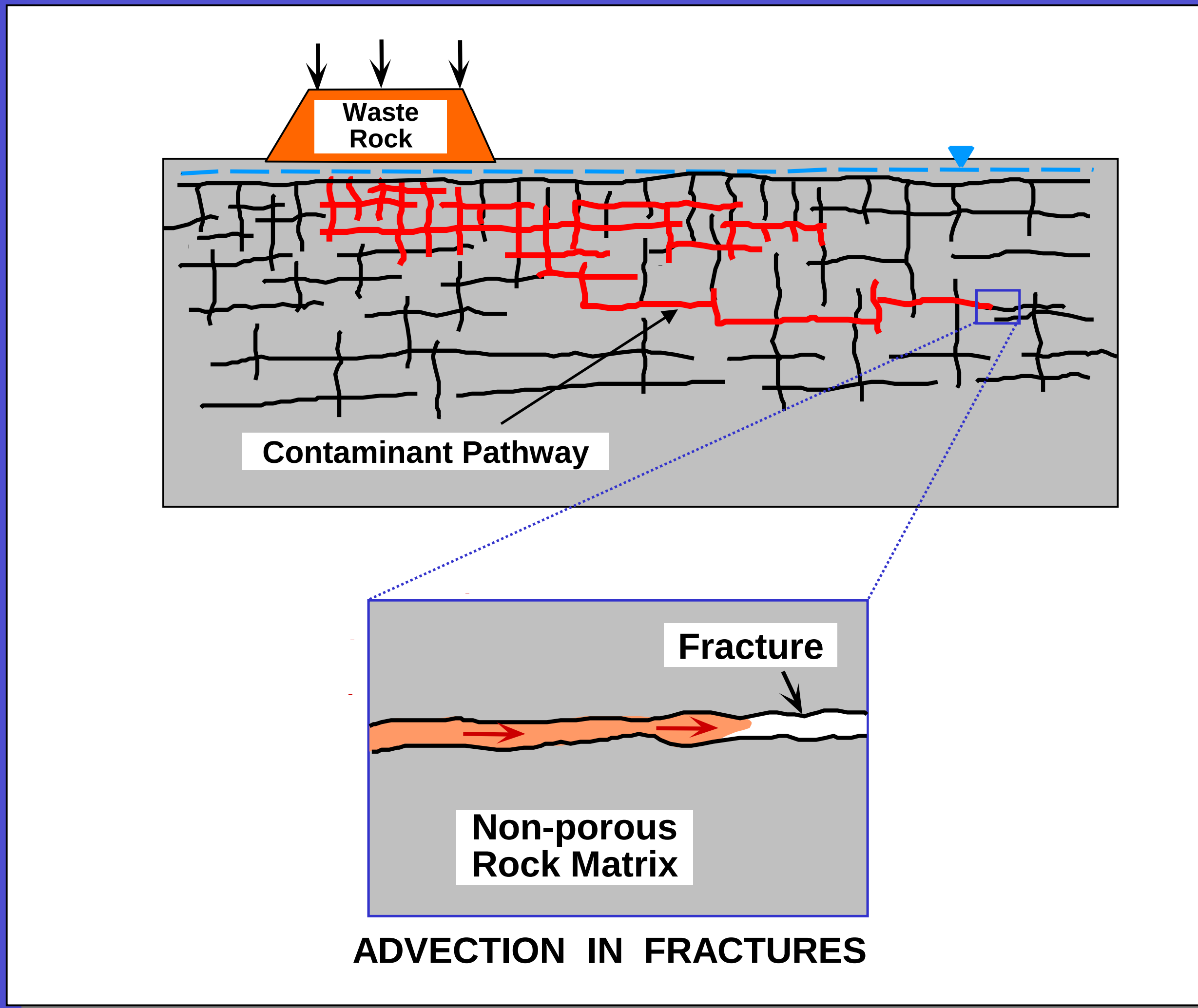

## Porous



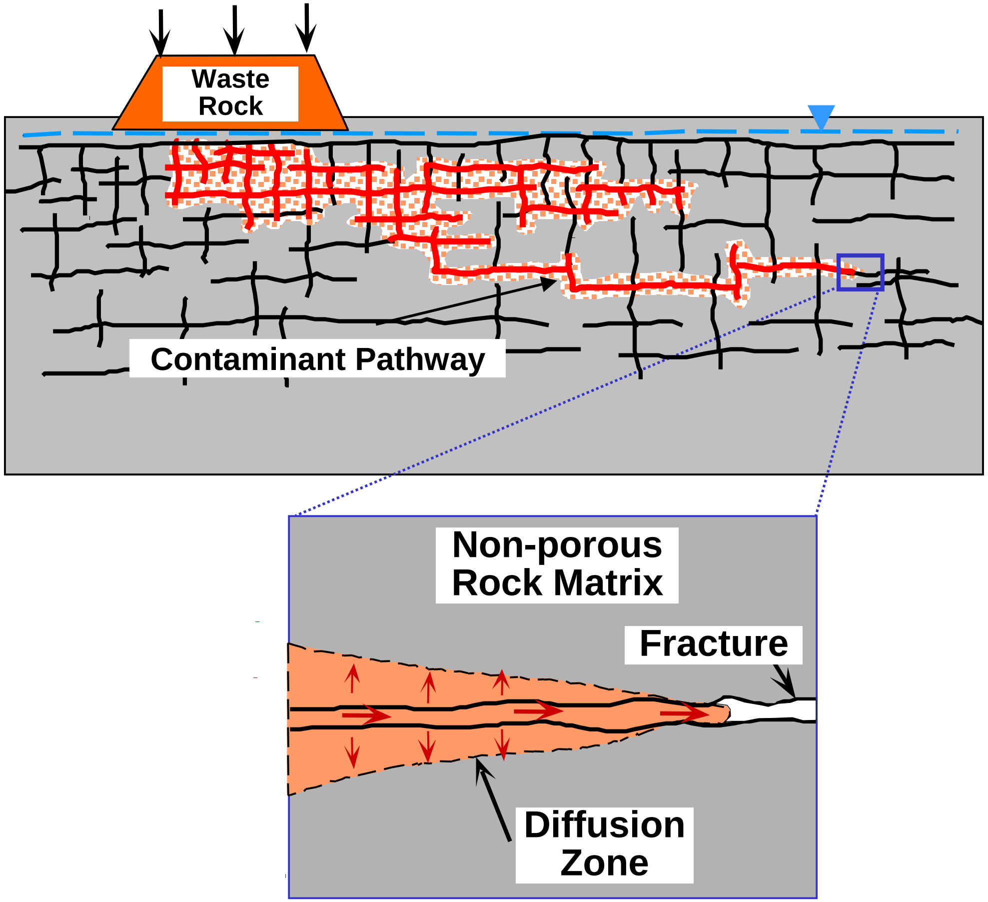
# Contaminant Migration in Porous Media



# Plume Migration in Fractured Non-Porous Rock

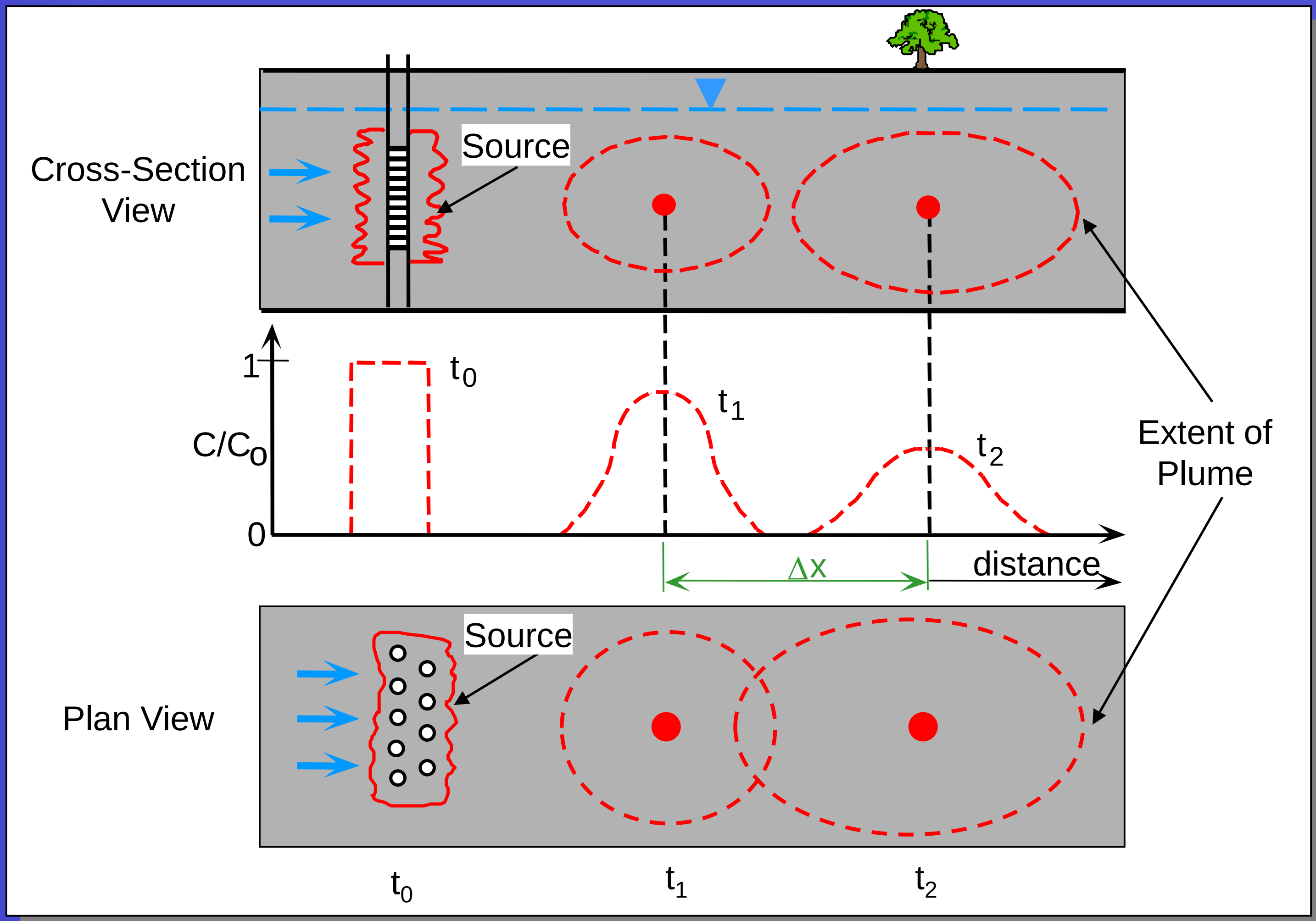


# Plume Migration in Fractured Non-Porous Rock




ADVECTION AND DIFFUSION

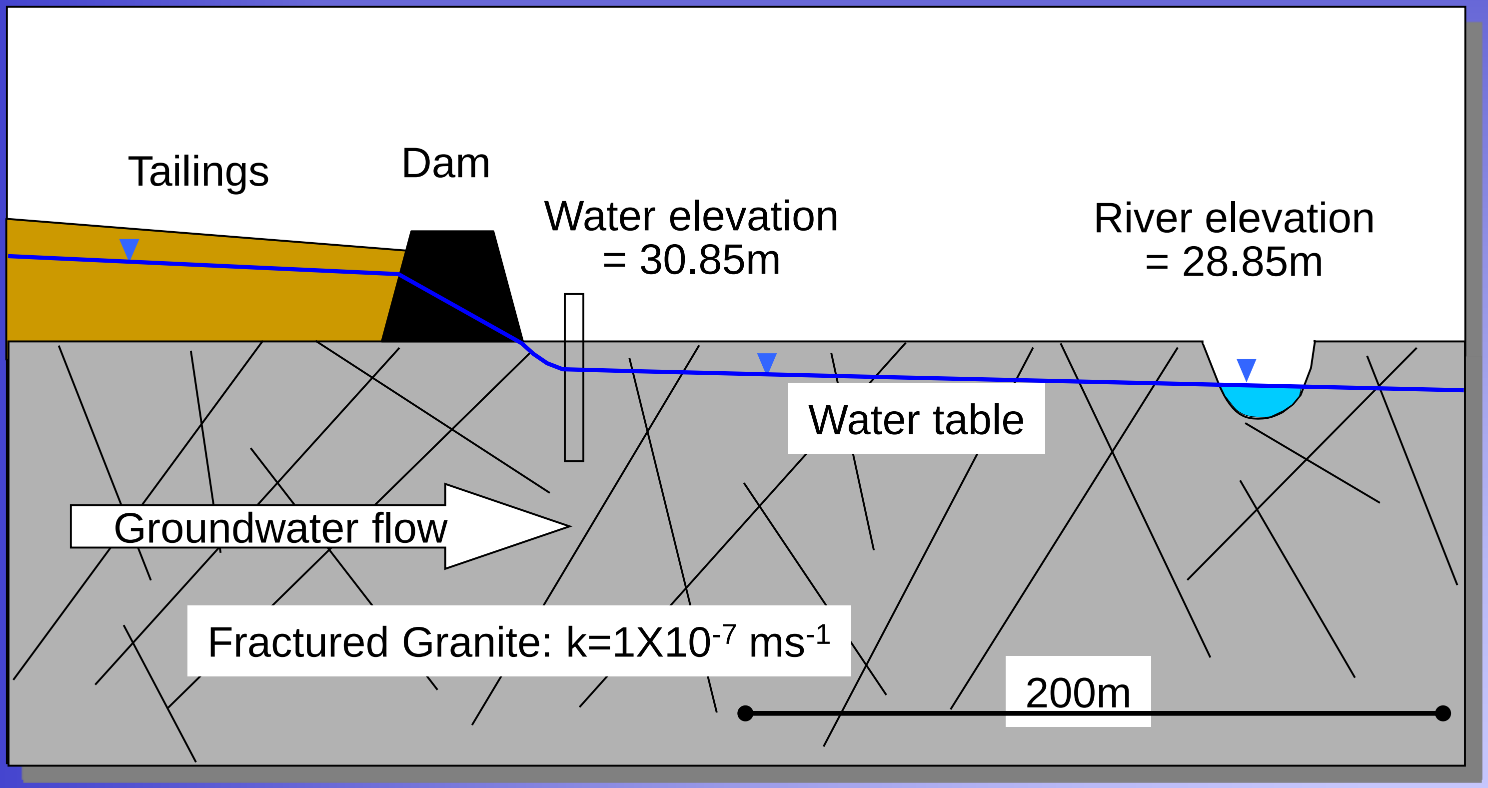
# Extent of Plume



# Significance of Flow Through Fractures

- May be non-uniform (follows fractures)
- Complex to monitor (hit and miss)
- Lower porosities than porous media / much higher velocities and shorter travel times

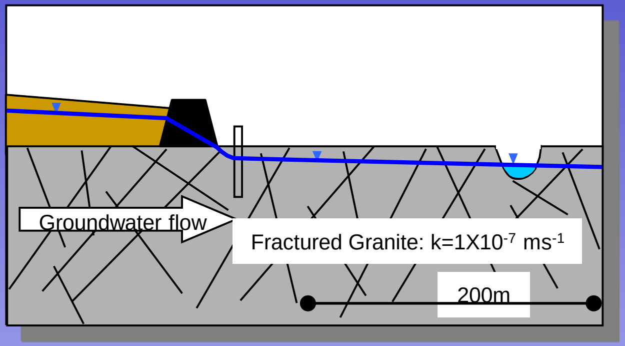
# Example: Travel Time thought Fractured Granite



# Example: Travel Time thought Fractured Granite

## Assume

- Porosity = 0.004
- Steady flow
- Hydraulic gradient 0.01




## Velocity

$V = k/n\ dh/dl = 1X10^{-7}ms^{-1}/0.004 * 0.01 = 2.5X10^{-7}ms^{-1}$

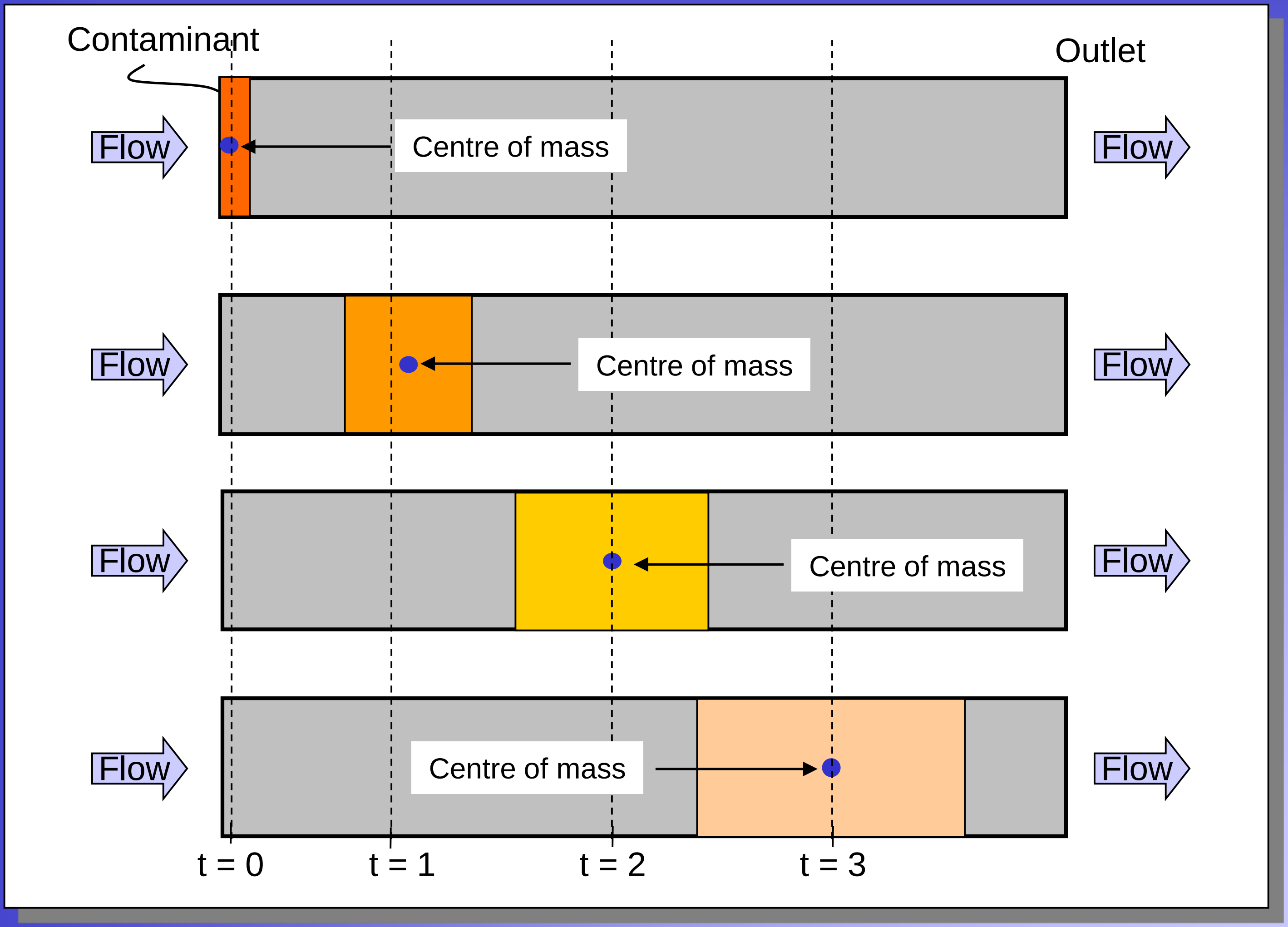
$= 7.9\ ma^{-1}$

## Time

Time = distance/velocity = 200m/ 7.9 $ma^{-1}$ = ~25a

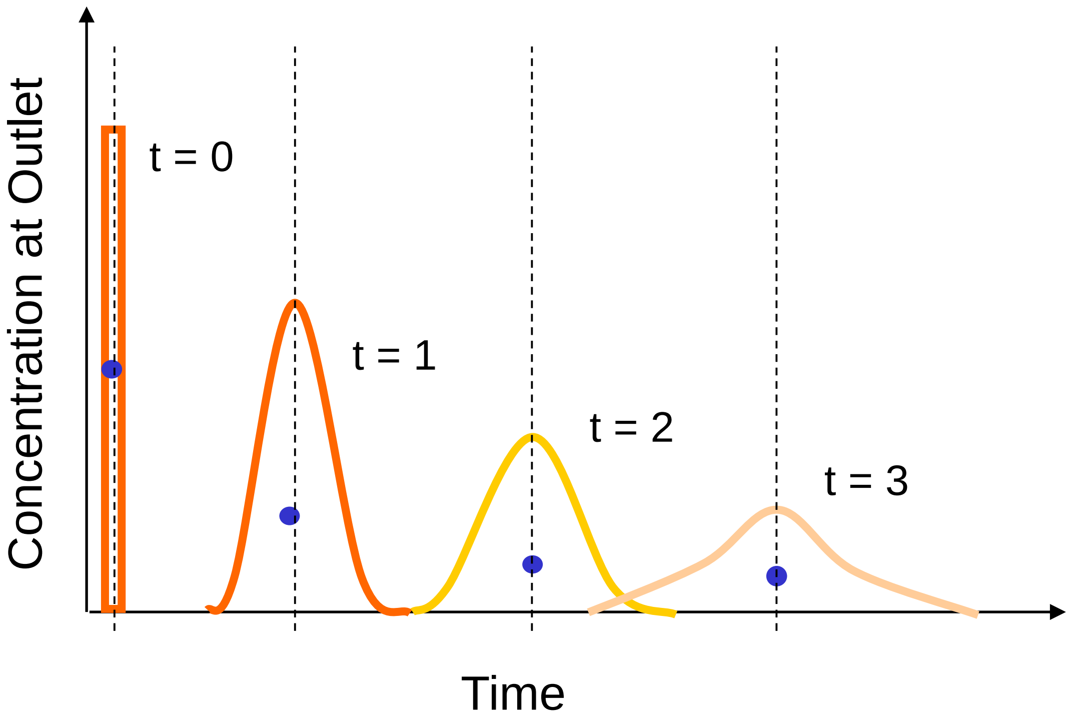
This value is same as the example with more permeable sand $k=1X10^{-5}ms^{-1}$

# Effect of Dispersion on Travel Times



# Effect of Dispersion on Travel Times

Lower concentrations arrive earlier as a result of dispersion. Important if low relative concentrations trigger regulatory or environmental limits



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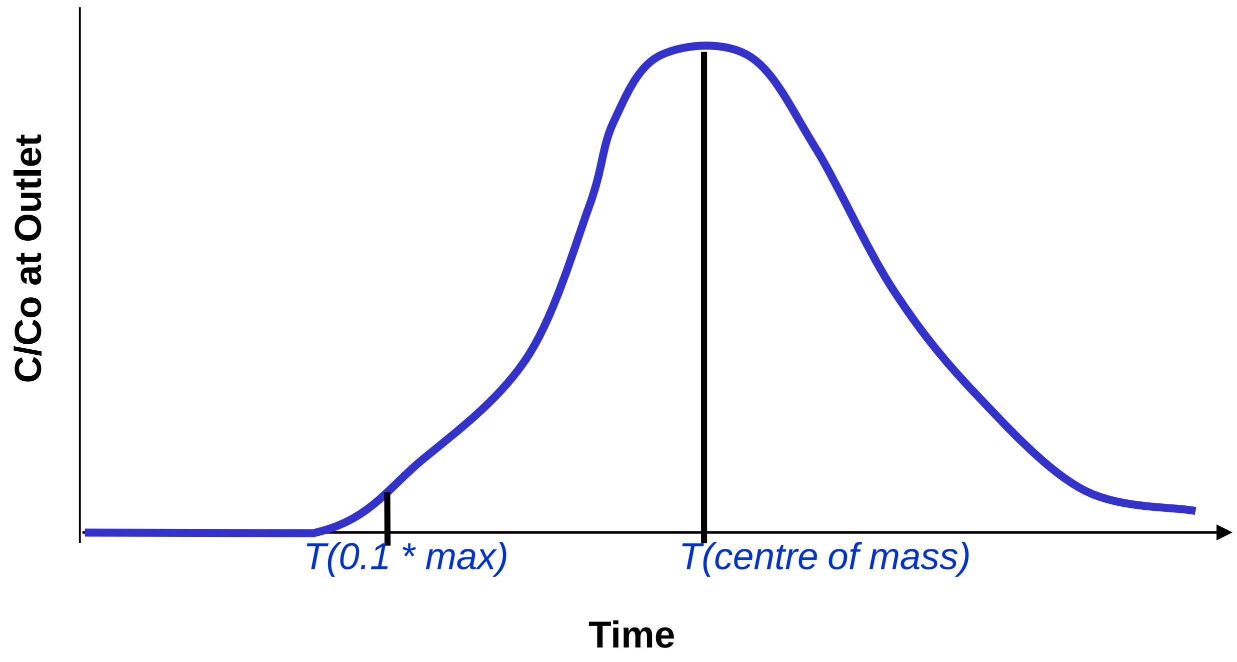

# Attenuation and Retardation of Contaminants

- Many dissolved chemical constituents “react” with geologic media and thereby move slower than groundwater
- Reactions including “sorption”, ion exchange and mineral precipitation
- A simple “model” for attenuation is based on the “distribution” between water and solids is known as the distribution coefficient (Kd)

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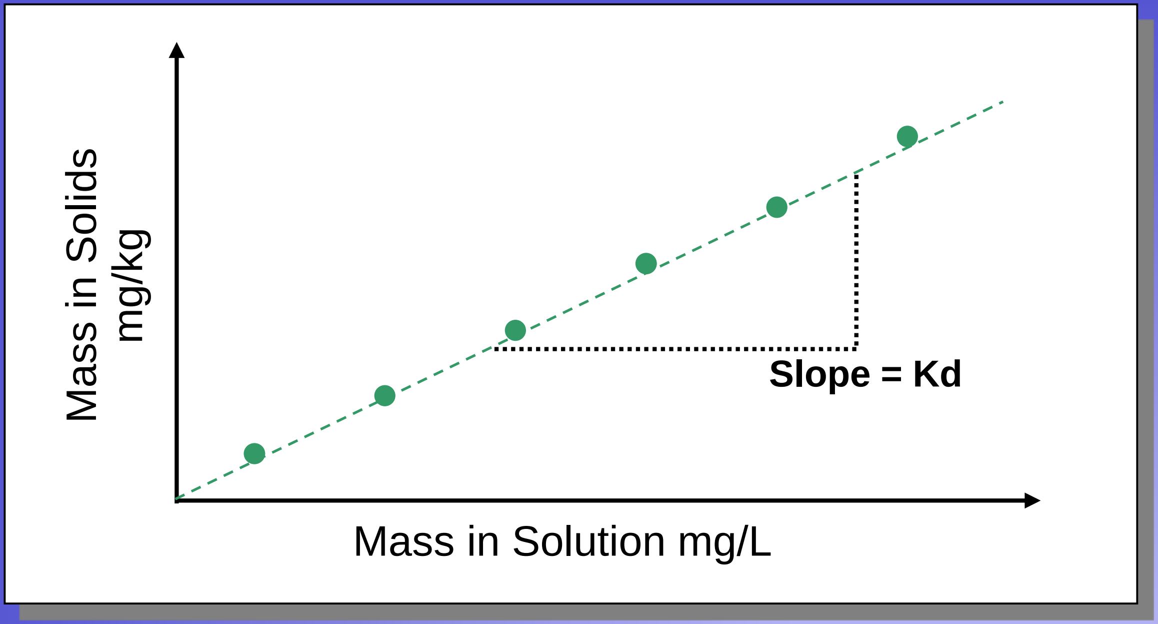
# Distribution Coefficient (Kd)




- Good for many constituents at low concentrations
- Usually not valid over a wide range of concentrations or geochemical conditions
- units of mL/g or L/kg are common

# Retardation Coefficient (R)

- $R = 1 + Kd\ \rho_b/n$

  Where: $\rho_b$ = bulk density ( kg/L or g/cm$^3$)

  n = porosity (unitless)

  Kd = distribution coefficient (mL/g or L/kg)

- Generally $\rho_b$ is in the range of 3 to 6 kg/L for unconsolidated sediments
- So that $R \simeq 1 + 4\ Kd$ (so $R \geq 1$)

# Velocity of Retarded Solutes ($v_s$)

- $v_s = v_w / R$

  Where $v_w$ is the average velocity of the groundwater
- For example, in sand if the following Kd values fo arsenic (As) and Ra-226 would give:

| | Kd (kg/L) | R |
|---|---|---|
| As | 1.3 | 6.2 |
| Ra-226 | 1000 | 4300 |

- For the groundwater travel time calculated in a previous example:

| Substance | Travel Time |
|---|---|
| water | 25a |
| As | 155a |
| Ra-226 | 107,500a |

# Factors affecting Attenuation (Kd values)

- Metals generally have higher attenuation in organic materials (swamps, lake sediments etc.)
- Clays result in higher attenuation
- Iron oxides (rusty red-brown colour) can also cause higher attenuation
- Attenuation is higher in porous materials than in fractured rock
- Specific chemical reactions can result in high attenuation (detailed chemical modelling maybe appropriate)

# Flux and Loading Rates

- Mass Flux = Rate of mass crossing an area per unit time [ $M\ L^{-2}\ T^{-1}$]
- Loading Rate = Mass entering / leaving per unit time [$M\ T^{-1}$]
- In groundwater:

  Mass Flux = $C_i * q_i$

  where $q_i$ is the volumetric flux [$L^3\ L^{-2}\ T^{-1}$]

  Loading Rate = C * Q

  Where Q is the flow rate [$L^3\ T^{-1}$]

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# Example: Tailings Near a River

Groundwater below tailings has a cyanide level of 100 mg/L with no attenuation/ degradation.

What is the cyanide flux to the river?

Calculate:

$q = k\ dh/dl = 1X10^{-5} m\ s^{-1} = 1X10^{-7} m\ s^{-1}$

$= 3.15\ m\ a^{-1}$ or $3.15\ m^{3}\ m^{-2}\ a^{-1}$

If $C = 100\ mg\ L^{-1} = 100 g\ m^{-3} = 0.1\ kg\ m^{-3}$

Then mass flux $= C * q = 0.1\ kg\ m^{-3} * 3.15\ m^{3}\ m^{-2}\ a^{-1}$

$= 0.3\ kg\ m^{-2}\ a^{-1}$ to the river

# Tailings and River Example (con't)

The contaminated groundwater zone is 10m deep and 200m wide (along the dam)

What is total loading of cyanide to the river?

Calculate:

$q = Q * A$

$= 3.15\ m^3\ m^{-2}\ a^{-1} * (200 * 10) m^2$

$= 6300\ m^3\ a^{-1}$

Mass load $= Q * C$

$= 6300\ m^3\ a^{-1} * 0.1\ kg\ m^{-3}$

$= 630\ kg\ a^{-1}$ to the river

# Example: Considering Dilution

What flow rate in the river is necessary to assimilate the average annual cyanide load if the concentration in the river must not exceed 1mg/L ? (Assume that cyanide upstream is negligible).

Calculate:

Mass load in river = 630 kg $a^{-1}$ to the river

If C = 1 mg $L^{-1}$ = 1 g $m^{-3}$ = 0.001 kg $m^{-3}$

Then Q = Load / C

= 630 kg $a^{-1}$ / 0.001 kg $m^{-3}$

= 630,000 $m^3$ $a^{-1}$

= 1726 $m^3$ $day^{-1}$

= 20 L $s^{-1}$