

9 Sediment-Water Exchange

- ◆ Introduction
- ◆ Sediment-water partitioning
- ◆ Particle settling and deposition
- ◆ Sediment erosion and resuspension
- ◆ Transport equation with sediments
- ◆ Contaminant transport within sediment bed
- ◆ Model of sediment-water exchange
- ◆ Contaminated sediment remediation

Interest in Sediments

- ◆ "Geo-morphology"
- ◆ Sediment as pollutant
- ◆ Sediment as carrier of pollutants

Table 9-1 Sediment grade scale (adapted from ASCE, 1975)

Classification

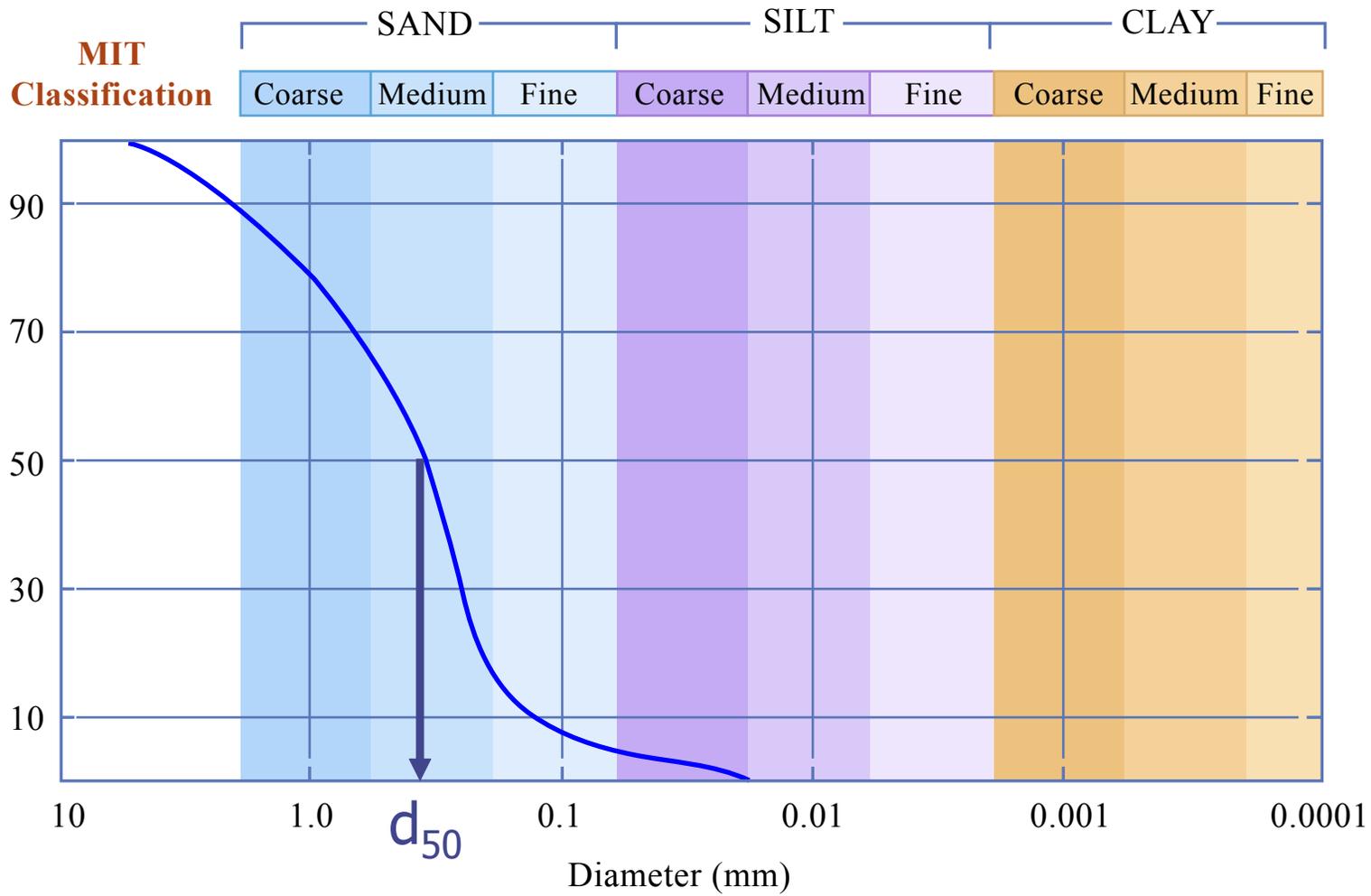
Class name	Diameter (mm)	ϕ	Class name	Diameter (mm)	ϕ
Very coarse gravel	64-32	-5.5	Very fine sand	1/8-1/16	3.5
Coarse gravel	32-16	-4.5	Coarse silt	1/16-1/32	4.5
Medium gravel	16-8	-3.5	Medium silt	1/32-1/64	5.5
Fine gravel	8-4	-2.5	Fine silt	1/64-1/128	6.5
Very fine gravel	4-2	-1.5	Very fine silt	1/128-1/256	7.7
Very coarse sand	2-1	-0.5	Coarse clay	1/256-1/512	8.5
Coarse sand	1-1/2	0.5	Medium clay	1/512-1/1024	9.5
Medium sand	1/2-1/4	1.5	Fine clay	1/1024-1/2048	10.5
Fine sand	1/4-1/8	2.5	Very fine clay	1/2048-1/4096	11.5

Non-cohesive

cohesive

ASCE, 1975; $\phi = -\ln(d_{mm})/\ln(2)$

Most environmental interest in finer fractions



Grain Size Distribution

Figure by MIT OCW.

Equilibrium Partitioning

$$K_p = \frac{c_s}{c_d}$$

Simplest model:
two phases

Partition (or distribution) coefficient:

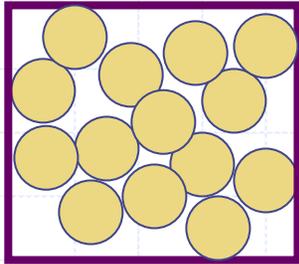
Sorbed phase conc c_s (mass contaminant per mass solid) divided by dissolved phase conc c_d (mass contaminant per volume solvent) in equilibrium

Units of K_p : volume/mass, e.g., cm^3/g

More complicated partitioning models

K_p depends on contaminant, its concentration, concentration of organic matter, redox potential, etc. Typical values: 10^1 to $10^2 \text{ cm}^3/\text{g}$ (hydrophilic) to 10^4 to $10^5 \text{ cm}^3/\text{g}$ (hydrophobic)

In sediment bed



Unit volume
with porosity ϕ

Mass of dissolved contaminant/volume

$$= \phi c_d$$

Mass of sorbed contaminant/volume

$$= \rho_s c_s (1 - \phi) = \rho_s K_p c_d (1 - \phi)$$

↑ if equilibrium

Ratio of sorbed to total mass

$$f = \frac{\rho_s K_p (1 - \phi)}{\rho_s K_p (1 - \phi) + \phi} = \frac{K_p \rho}{K_p \rho + 1}$$

$$\rho = \rho_s (1 - \phi) / \phi = \rho_{b,d} / \phi$$

Solid-water phase ratio
(solid mass/water mass)

$$\rho_{b,d} = \rho_s (1 - \phi)$$

Bulk (dry) sediment density

$$\rho_{b,w} = \rho_s (1 - \phi) + \phi$$

Bulk (wet) sediment density

Surficial sediments

$$\rho_s \sim 1.5 - 2.5 \text{ g/cm}^3; \phi \sim 0.6 - 0.8 \Rightarrow$$

$$\rho_{b,d} \sim 0.3-1 \text{ g/cm}^3, \rho_{b,w} \sim 1.1-1.6 \text{ g/cm}^3, \rho \sim 0.4-1.7 \text{ g/cm}^3$$

$$f = \frac{K_p \rho}{K_p \rho + 1}$$

$\rho \sim 1 \Rightarrow$ for $K_p \gg 1$ most contamination is sorbed to particles

While most of the contaminant is associated with solids, the dissolved phase is very important because it is more bio-available and amenable to sediment-water exchange

Sediment quality criteria often derived from target dissolved phase concentrations assuming equilibrium partitioning

In water column

“porosity” ~ 1 so $\rho = \rho_s(1 - \phi) / \phi \equiv [TSS]$

$[TSS] \sim 1$ to 100 mg/L (10^{-4} to 10^{-6} g/cm³)

$$f = \frac{K_p \rho}{K_p \rho + 1} = \frac{K_p [TSS]}{K_p [TSS] + 1} = \frac{(10^{-4} \text{ to } 10^{-6}) K_p}{(10^{-4} \text{ to } 10^{-6}) K_p + 1}$$

For hydrophobic contaminants ($K_p \sim 10^4$ to 10^5) concentrations in sorbed and dissolved phases can be comparable. Hydrophylic contaminants are mostly in dissolved phase

Non-equilibrium conditions

$$\frac{dc_d}{dt} = \kappa \left(\frac{c_s}{K_p} - c_d \right)$$

Rate of increase of dissolved phase mass

$$\frac{d(\rho c_s)}{dt} = \kappa \left(c_d - \frac{c_s}{K_p} \right)$$

Rate of increase of sorbed phase mass

κ Rate constant (t^{-1}); e.g. (Wu and Gschwend, 1986)

$$\kappa = \frac{0.2(1 - \phi)D_m K_p \rho}{\phi R^2}$$

R = aggregate radius, D_m = molecular diffusivity

$$\frac{d}{dt}(c_d + \rho c_s) = 0$$

Total mass is conserved

Non-equilibrium, cont'd

$$\kappa/K_p$$

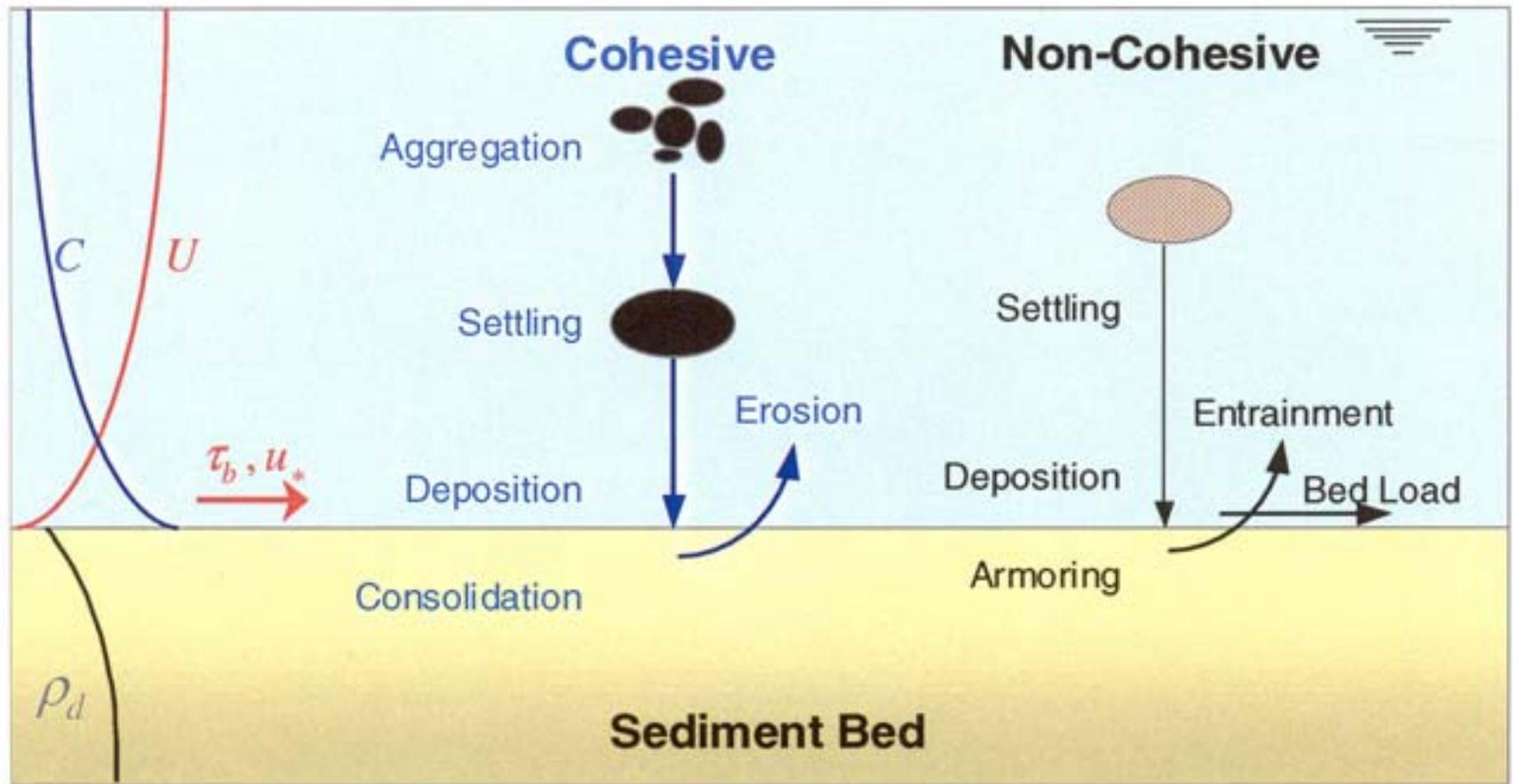
Time scale for desorption from particle
= days to months => equilibrium
assumption not very good for
suspended sediments (may be OK for
stationary sediments)

$$\frac{d}{dt}(c_d + \rho c_s) = 0 \quad \text{Total mass is conserved}$$

Additional Comments

- ◆ Fine particles usually most important
 - Most easily resuspended
 - Settle most slowly
 - Probably have highest $f_{oc} \Rightarrow K_p$
 - Highest $\kappa \sim (\text{diameter})^{-2}$
 - Models often have multiple particle sizes with individual settling velocity, tendency to resuspend, and κ

Sediment movement



Modes of transport

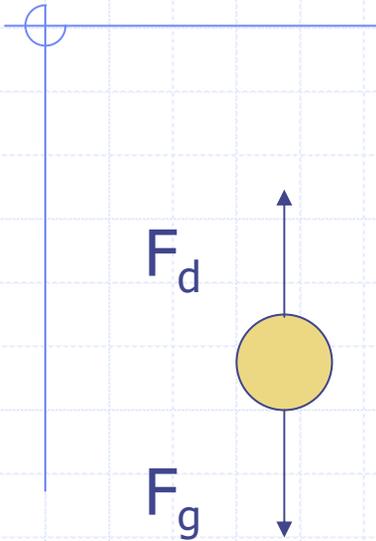
- ◆ Settling & deposition (non-cohesive and cohesive)
- ◆ Erosion & resuspension (non-cohesive and cohesive)
- ◆ Bed-load (non-cohesive)

Particle settling (WWT jargon)

- ◆ Discrete (Type 1) (non-cohesive)
- ◆ Flocculant (Type 2) (cohesive)
- ◆ Hindered or zone (Type 3)
- ◆ Compression (Type 4)

Focus on Types 1 and 2

Terminal velocity



$$F_g = (\rho_s - \rho_f)g \frac{\pi d^3}{6}$$

$$F_d = \frac{1}{2} \rho_f C_d w_s^2 \frac{\pi d^2}{4}$$

Equating,
$$C_d = \frac{4dg(s-1)}{3w_s^2}$$

$$s = \rho_s / \rho_f$$

$$C_d = f(R); R = \text{Reynolds number} = w_s d / \nu$$

Applicable to cohesive and non-cohesive sediments, but aggregate shapes and densities are ill-defined for cohesive sediments

Spherical particles

$R < 1$; $d < 100 \mu\text{m}$ (Stokes settling)

$$F_d = 3\pi\rho v d w_s$$

$$C_d = \frac{24}{R} \quad w_s = \frac{g(s-1)d^2}{18\nu}$$

$R < 10^4$ (Metcalf & Eddy, 1991)

$$C_d = \frac{24}{R} + \frac{3}{\sqrt{R}} + 0.34$$

More generally ($0.01 \text{ mm} < d < 100 \text{ mm}$; Dietrich, 1982)

$$\log w^* = -3.76715 + 1.92944(\log D^*) - 0.09815(\log D^{*2}) \\ - 0.00557(\log D^{*3}) + 0.00056(\log D^{*4})$$

$$w^* = \frac{w_s^3}{(s-1)g\nu} \quad D^* = \frac{(s-1)gd^3}{\nu^2}$$

Spherical & non-spherical particles

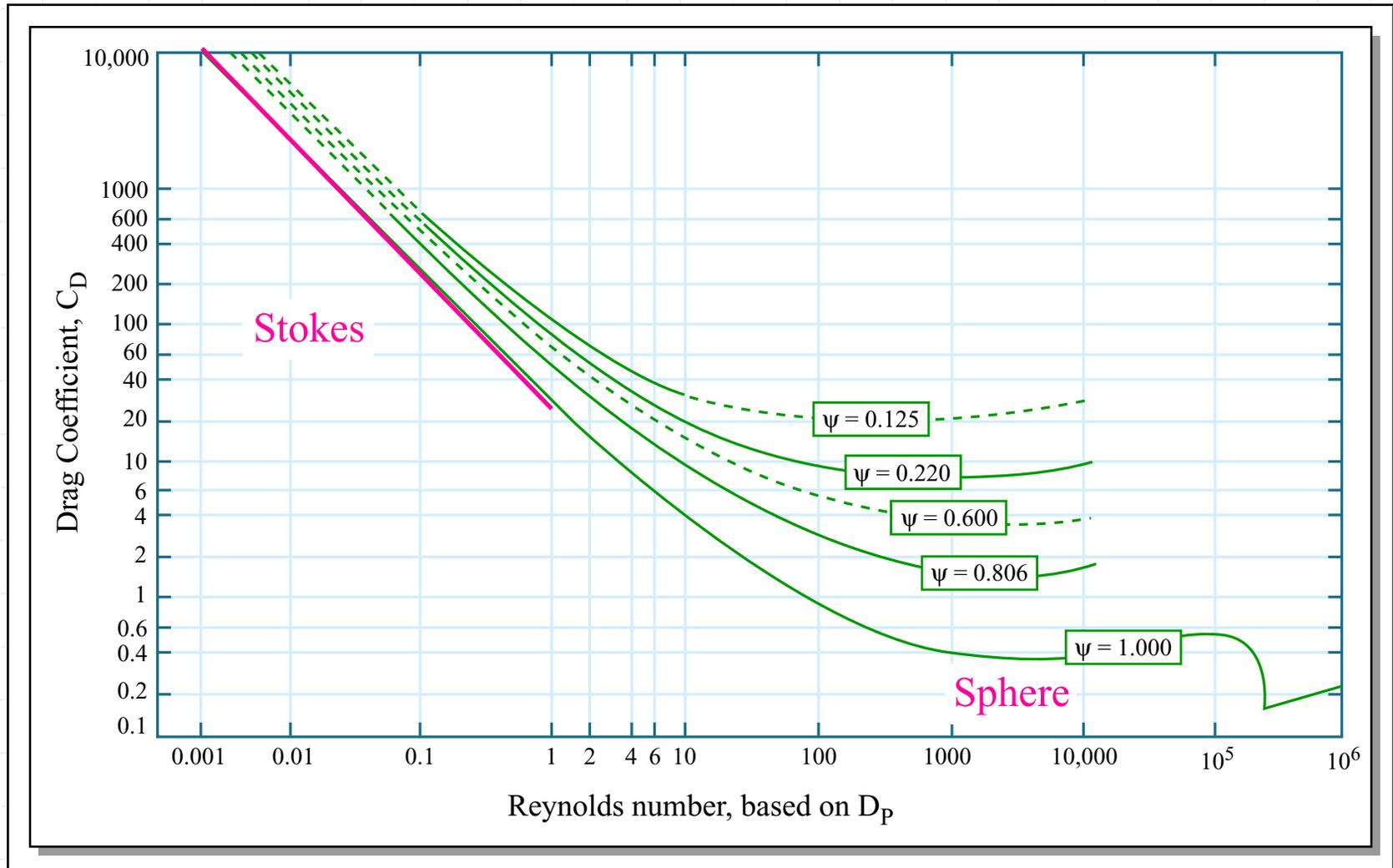


Figure by MIT OCW.

$$\Psi = \frac{\pi D_p^2}{A_s}$$

Surface area of equivalent sphere/surface area of particle

Brown et al. (1950)

Settling of Cohesive Sediments

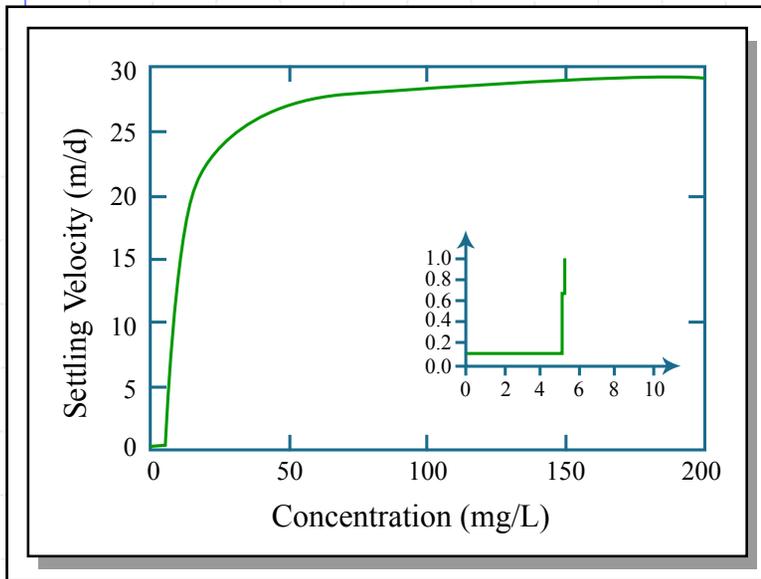


Figure by MIT OCW.

Settling velocity depends on concentration. Empirical formula from EPA (2004):

$$w_s (m/d) = \frac{0.1 m/d C_{WL} + 30 m/d (C_{COH} - C_{WL})}{C_{COH}}$$

C_{WL} = wash load concentration (5 mg/L); C_{COH} = cohesive sediment concentration (mg/L). Within range of empirical observations, e.g., Hawley (1982)

Sewage particles

Table 9.2 Summary of settling velocities (percent settling faster than indicated value) (after Stolzenbach and Adams, 1998)

w_s (cm/sec)	EPA (1982)		Wang (1988)		Wang (1988)	Faisst (1976, 1980)	Ozturgut & Lavelle (1986)	Lavelle et al. (1988)	McCave & Gross (1991)	Albro et al. (1996)
	Prim Effl	Raw	Effl ¹	Sludge ¹	Column Sludge ^{2,4}	Sludge	Effl ³	Sludge ⁴	Nat sed	Sludge
1	–	5	–	–	–	–	–	–	–	4-15
10 ⁻¹	5	40	–	–	0-25	0-5	–	10-20	–	26-55
10 ⁻²	20	60	≈3	≈3	10-60	5-40	5-25	25-30	10	>55-84 ⁵
10 ⁻³	50	85	≈10	≈30	30-75	25-70	50-60	50-80	40-45	–
10 ⁻⁴	–	–	≈20	≈60	45-85	50-80	≈70	95-100	100	–

¹Holography

²Column

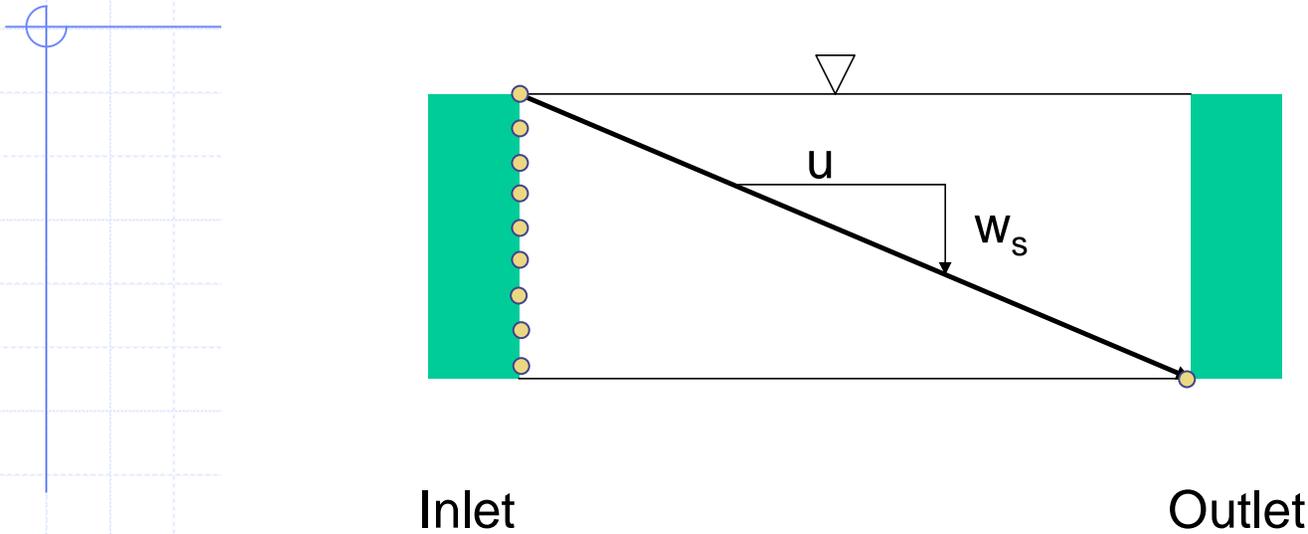
³Computed

⁴Range for sludge reflects coagulation; highly coagulated samples settle faster

⁵Indicated percentages are for 0.04 cm/sec

Often a wide range of settling velocities

Settling Basins: discrete settling



Time to settle $T_s = h/w_s$

Hydraulic residence time $T_{res} = V/Q = Ah/Q$

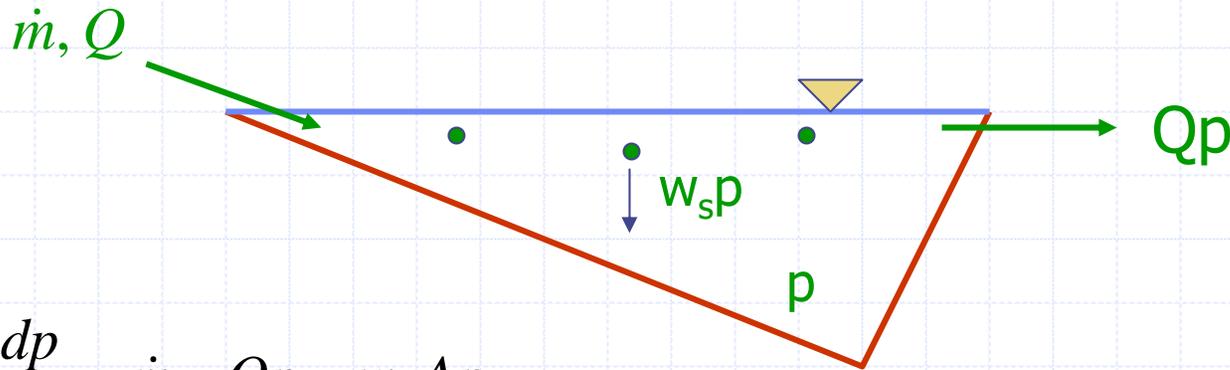
$T_{res} > T_s \Rightarrow Ahw_{sc}/Qh > 1$

$w_{sc} > Q/A$ or $Q < Aw_{sc}$ or $A > Q/w_{sc}$

Comments

- ◆ Q/A = overflow rate (really a velocity); particles settling faster will deposit
- ◆ Flow capacity depends on area (not depth) => make tanks as shallow as practical
- ◆ Increase area using stacked clarifiers, inclined plates/tubes, etc.
- ◆ Similar concepts apply to field: deposition at river deltas, in ponds & reservoirs, downstream from outfalls
- ◆ Example of particulate phosphorus loading in reservoir (Vollenweider plots)

Retention in lakes & reservoirs: critical phosphorus loading



$$V \frac{dp}{dt} = \dot{m} - Qp - w_s Ap$$

In steady state

$$\frac{\dot{m}}{A} = \frac{Q}{A} p + w_s p$$

$$p = \frac{\dot{m} / A}{Q / A + w_s}$$

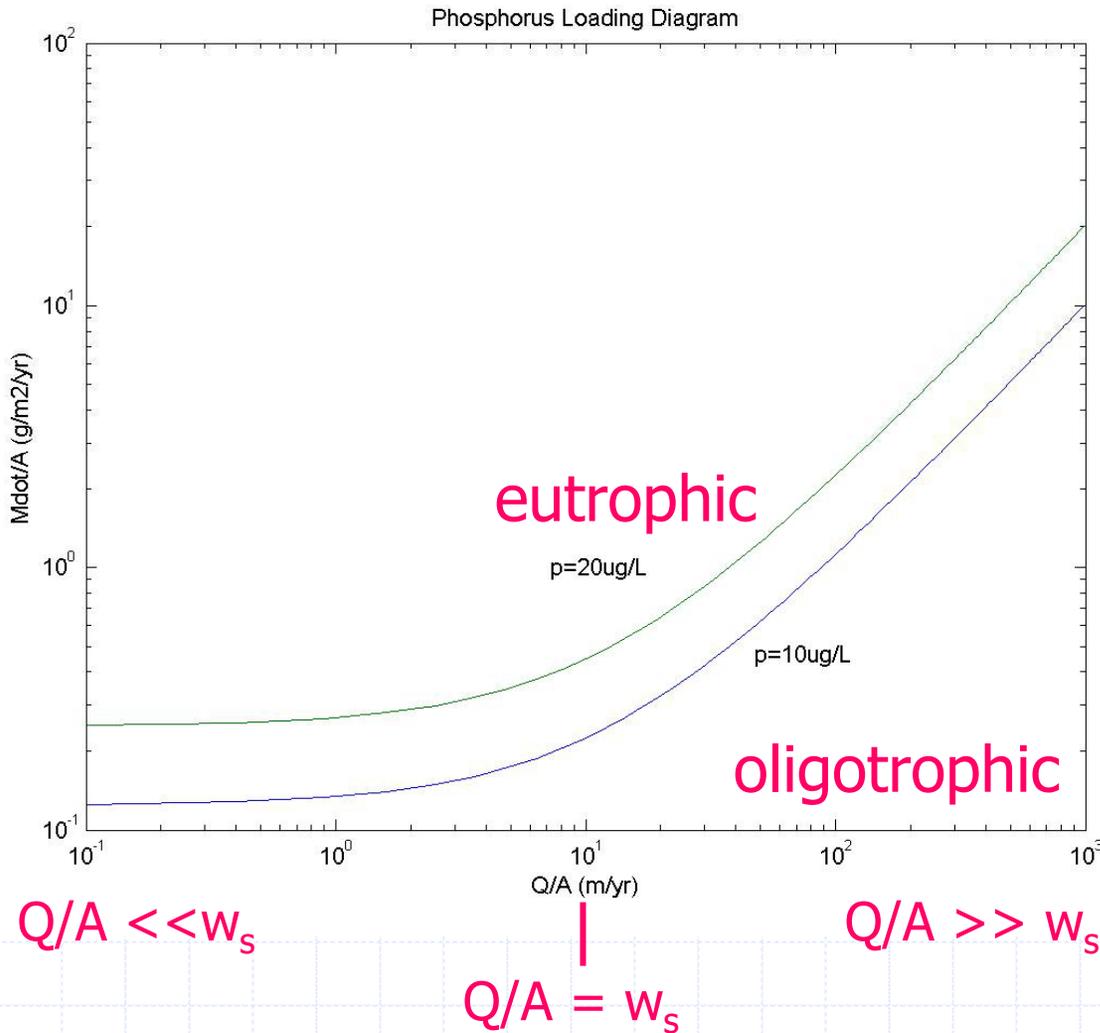
V = impoundment volume

A = impoundment area

Q/A = impoundment
"overflow rate"

p = average P concentration

Phosphorous loading diagram

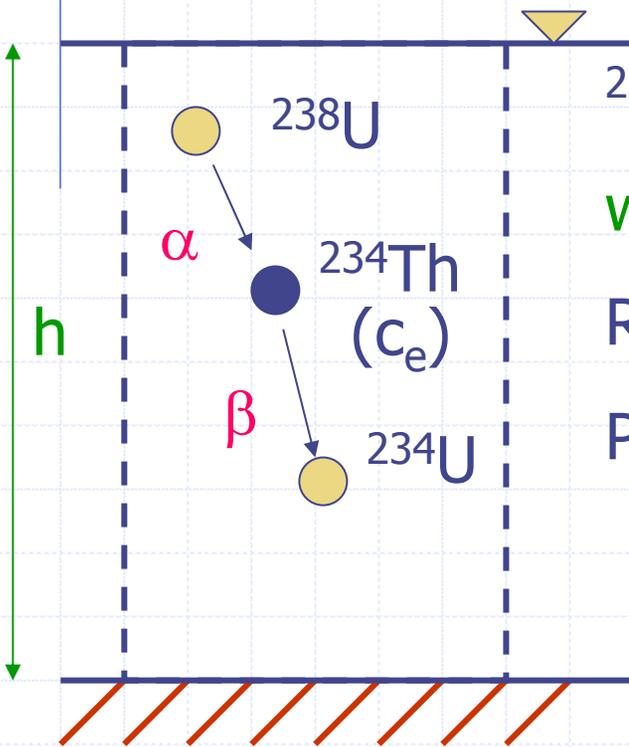


$$w_s = 10\text{m/yr}$$

After Vollenweider (1975); Chapra (1997)

Particle scavenging

Removal of marine contaminants (e.g., metals) by natural particle settling



^{234}Th : particle-reactive tracer; $t_{1/2} = 24.1$ d

w/o deposition $c_e =$ equil conc of ^{234}Th :

Rad decay = $-\lambda c_e$, $\lambda =$ decay rate ($\ln 2/t_{1/2}$)

Production = λc_e (must be same in equil)

Particle scavenging, cont'd

With deposition, ^{234}Th conc $c < c_e$

f = fraction of ^{234}Th sorbed to particles

$$f = \frac{K_p [TSS]}{K_p [TSS] + 1}$$

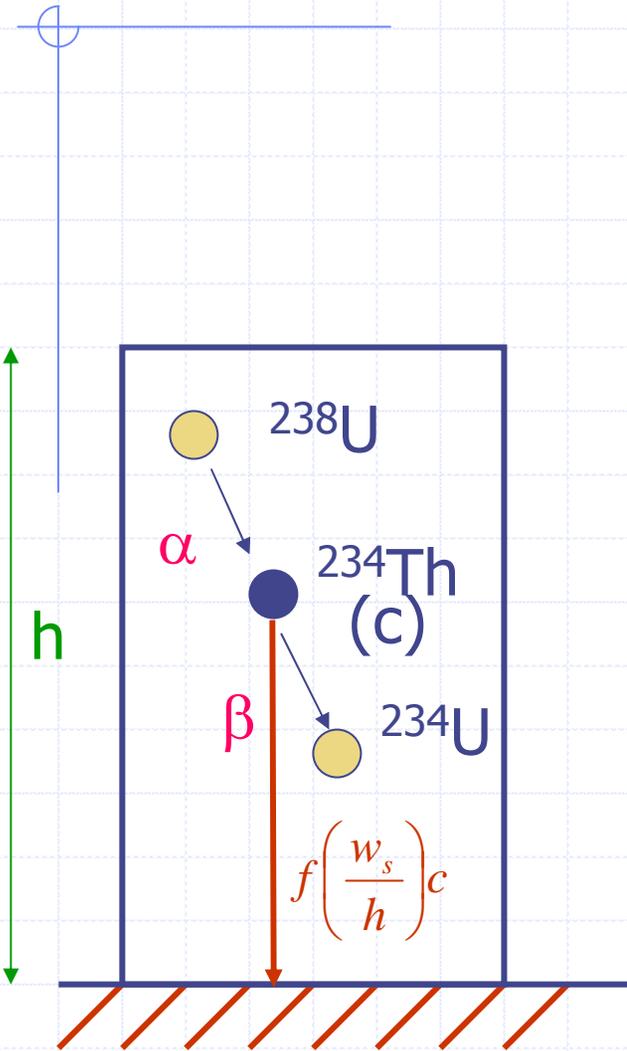
fw_s/h is effective ^{234}Th removal rate (t^{-1})

$$c_e \lambda = c \left(\lambda + \frac{fw_s}{h} \right)$$

$$\frac{fw_s}{h} = \frac{(c_e - c)\lambda}{c}$$

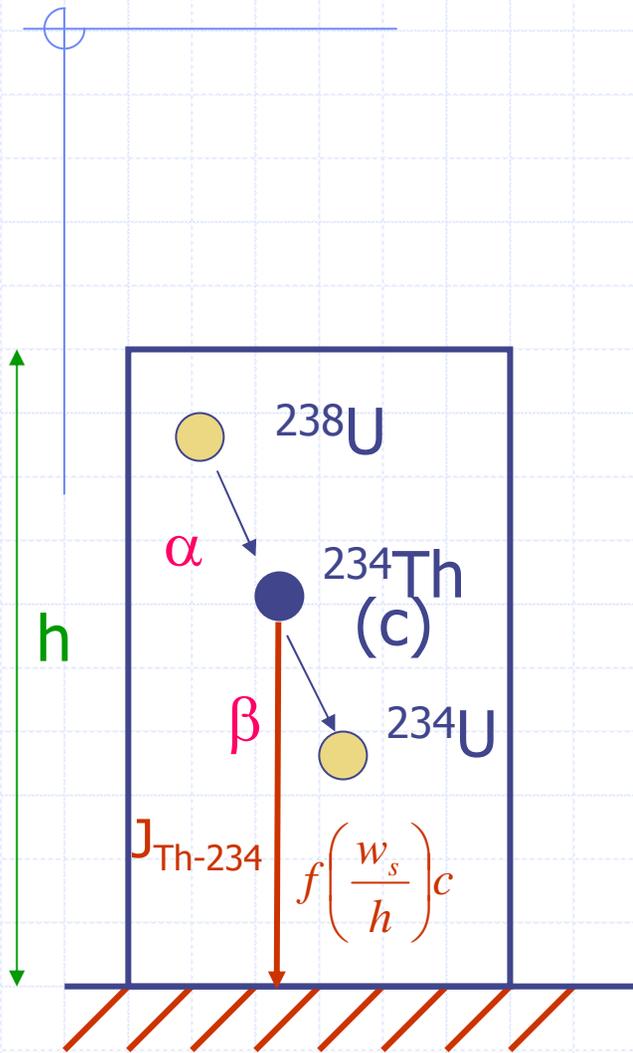
$$w_s = \frac{(c_e - c)\lambda h}{cf}$$

c_e measured offshore;
 c measured locally $\Rightarrow w_s$



Particle scavenging, cont'd

Use ^{234}Th deposition to trace deposition of another metal (call it x), with different partitioning



$$f_x = \frac{K_{px} [TSS]}{K_{px} [TSS] + 1}$$

$$w_s = \frac{(c_e - c)\lambda h}{cf}$$

$$J_{\text{Th-234}} = fcw_s = (c_e - c)\lambda h$$

$$J_x = f_x c_x w_s = \frac{f_x c_x}{fc} (c_e - c)\lambda h$$

Deposition

Flux of settling particles

$$w_s C \quad C = \text{sediment concentration (TSS)}$$

Deposition rate, D

$$D = p w_s C \quad p = \text{probability of depositing (sticking)}$$

For non-cohesive sediments, $p = 1$

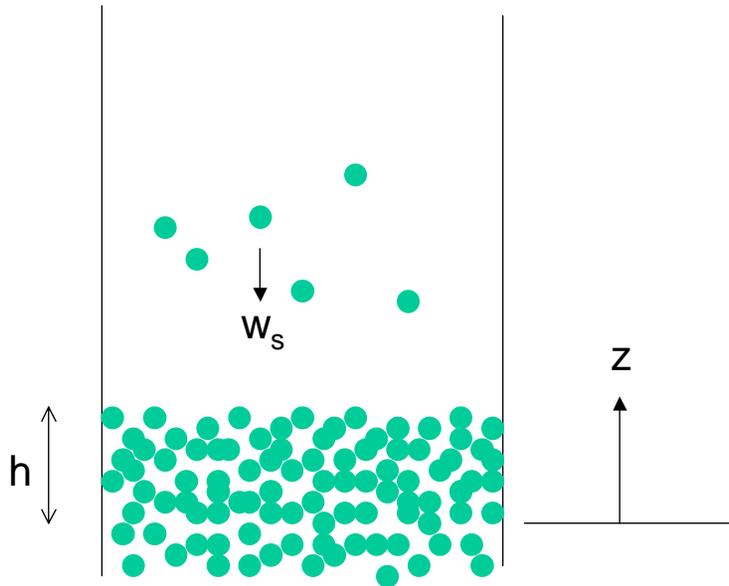
For cohesive sediments

$$p = (1 - \tau / \tau_{c,d}) \quad \tau < \tau_{c,d} \quad \tau_{c,d} = \text{critical depositional shear stress}$$

$$0.06 < \tau_{c,d} < 1.1 \text{ N/m}^2$$

(Mehta & Partheniades, 1975;
Ziegler et al, 1995)

Particle accumulation on bottom



Rate of mass approaching interface/unit area = D

Rate of accumulation in surface sediments

$$\frac{d}{dt} [h\rho_s(1-\phi)]$$

Equating

$$w_o = \frac{dh}{dt} = \frac{D}{\rho_s(1-\phi)}$$

If $\phi = 0.8$, $\rho_s = 2.5 \text{ g/cm}^3$, $\rho_s(1-\phi) = 0.5$

How to determine $w_0 = dh/dt$?

- ◆ Depth of natural, accidental or intentional marker
 - e.g., paint pigments in Fort Point Channel
- ◆ Decay of radioactive tracer
 - e.g., ^{210}Pb ,

Fort Point Channel

Recall discussion in Chapter 4

Fluorescent dye
and pigment
particles released
May '90 and July
'91

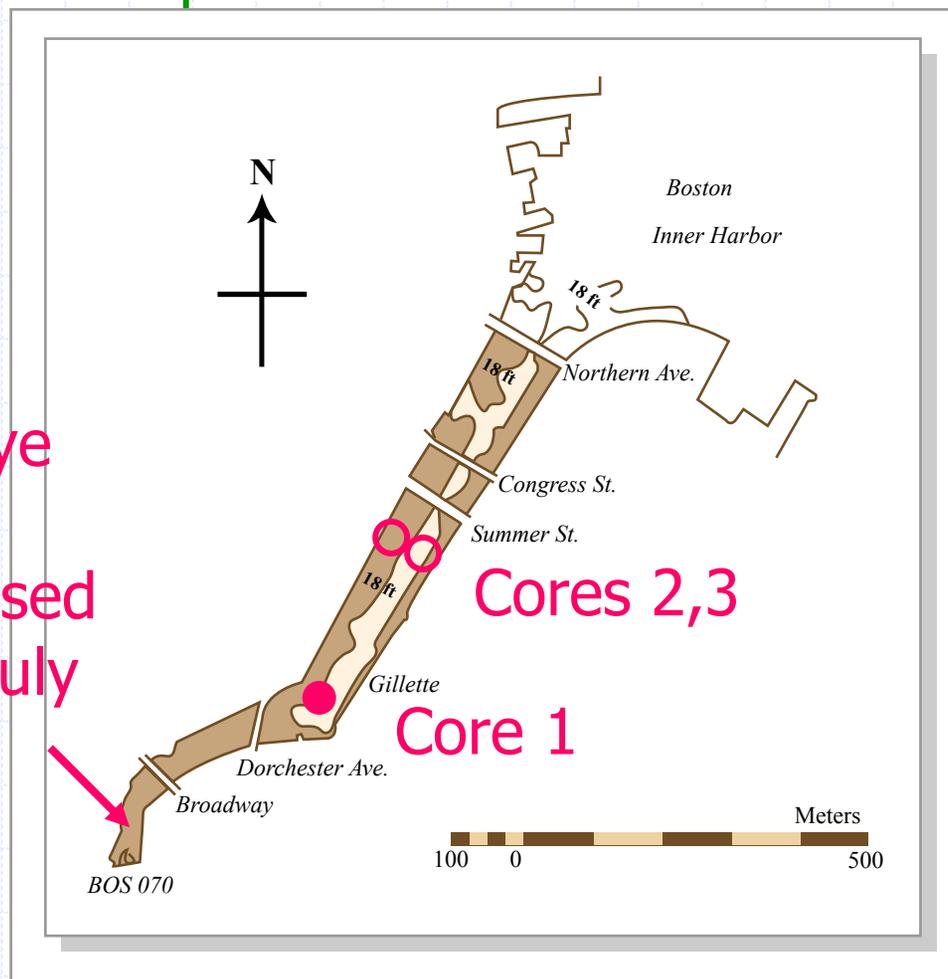
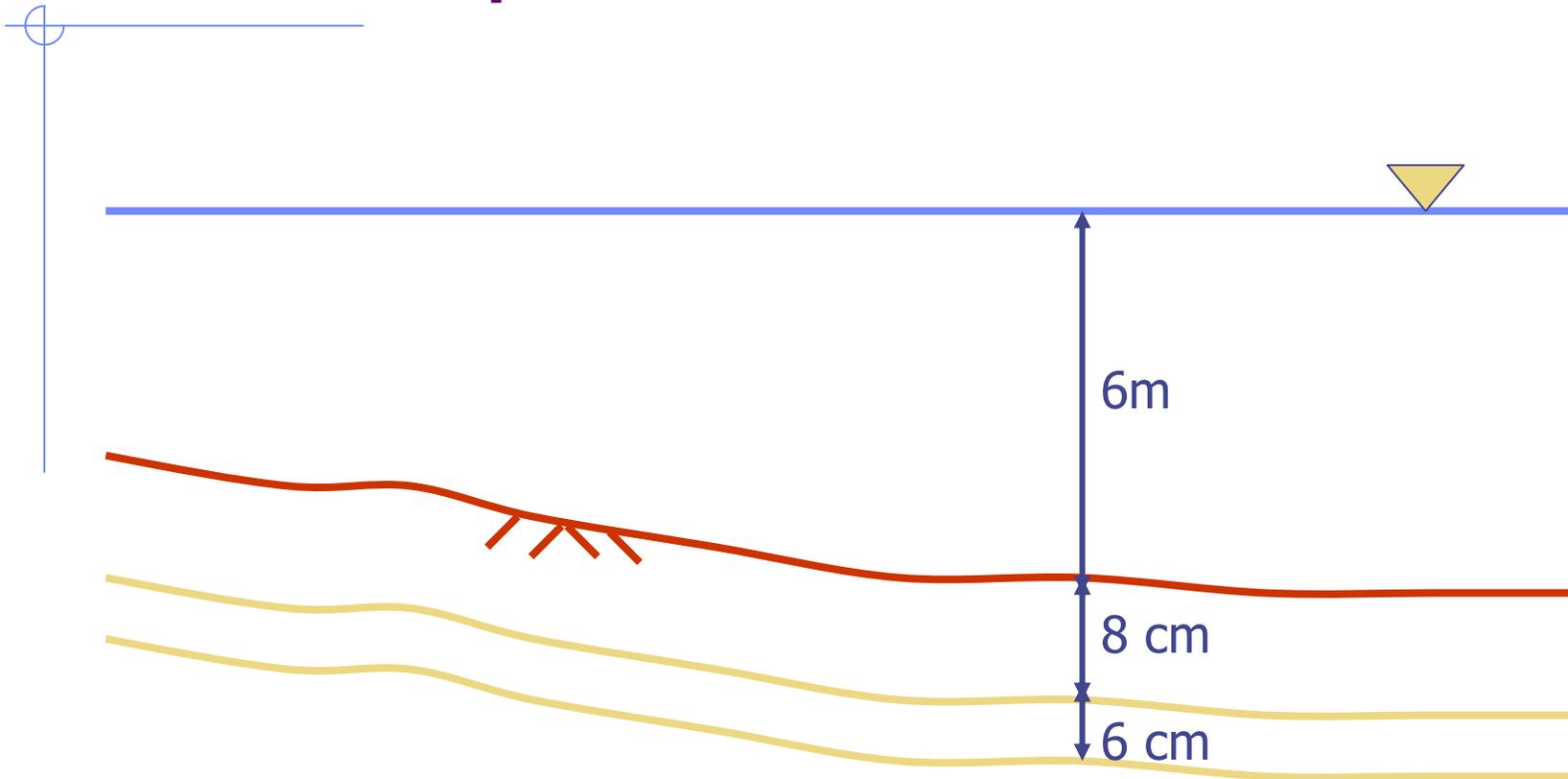


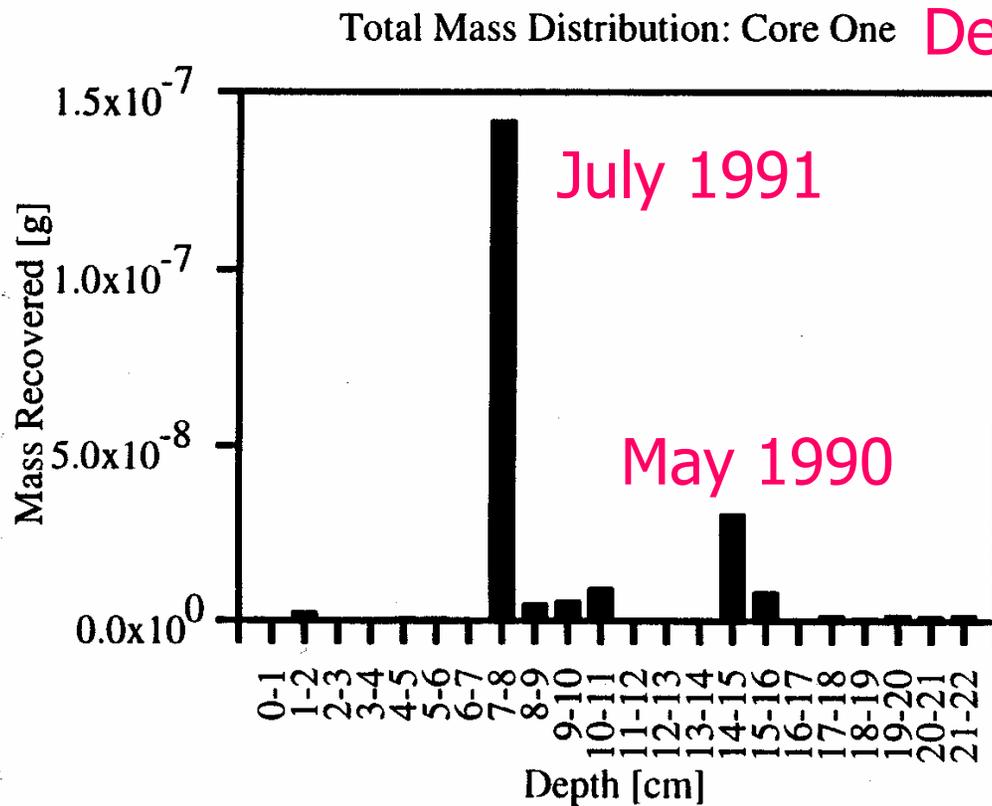
Figure by MIT OCW.

Paint chips as markers



Stolzenbach and Adams (1998)

Pigment surveyed with freeze corer



May '90 to Dec '93

14 cm/3.6 yr = 3.9 cm/yr

Jul '91 to Dec '93

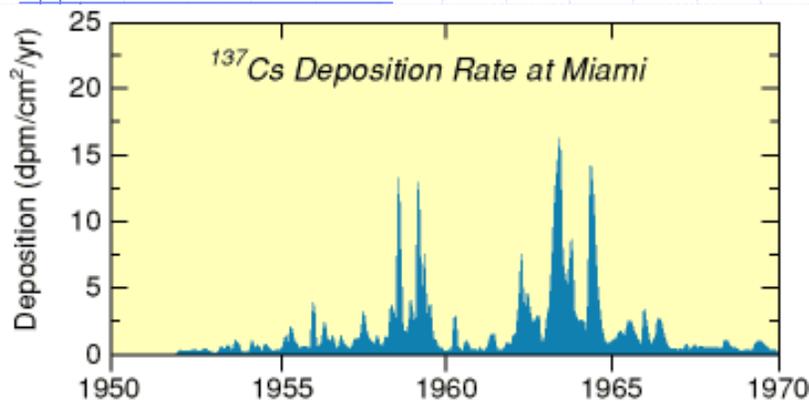
8 cm/2.4 yr = 3.3 cm/yr

Stolzenbach and Adams (1998)

Comments

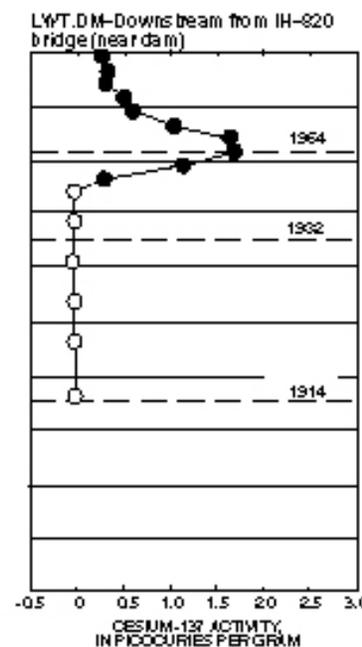
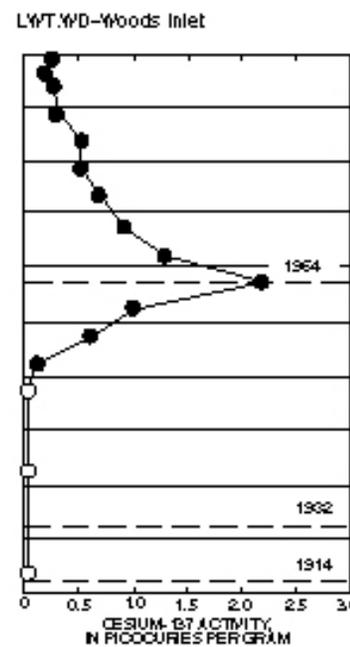
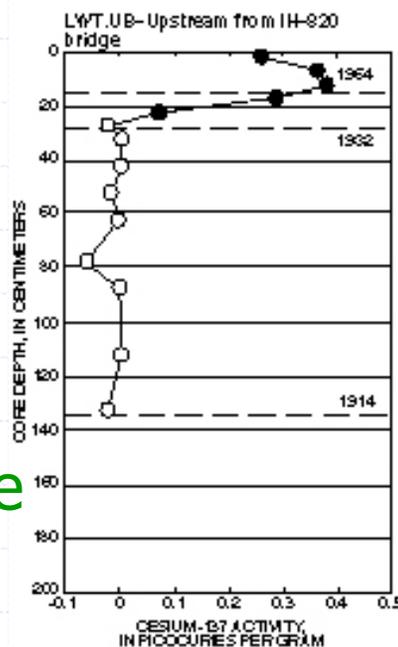
- ◆ Deposition rates of 1-4 cm/yr in FPC (three cores)
- ◆ Loading rates for all FPC sediment sources ~ 0.14 cm/yr
- ◆ Substantial import of (contaminated) sediment

Cs-237



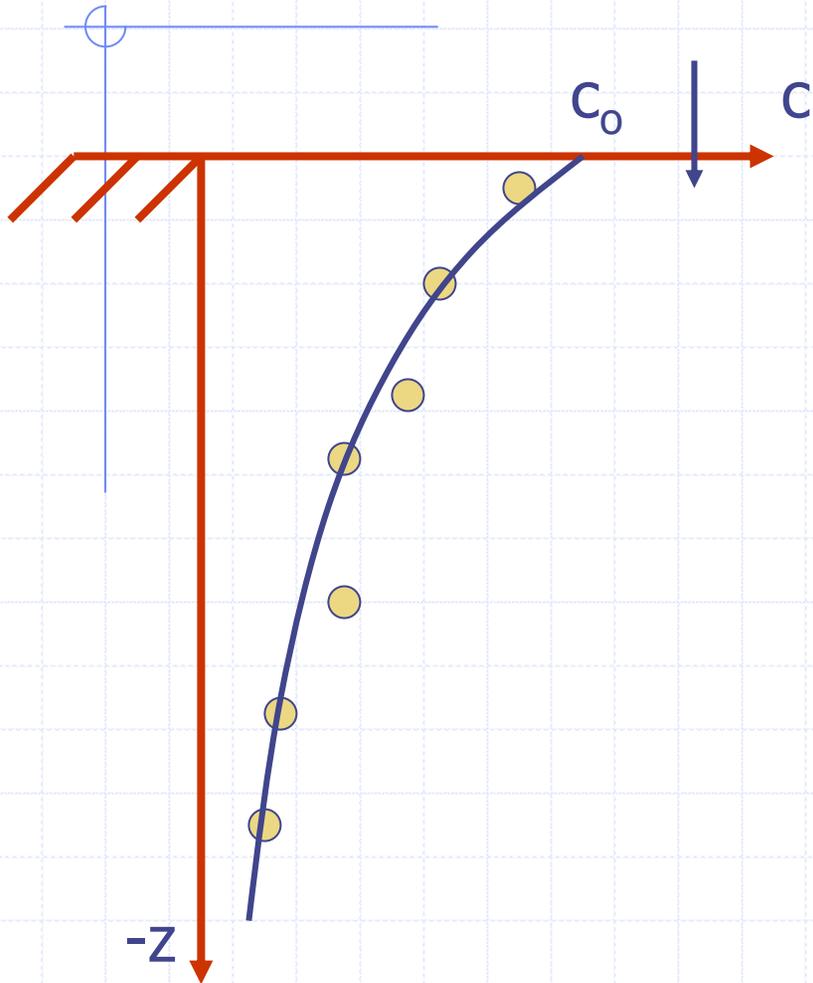
Fallout from bomb testing

USGS Gravity cores, Lake Worth, TX, 2000-01



EXPLANATION
 ● Detection ○ Concentration less than reporting limit

Measuring deposition with Excess ^{210}Pb



Pb-210 particle reactive tracer; $t_{1/2} \sim 23$ yr

c = excess concentration

Relative to (moving) interface, steady state, no sediment mixing

$$-w_o \frac{dc}{dz} = -\lambda c$$

$$\frac{c}{c_o} = e^{-\frac{\lambda z}{w_o}}$$

Alternatively

$$w_o = \frac{1}{c_o} \lambda \int_{-\infty}^0 c(z) dz$$

Erosion and Resuspension

Associated with bottom shear stress

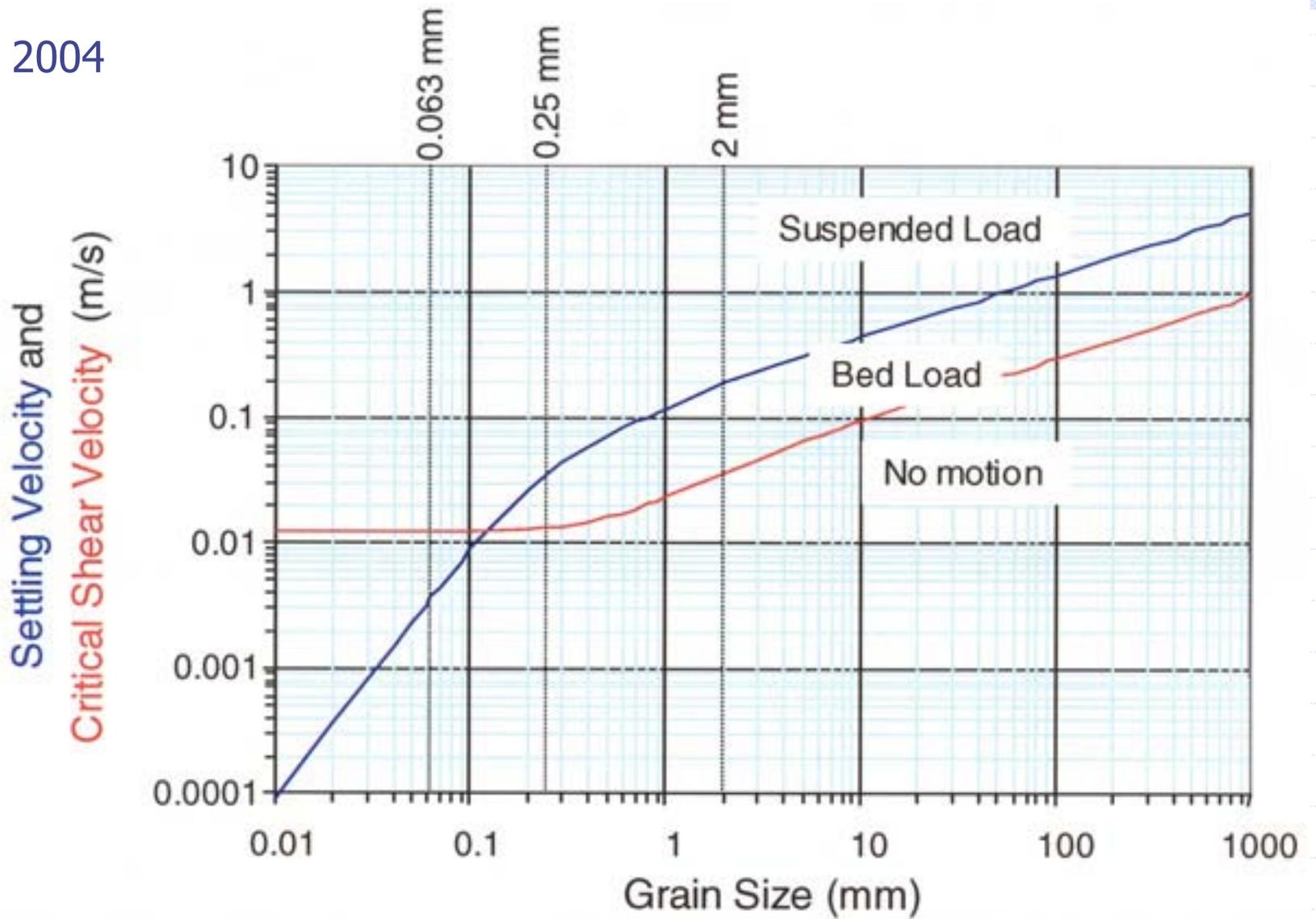
$$\tau = -\rho \overline{u'w'} = \rho E_z \frac{\partial u}{\partial z}$$

$$\tau = \rho c_f \bar{u}^2$$

c_f is bottom friction factor

Erosion of non-cohesive seds

- ◆ Critical shear stress τ_c required to initiate particle motion
- ◆ $w_s > (\tau/\rho)^{0.5} > (\tau_c/\rho)^{0.5} \Rightarrow$ bedload
- ◆ $(\tau/\rho)^{0.5} > w_s, \tau_c \Rightarrow$ suspended load
- ◆ Re-suspension flux depends on near-bed concentration; many formulations



colloids	clay	silt	sand			gravel	cobble	boulder
			F	M	C			
0.001	0.005	0.075	0.425	2	4.75	75	300	

Cohesive sediments

Many formulations; most apply for shear stress above a critical erosional shear stress, $\tau_{c,e}$

Erosion rate E (g/m²-s)

$$E = M \left(\frac{\tau}{\tau_{c,e}} - 1 \right)^n$$

$$\tau_{c,e} = 0.05 \text{ to } 0.3 \text{ N/m}^2;$$

$$M = 0.1 \text{ to } 3 \text{ g/m}^2\text{-s}; n = 1-3$$

Cohesive sediments, cont'd

Erosion potential ε (g/m²)

$$\varepsilon = \frac{a_o}{T_d^m} \left(\frac{\tau}{\tau_{c,e}} - 1 \right)^n \quad T_d = \text{time (days) after deposition}$$

$$\tau_{c,e} = 0.1 \text{ N/m}^2 ; a_o = 50; m = 2; n = 2.7$$

Erosion over specified time interval ~ 1 hr

Above parameters from Ziegler, et al., 1995 for
Watts Bar Reservoir, TN

Measurement of erosion

- ◆ Linear laboratory flume
- ◆ Linear flume in field
- ◆ Laboratory annular flume
- ◆ Portable resuspension device (Shaker; Tsai and Lick, 1986)



Sedflume (after McNeil et al., 1996)

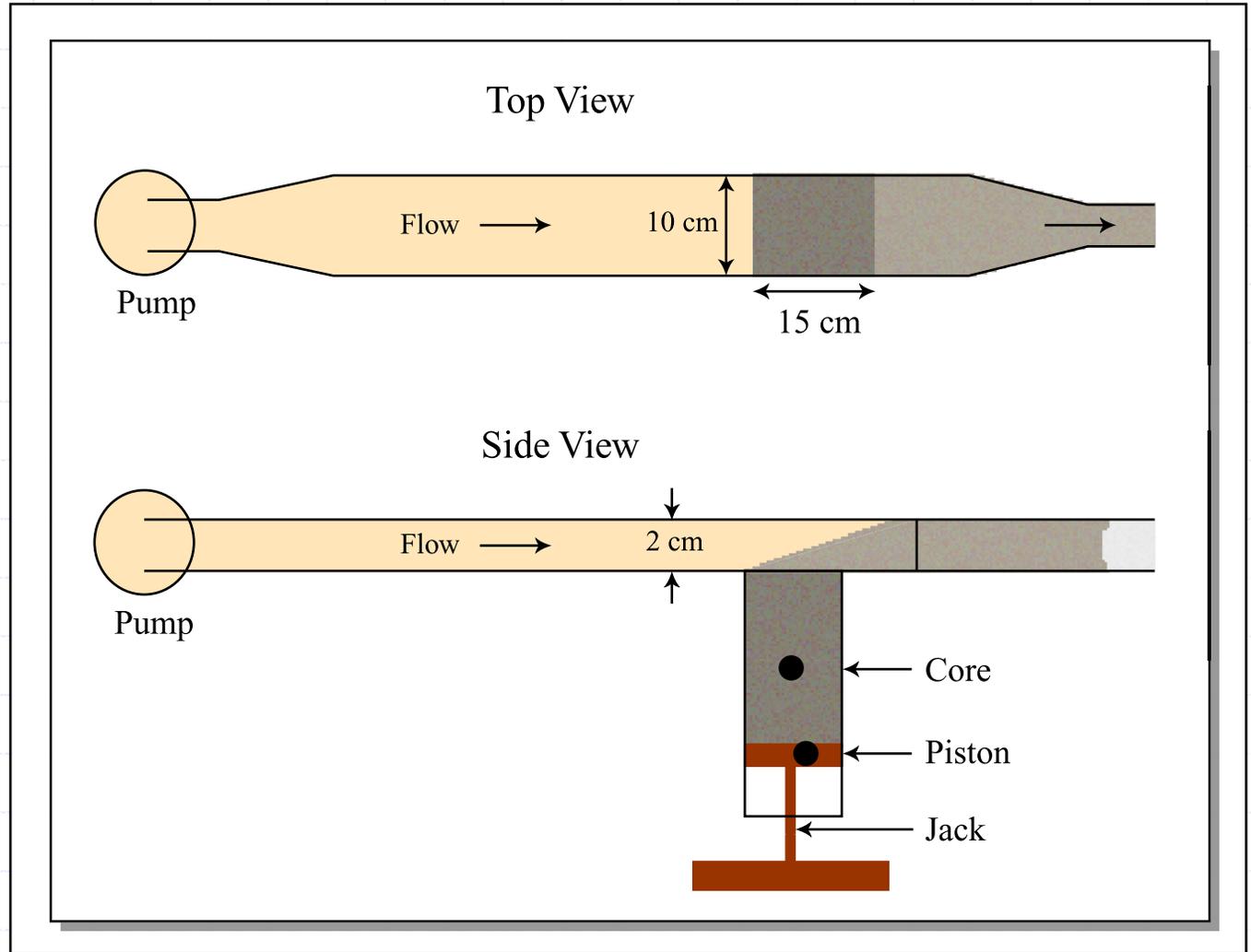
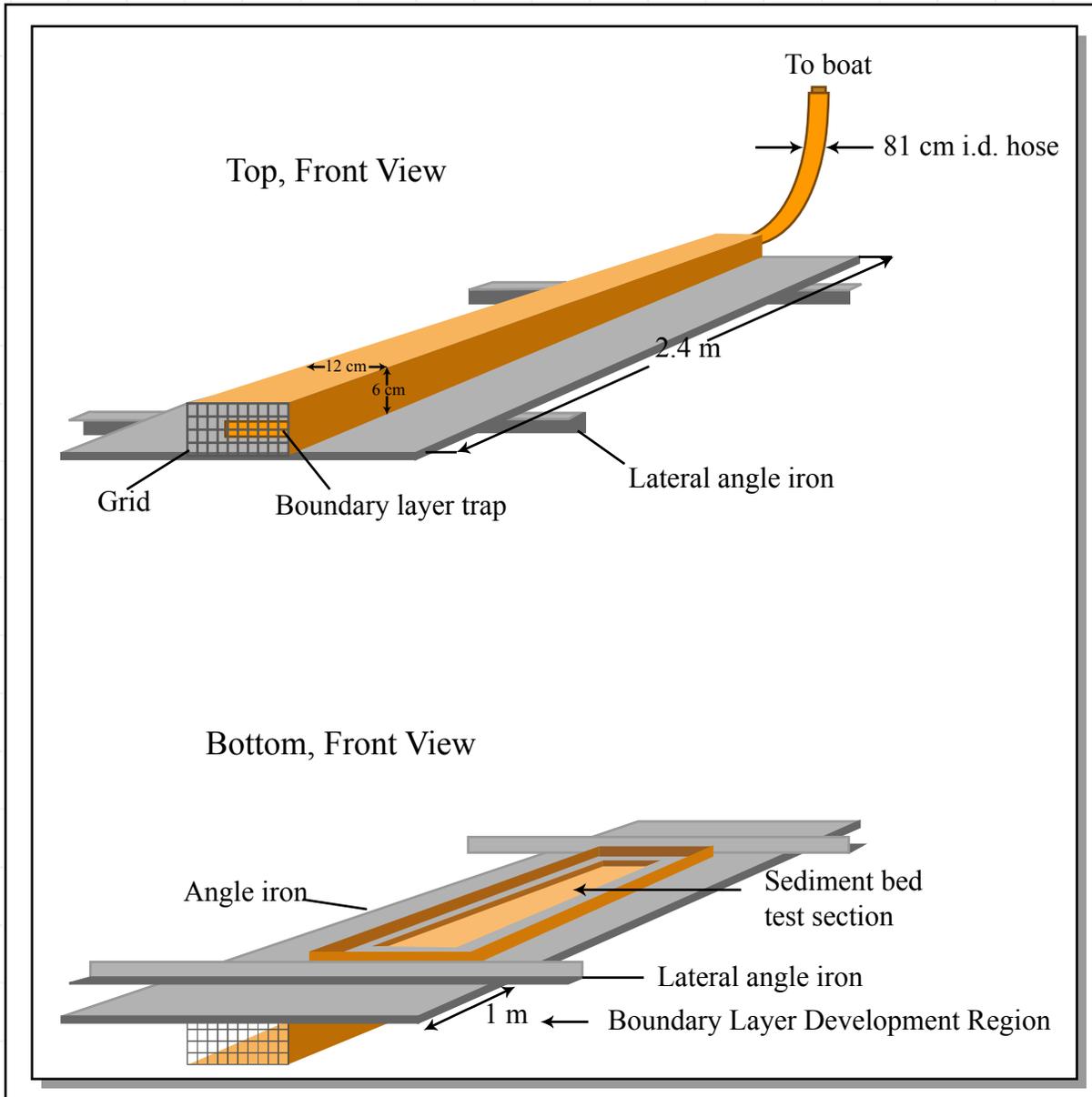


Figure by MIT OCW.

Measures erosion rates in the lab



Ravens &
Gschwend
(1999)

Measures erosion
rates in the field

Figure by MIT OCW.

Comments

- ◆ $\tau_{c,e}$ increases & E decreases with time after deposition and depth below sediment bed reflecting increased strength due to compaction, armoring from larger particles
- ◆ Regions with $\tau > \tau_{c,e}$ on regular or intermittent basis exhibit erosional tendencies
- ◆ Net erosion (erosion – deposition)

$$\phi = E - D = M \left[\frac{\tau}{\tau_{c,e}} - 1 \right]^n - w_s c \left[1 - \frac{\tau}{\tau_{c,d}} \right]$$

Transport Equation with Sediments

$$\frac{\partial c}{\partial t} + \frac{\partial}{\partial x}(uc) + \frac{\partial}{\partial y}(vc) + \frac{\partial}{\partial z}(w - w_s)c = \frac{\partial}{\partial x}\left(E_x \frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(E_y \frac{\partial c}{\partial y}\right) + \frac{\partial}{\partial z}\left(E_z \frac{\partial c}{\partial z}\right)$$

z positive upward, origin at sediment interface;
c = sediment concentration; w_s = settling velocity

Neglecting horizontal transport & vertical water velocity

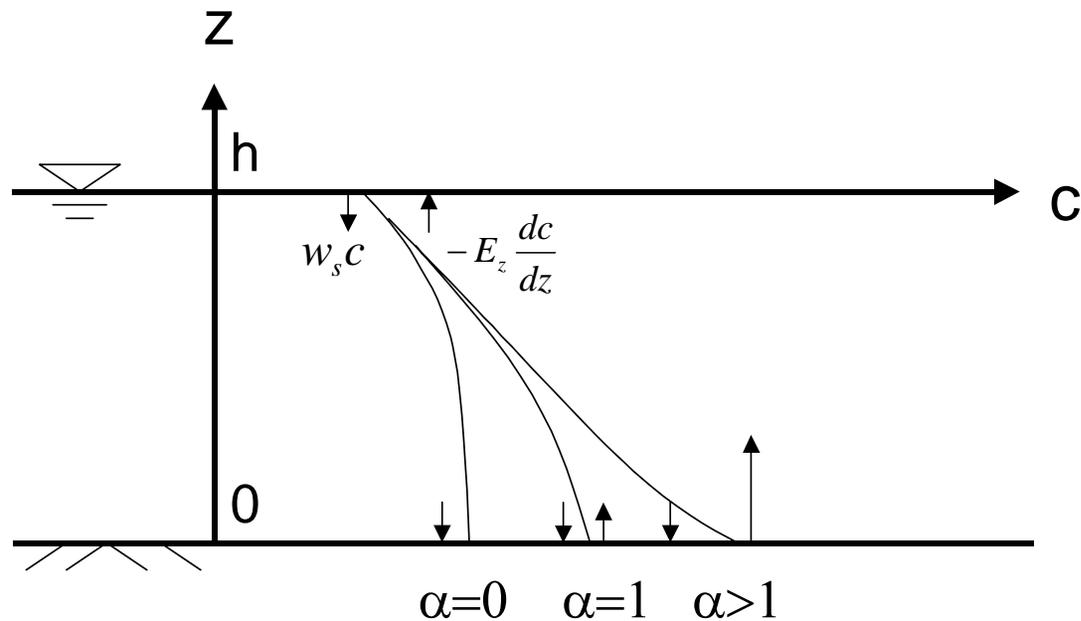
$$\frac{\partial c}{\partial t} - \frac{\partial}{\partial z} w_s c = \frac{\partial}{\partial z} \left(E_z \frac{\partial c}{\partial z} \right)$$

Boundary conditions

$$-w_s c - E_z \frac{\partial c}{\partial z} = 0 \quad \text{at surface (z = h)}$$

$$-w_s c - E_z \frac{\partial c}{\partial z} = (\alpha - 1)w_s c \quad \text{at bottom (z = 0)}$$

Surface and bottom BCs



α denotes relative amount of erosion

Vertical sediment distribution

Under steady state

$$-w_s c = E_z \frac{dc}{dz}$$

Logarithmic velocity profile in channel; turbulent diffusivity = viscosity

$$\frac{c(z)}{c_a} = \left[\left(\frac{h-z}{z} \right) \left(\frac{a}{h-a} \right) \right]^{w_s / \kappa u_*}$$

$w_s / \kappa u_*$ Rouse number

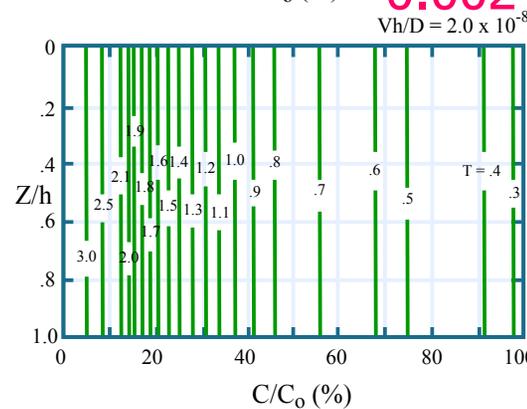
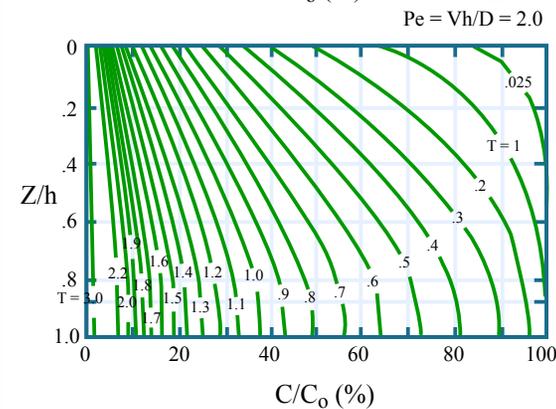
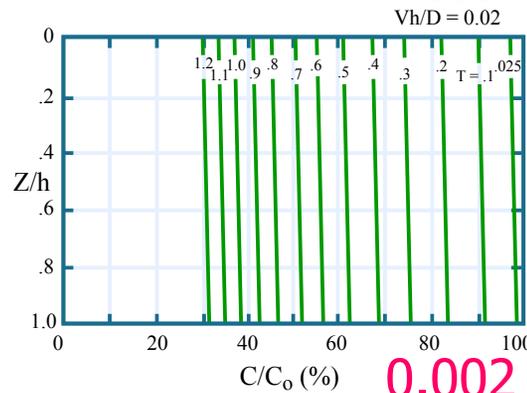
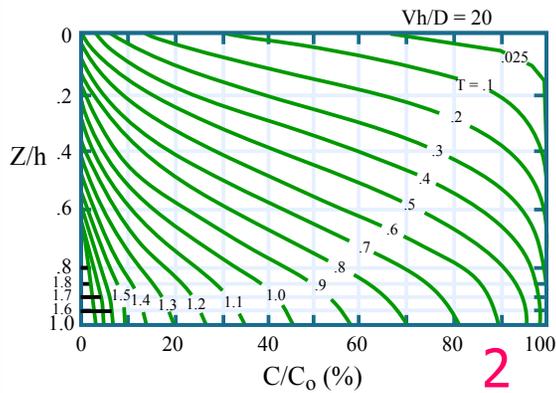
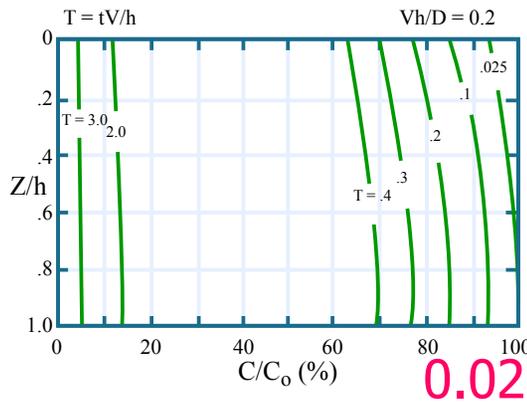
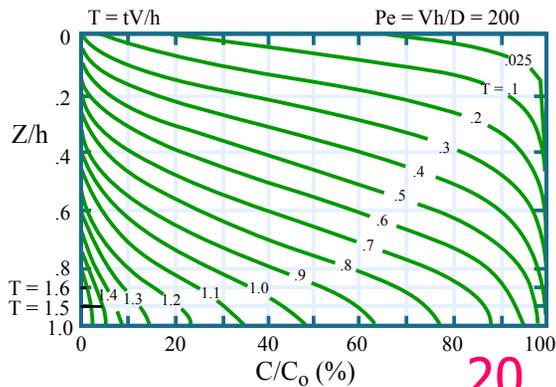
Depth-average E_z ($= 0.07u_*h$)

$Pe = \frac{w_s h}{E_z}$ Peclet number $\sim 6 w_s / \kappa u_*$

$$T = tw_s/h$$

$$Pe = 200$$

$$0.2$$



$c(z/h, T, Pe)$

No erosion
($\alpha=0$)

Constant E_z

$$Pe = \frac{w_s h}{E_z}$$

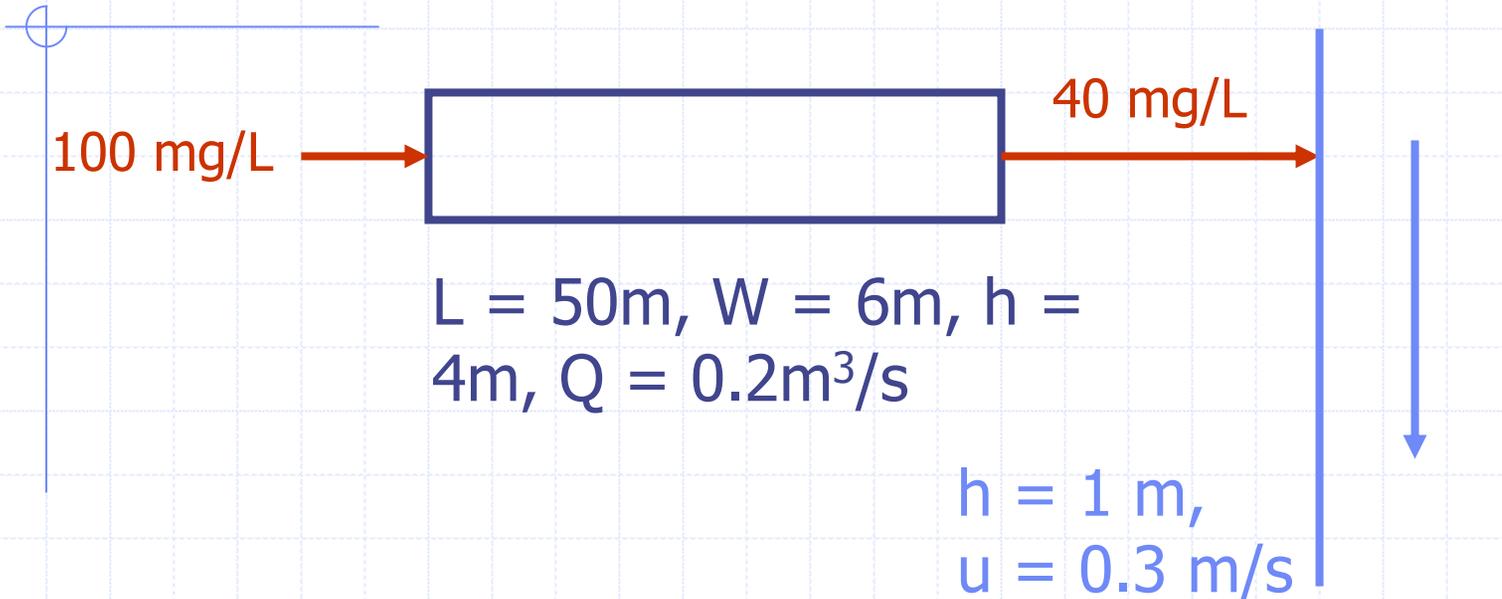
$Pe < 0.2 \Rightarrow$
well-mixed)

$Pe > 100 \Rightarrow$
stratified

Dhamothran et al (1981)

Figure by MIT OCW.

Application: Settling basin & river



$$Pe = w_s h / E_z$$

$$E_z = 0.07 u_* h; \text{ assume } u_* \sim 0.05 u \Rightarrow E_z = 0.0035 u h$$

$$Pe = \sim 300 w_s / u$$

$$w_s = 10^{-2} \text{ to } 10^{-6} \text{ m/s (Table 9.2)}$$

Table 9.2 Summary of settling velocities (percent settling faster than indicated value)
(after Stolzenbach and Adams, 1998)

w_s (cm/sec)	EPA (1982)		Wang (1988)		Wang (1988)	Faisst (1976, 1980)	Ozturgut & Lavelle (1986)	Lavelle et al. (1988)	McCave & Gross (1991)	Albro et al. (1996)
	Prim Effl	Raw	Effl ¹	Sludge ¹	Column Sludge ^{2,4}	Sludge	Effl ³	Sludge ⁴	Nat sed	Sludge
1	–	5	–	–	–	–	–	–	–	4-15
10 ⁻¹	5	40	–	–	0-25	0-5	–	10-20	–	26-55
10 ⁻²	20	60	≈3	≈3	10-60	5-40	5-25	25-30	10	>55-84 ⁵
10 ⁻³	50	85	≈10	≈30	30-75	25-70	50-60	50-80	40-45	–
10 ⁻⁴	–	–	≈20	≈60	45-85	50-80	≈70	95-100	100	–

¹Holography

²Column

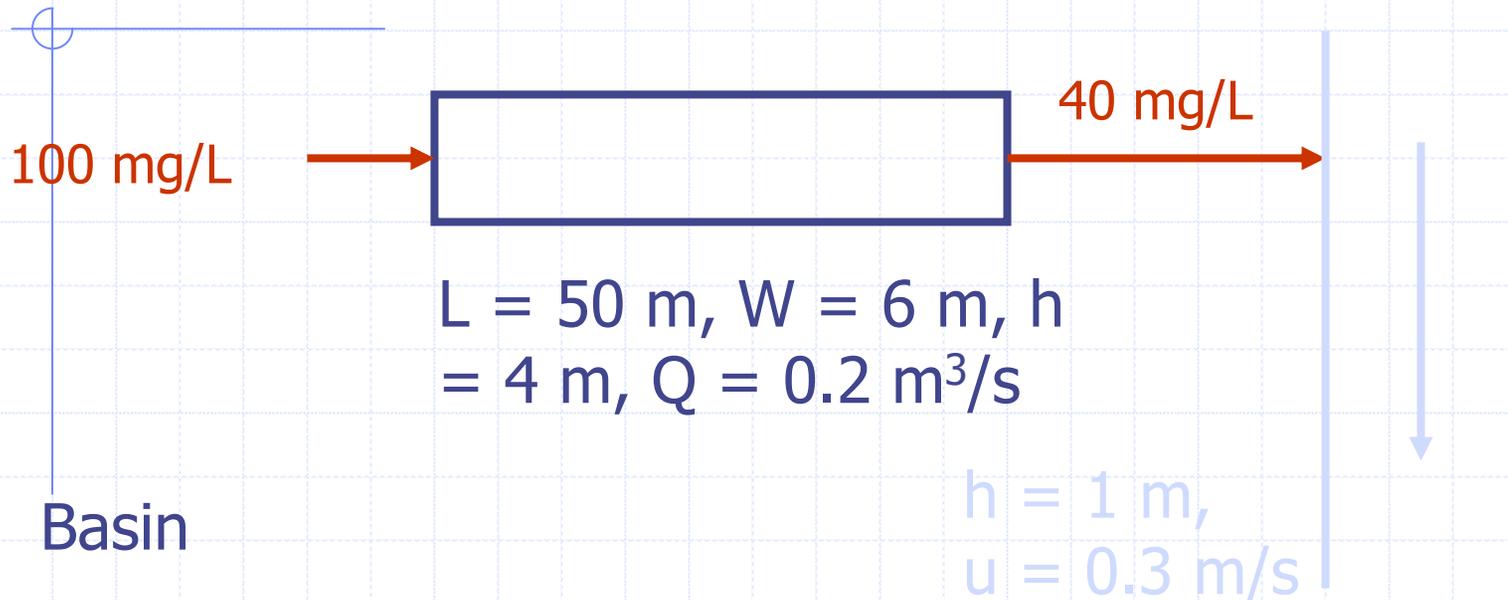
³Computed

⁴Range for sludge reflects coagulation; highly coagulated samples settle faster

⁵Indicated percentages are for 0.04 cm/sec

Often a wide range of settling velocities

Focus on Basin



$$u = Q/hW = 0.0083 \text{ m/s}$$

$$Pe = \sim 300w_s/u \text{ (second column of Table 9.3)}$$

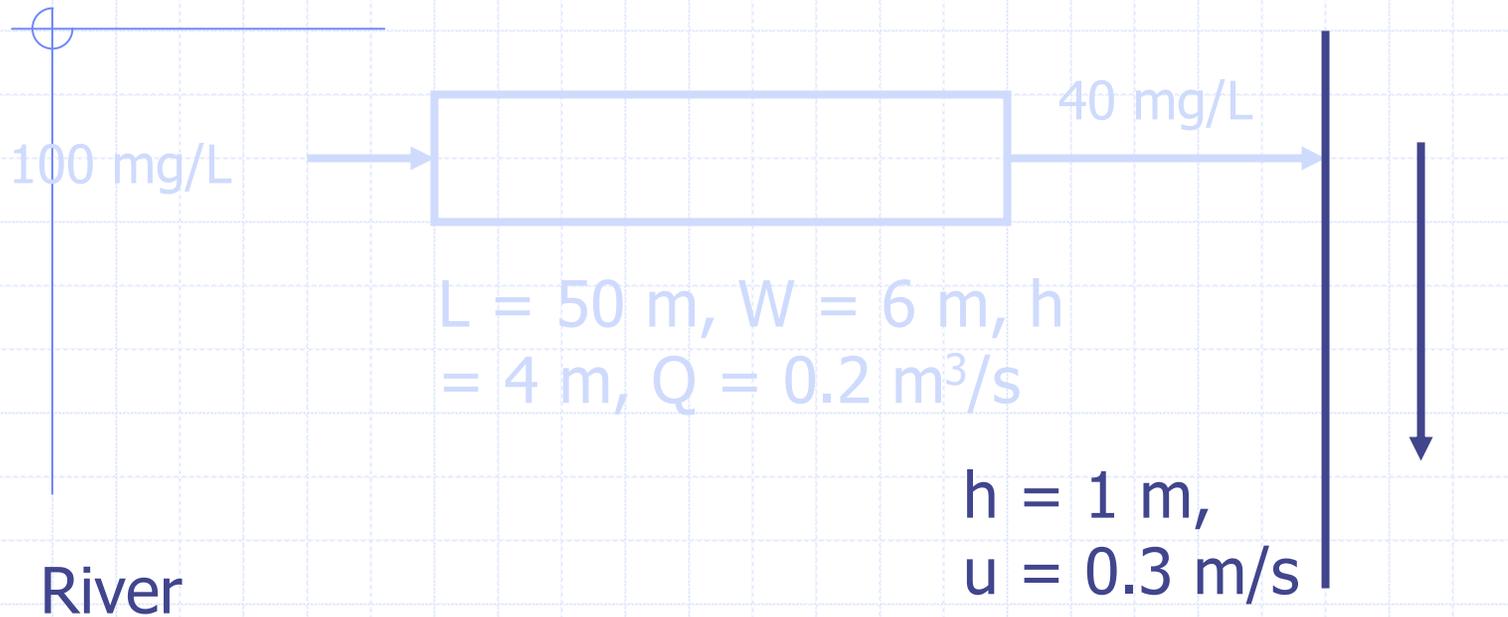
$$w_{sc} = Q/A = Q/LW = 7.7 \times 10^{-4} \text{ m/s}$$

(faster settling particles theoretically removed)

Pe for settling basin and river

W_s (m/s)	$Pe = w_s h / E_z$ (Basin)	$Pe = w_s h / E_z$ (River)
10^{-2}	340	
10^{-3}	34	
10^{-4}	3.4	0.1
10^{-5}	0.34	0.01
10^{-6}	0.034	0.001

Focus on River



$$Pe = \sim 300w_s/u \text{ (third column of Table 9.3)}$$

Comments

- ◆ In basin, turbulence insufficient to mix particles that settle ($Pe > 30$)
- ◆ In river, turbulence sufficient to mix particles that don't settle in basin ($Pe < 0.1$) (river can be treated as well mixed)
- ◆ In basin, $\tau_b = \rho u_*^2 = 0.07 \text{ N/m}^2 < \tau_{c,e}$
- ◆ In river, $\tau_b = \rho u_*^2 = 0.22 \text{ N/m}^2 < \sim \tau_{c,e}$ (possible resuspension)

Vertically well-mixed conditions

$$Pe < 0.2$$

3-D equation

$$\frac{\partial c}{\partial t} - \frac{\partial}{\partial z} w_s c = \frac{\partial}{\partial z} \left(E_z \frac{\partial c}{\partial z} \right)$$

Vertical integration

$$h \frac{\partial \bar{c}}{\partial t} = \underbrace{\left[w_s c + E_z \frac{\partial c}{\partial z} \right]_{surf}}_{=0} - \left[w_s c + E \frac{\partial c}{\partial z} \right]_{bot}$$

Vertically well-mixed conditions, cont'd

No resuspension ($\alpha = 0$)

$$\frac{d\bar{c}}{dt} = -\frac{w_s \bar{c}}{h}$$

$$\bar{c} = c_o \exp(-w_s t/h)$$

c_o = initial depth-averaged concentration

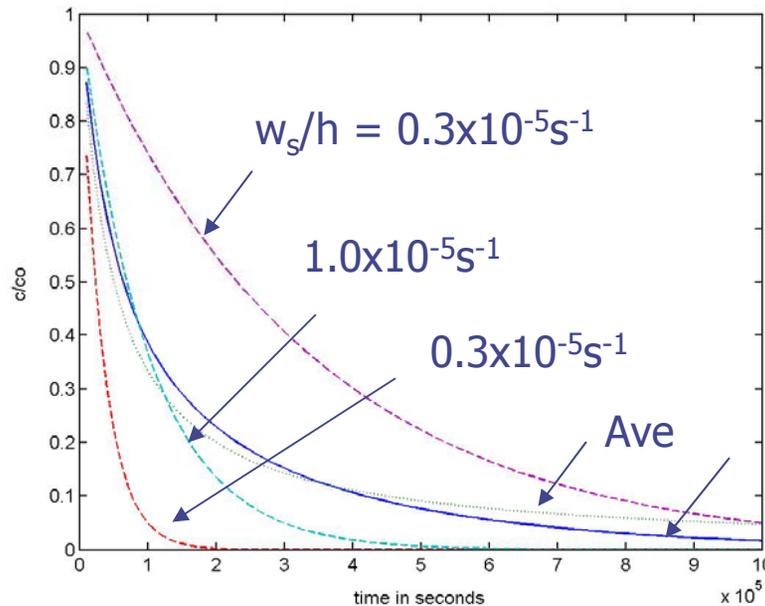
w_s/h = first order removal rate, κ_s

Partially-mixed conditions sometimes analyzed using $\kappa_s > w_s/h$ (because near bottom concentrations are greater than c_o)

Multiple size fractions

$$\frac{d\bar{c}}{dt} = -\sum_i \frac{w_s c_i}{h}$$

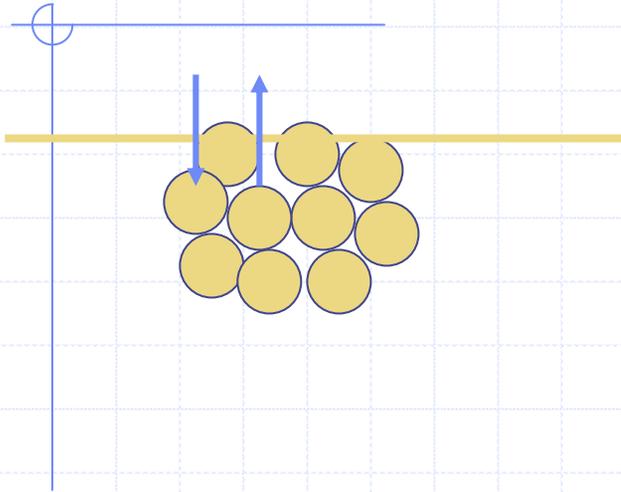
First order settling of different size fractions can resemble second order settling:



$$c = \frac{c_o}{1 + Btc_o}$$

2nd O settling ($Bc_o = 3 \times 10^{-4} \text{ s}^{-1}$)

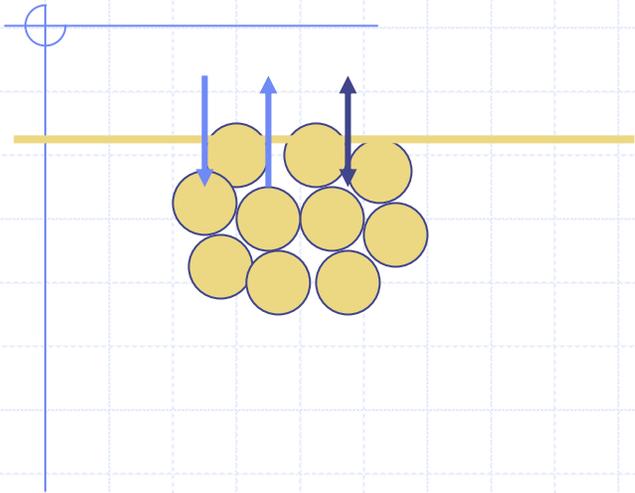
Contaminant transport within & across the sediment bed



Porewater advection (GW movement; sediment compaction; wave or bedform induced pressures; bioturbation)

$$J_a = \phi u c_d$$

Contaminant transport within & across the sediment bed



Porewater advection (GW movement; sediment compaction; wave or bedform induced pressures; bioturbation)

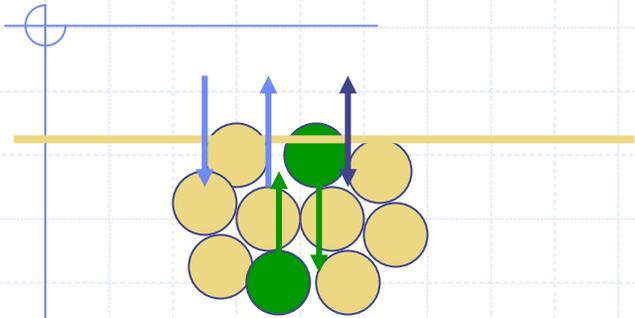
$$J_a = \phi u c_d$$

Porewater diffusion

$$J_d = -\phi D' dc_d / dz$$

$$D' = \phi D_m$$

Contaminant transport within & across the sediment bed



Porewater advection (GW movement; sediment compaction; wave or bedform induced pressures; bioturbation)

Bulk sediment motion ("turbulence")

$$J_b = -D_b d(c_d + \rho_s c_s) / dz$$

$$J_a = \phi u c_d$$

Porewater diffusion

$$J_d = -\phi D' dc_d / dz$$

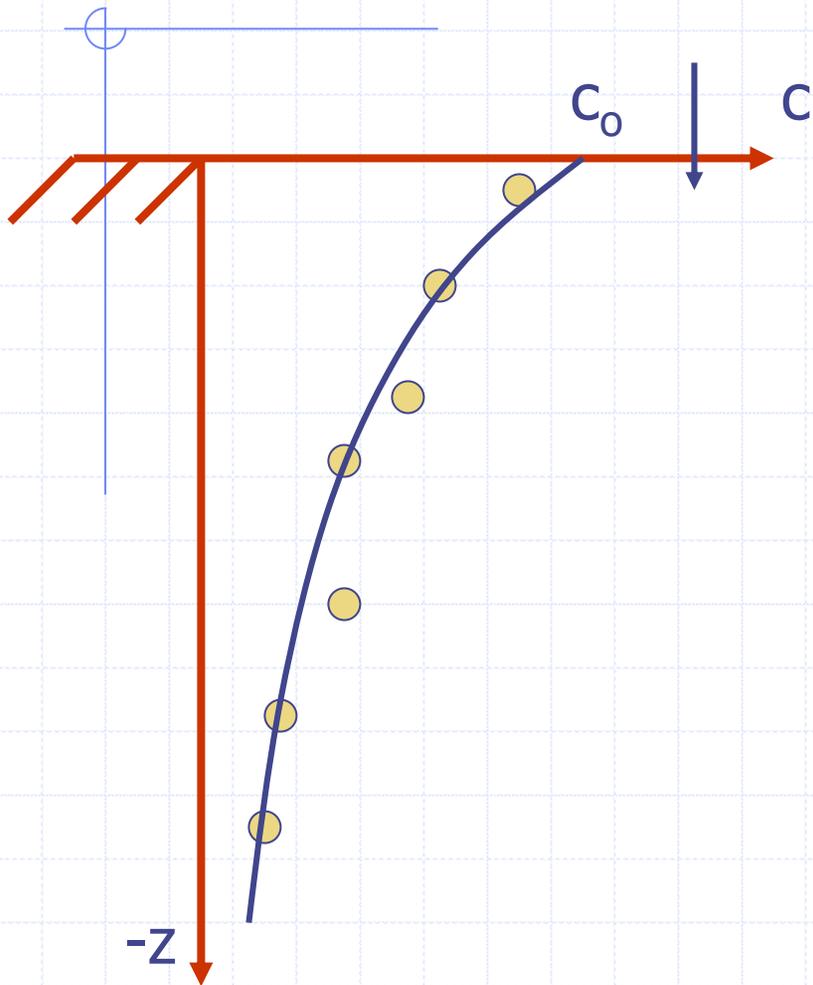
$$D' = \phi D_m$$

Sediment Profile Imaging



- ◆ Benthic fauna mix dissolved oxygen and other sediment characteristics (oxygen rich areas are light colored)
- ◆ Note feeding tubes near surface

Measuring bioturbation with ^{234}Th



Th-234 particle reactive tracer (c); $t_{1/2} \sim 24.1$ day

Relative to (moving) interface, steady state, including sediment mixing

$$-w_o \frac{dc}{dz} = D_b \frac{d^2c_s}{dz^2} - \lambda c$$

For $D_b \lambda \gg w_o$

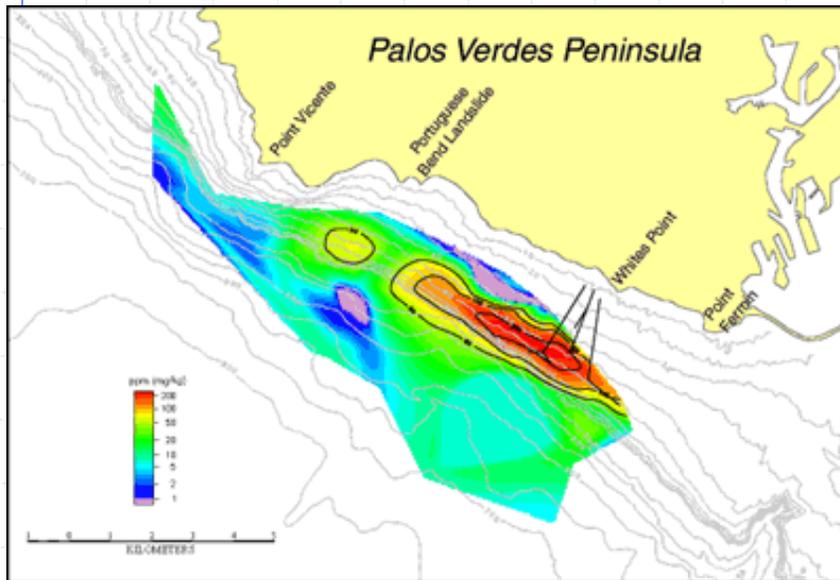
$$0 = D_b \frac{d^2c_s}{dz^2} - \lambda c$$

$$\frac{c}{c_o} = \exp(-\sqrt{\lambda/D_b} z)$$

Comments

- ◆ D_b correlates with w_o (reflecting flux of organic matter)
- ◆ Coastal sediments: $D_b = 10^{-7}$ to 10^{-6} cm^2/s
- ◆ Deep sea sediments: 10^{-9} to 10^{-8} cm^2/s

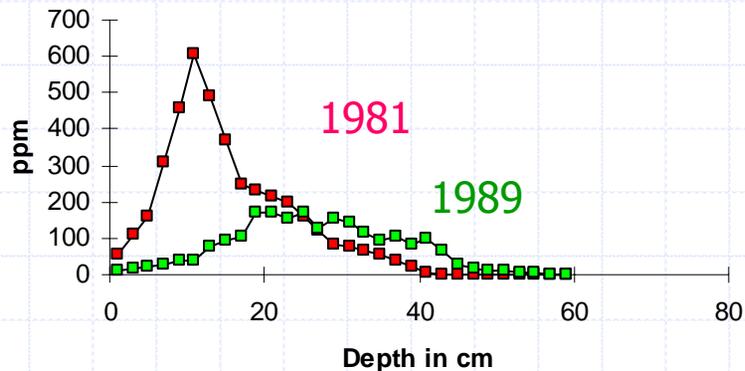
DDT on Palos Verdes Shelf (WE 9-4)



- ◆ DDT commonly used pesticide until 1970s (**Silent Spring**).
- ◆ ~ 1700T discharged by LACSD's White Point outfall (60m depth) (**also agricultural run-off**)
- ◆ ~100T (p-p'-DDE) still buried in sediment
- ◆ Issues of environmental racism
- ◆ EPA Superfund Site (Montrose Chemical Co.)

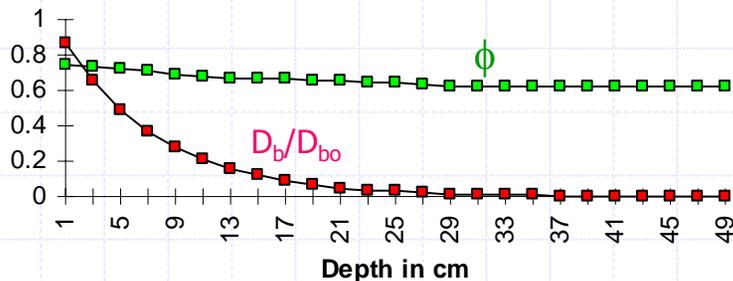
Vertical Profiles

Core 8C 1981 (solid) to 1989 (open)



Concentration vs depth
(USGS; Lee, 1994)

Vertical distribution of porosity (open squares) and bioturbation coefficient (closed squares)

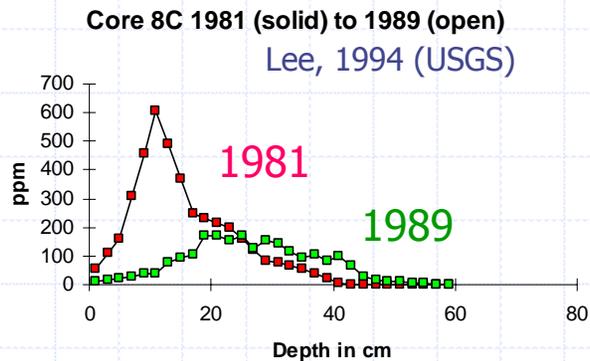


Exponential distribution
of porosity and
bioturbation (latter based
on worm density)

Issues

- ◆ Contamination slowly decreasing. But is it biodegradation or surface loss?
- ◆ Will natural sedimentation cap contaminants? Decreasing since WWTP upgrade; introduce clean sediments from flood control reservoirs?
- ◆ Current strategy of institutional controls (public outreach, fish monitoring, etc.) Is this enough?
- ◆ Possible future capping. Will this work? (2000 pilot capping failed.)

Sediment Fate Processes



- ◆ Deposition of clean sediment (deposition velocity w in cm/yr)
- ◆ Biological mixing (D_b in cm^2/yr)
- ◆ Biodegradation (1st O rate λ in yr^{-1})
- ◆ Release to surface (k in cm/yr)

$$J = k\rho_s(1-\phi)c_{so}$$

Mass Transport in Sediments

$$(1 - \phi) \rho_s \frac{\partial c_s}{\partial t} + \frac{\partial}{\partial \zeta} [w(1 - \phi) \rho_s c_s] = \rho_s \frac{\partial}{\partial \zeta} \left\{ D_b \frac{\partial}{\partial \zeta} [(1 - \phi) c_s] \right\} - \lambda(1 - \phi) \rho_s c_s$$

Boundary conditions

$$D_b \frac{\partial c_s}{\partial \zeta} = (k + w_o) c_s \quad \text{at} \quad \zeta = 0$$

ζ = depth below
(moving) sediment bed

$$c_s = 0 \quad \text{at} \quad \zeta = \infty$$

Use observations to calibrate unknown parameters w , D_b , λ and k

Simplification

$$\frac{\partial c_s''}{\partial t} + \frac{\partial}{\partial \zeta} (w_o c_s'') = D_{bo} \frac{\partial}{\partial \zeta} [e^{-\zeta/L} \frac{\partial}{\partial \zeta} c_s''] - \lambda c_s''$$

where

$$c_s'' = (1 - \phi) c_s / (1 - \phi_o)$$

$$w_o = w(1 - \phi) / (1 - \phi_o)$$

$$D_b = D_{bo} e^{-\zeta/L}$$

Spatial Moments

$$M_i = \int_0^{\infty} c_s \zeta^i d\zeta \quad M_i' = \int_0^{\infty} c_s e^{-\zeta/L} \zeta^i d\zeta \quad M_i'' = \int_0^{\infty} c_s'' \zeta^i d\zeta \quad M_i''' = \int_0^{\infty} c_s''' e^{-\zeta/L} \zeta^i d\zeta$$

$$\frac{dM_o''}{dt} = -kc_{so} - \lambda M_o''$$

4 moment equations
in 4 unknowns

$$\frac{dM_1''}{dt} - w_o M_o = D_{bo} c_{so} - \frac{D_{bo}}{L} M_o''' - \lambda M_1'$$

$$\frac{dM_2''}{dt} - 2w_o M_1 = 2D_{bo} M_o''' - \frac{2D_{bo}}{L} M_1''' - \lambda M_2''$$

$$\frac{dM_3''}{dt} - 3w_o M_2 = 6D_{bo} M_1''' - \frac{3D_{bo}}{L} M_2''' - \lambda M_3'''$$

$$w_o = 1.7 \text{ cm/yr}, D_{bo} = 44 \text{ cm}^2/\text{yr}, \lambda = 0.03 \text{ yr}^{-1}, k = 9.6 \text{ cm/yr}.$$

Surface loss $\lambda \overline{M_o''}$ and degradation loss $\overline{kc_{so}}$
comparable; times scale of each ~ 30 yrs

Sediment water exchange model

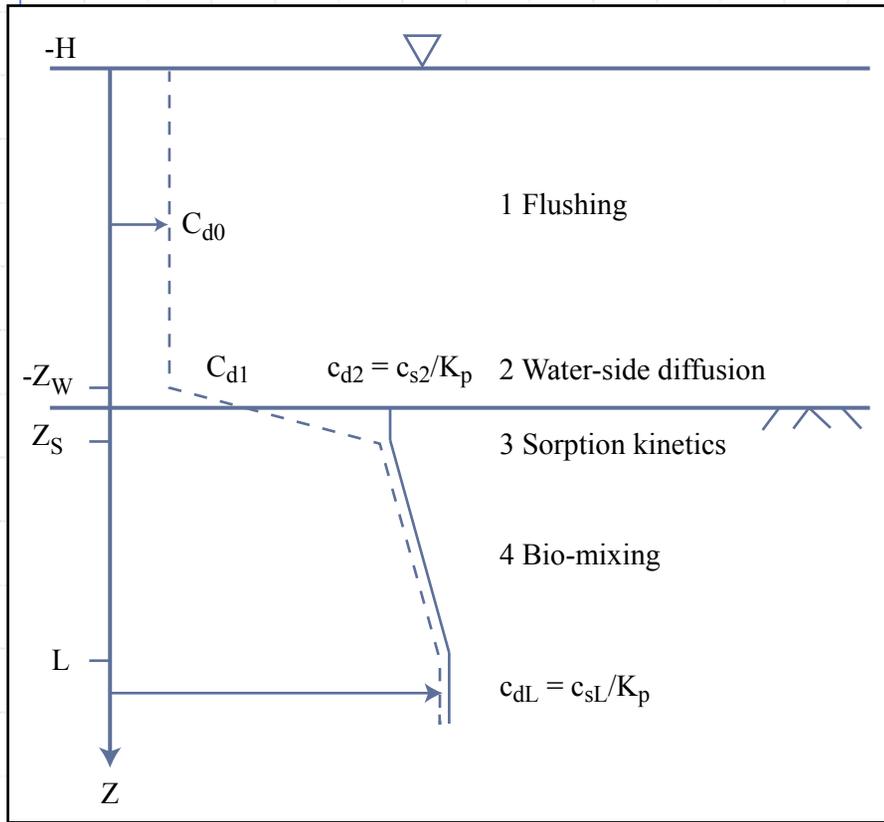


Figure by MIT OCW.

- ◆ Steady state
- ◆ Includes bioturbation, pore-water diffusion and sorption kinetics, but no resuspension, deposition or bio-degradation
- ◆ Colloidal transport included but not described here
- ◆ Applied to PAH's in Boston Harbor

Sediment water exchange model

$$0 = (D_b + D') \frac{d^2 c_d}{dz^2} + \frac{\kappa}{K_p} (c_s - K_p c_d) \quad \text{dissolved}$$

$$0 = D_b \rho \frac{d^2 c_s}{dz^2} + \frac{\kappa}{K_p} (K_p c_d - c_s) \quad \text{sorbed}$$

Boundary Conditions

$$c_d = c_{d1} \quad dc_s/dz = 0 \quad \text{at } z = 0$$

$$c_d K_p = c_s = c_{sL} \quad \text{at } z = L$$

Approximate Solution

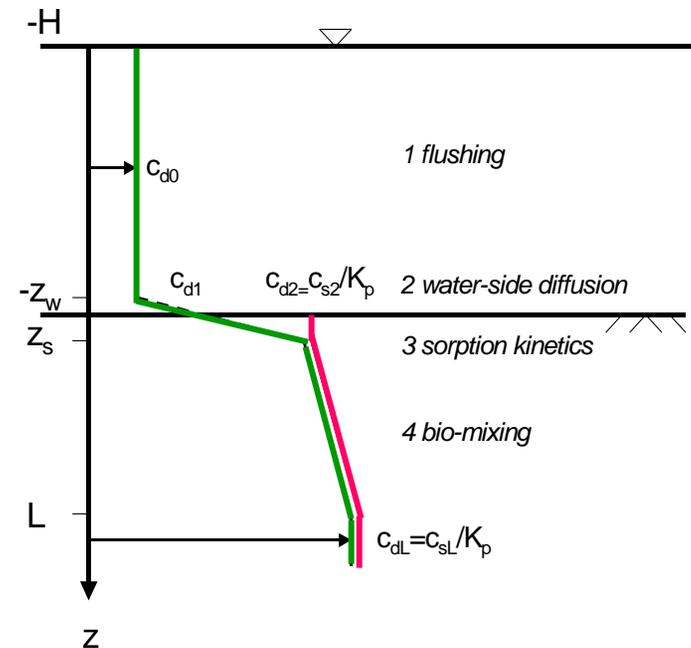
$$\frac{c_d - c_{d1}}{c_{sL}/K_p - c_{d1}} = \frac{1 - e^{-rz} + \varepsilon rz}{1 + \varepsilon rL}$$

$$\frac{c_s - K_p c_{d1}}{c_{sL} - K_p c_{d1}} = \frac{1 + \varepsilon(rz + e^{-rz})}{1 + \varepsilon rL}$$

$$c_{d1} = \frac{\phi(D_b + D')c_{s\infty} / K_p + (1 + \varepsilon rL)(D_m / \delta_w)c_{d0}}{(1 + \varepsilon rL)(D_m / z_w) + \phi(D_b + D')r}$$

$$r = \sqrt{\kappa / (D_b + D')}$$

$$\varepsilon = \frac{(D_b + D')}{\rho K_p D_b}$$



Flux to surface

Dissolved phase concentration
in equilibrium with c_{sL}

$$J = \frac{c_{sL} / K_p}{\frac{\tau}{H} + \frac{z_w}{D_m} + \frac{2.2R}{(1-\phi)[(D_b + D')D_m\rho_s K_p]^{1/2}} + \frac{L}{(1-\phi)\rho_s D_b K_p}}$$

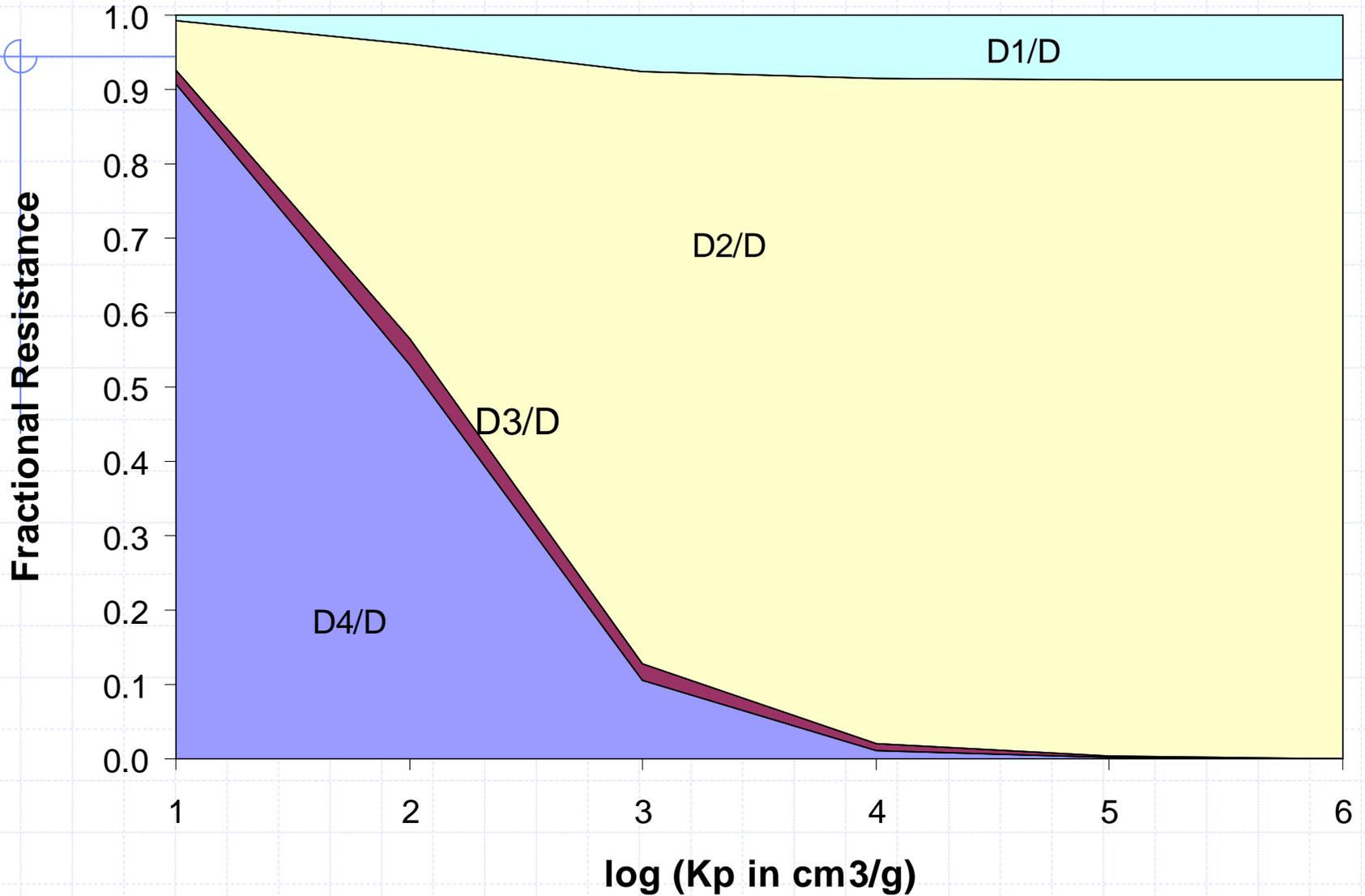
1 2 3 4

Denominator: 4 "resisters" in series: 1)
flushing, 2) water-side diffusion, 3)
sorption kinetics, 4) bio-mixing

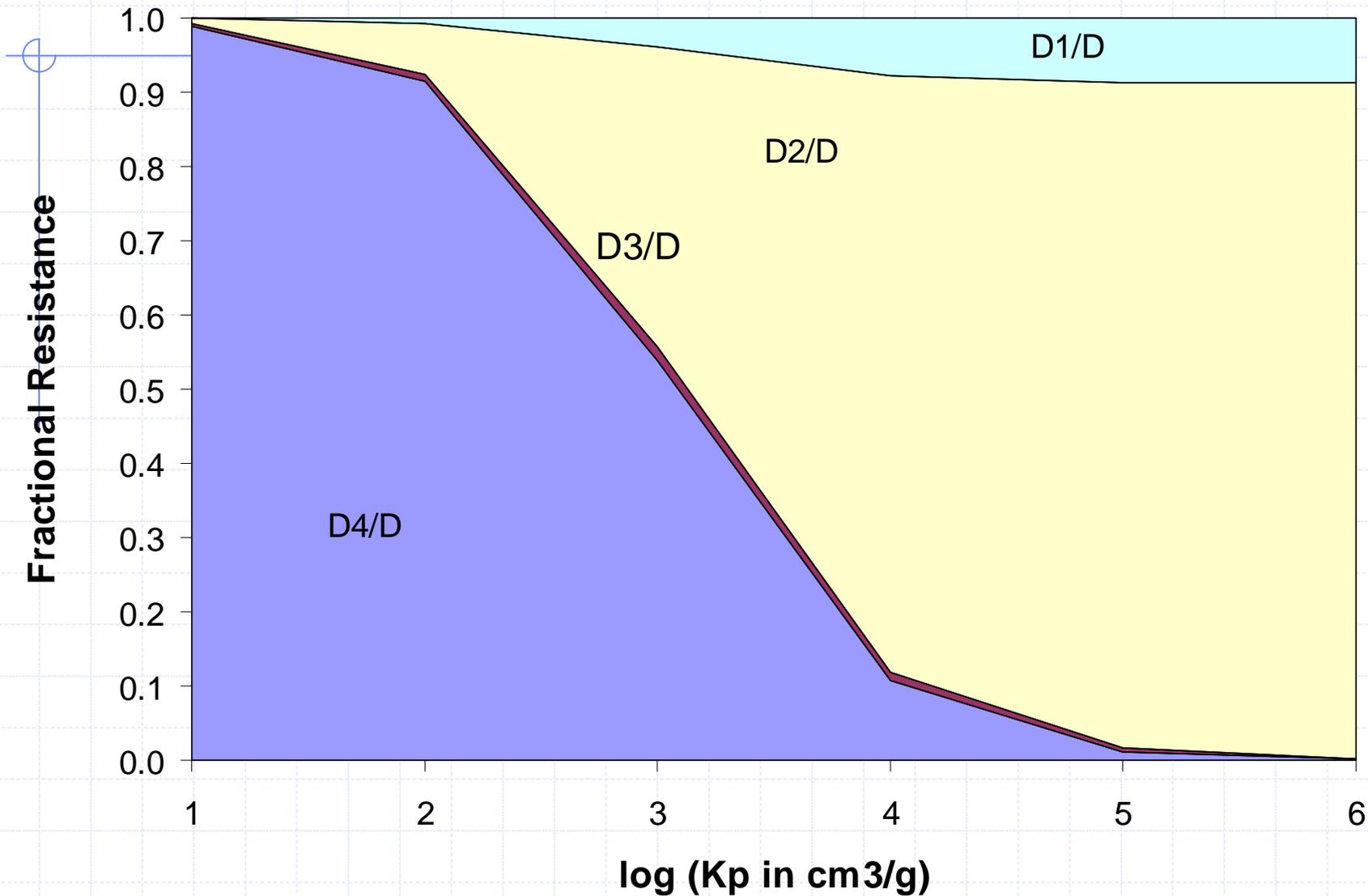
Parameters

Variable	Definition	Value(s)
D_m	Aqueous solution diffusivity	0.8×10^{-5} cm ² /s
D'	Aqueous solution diffusivity corrected for porosity	0.5×10^{-5}
D_b	Bioturbation coefficient	10^{-7} , 10^{-6} , 10^{-5} cm ² /s
K_p	Solid-water partition coefficient	10^1 to 10^6 cm ³ /g
L	Biologically active depth	5 cm
ϕ	Porosity	0.8
ρ_s	Sediment density	2.5 g/cm ³
	Sorbed concentration at $z = L$	10^{-6} g/g
R	Characteristic aggregate radius	0.01 cm
	Water-side boundary layer thickness	0.06 cm
	Hydrodynamic residence time of overlying water	5 day
H	Depth of overlying waterbody	6 m
	Desorption rate constant	Eq (9.5)

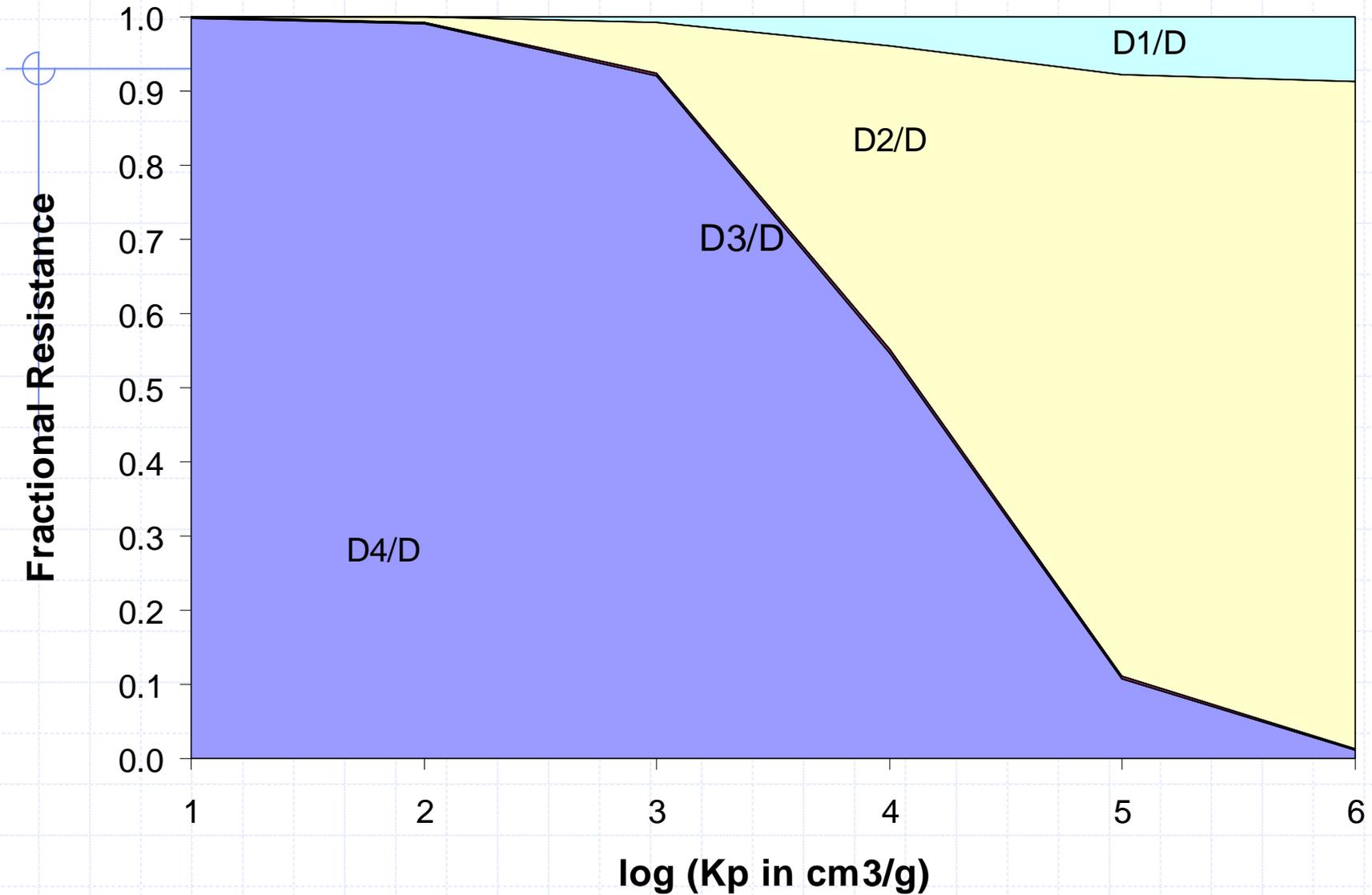
$D_b = 10^{-5} \text{ cm}^2/\text{s}$



$D_b = 10^{-6} \text{ cm}^2/\text{s}$



$Db = 10^{-7} \text{ cm}^2/\text{s}$



Comments

- ◆ Water side bl (2) controls for large K_p & D_b
- ◆ Bioturbation (4) controls for small K_p & D_b

(Resistance on side with smallest equilibrium concentration)

- ◆ Desorption not limiting factor
- ◆ Longest clean-up times for high K_p (nearly a century for benzo(a) pyrene ($K_p \sim 10^5$) in Boston Harbor)

Dealing with Contaminated Sediment

◆ Natural attenuation (**Let it sit**)

- If evidence of natural recovery (deposition, biodegradation)
- Or if other options problematic
- Combined w/ active monitoring & inst controls

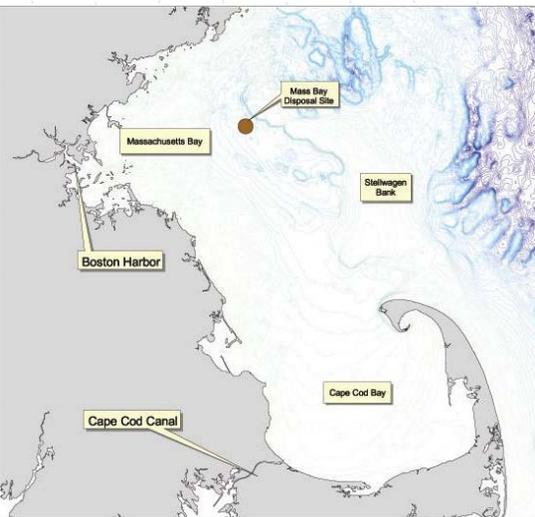
◆ Capping (**Cover it up**)

- With clean sediment
- *In situ* or in confined aquatic disposal (CAD) cells

◆ Dredging (**Remove it**)

- Environmental (remove contamination)
- Maintenance (keep harbors/channels open)
- Improvement (make harbors/channels deeper)

Boston Harbor Navigation Improvement Project



- ◆ Deepen to 38-40' (versus maintenance or environmental)
- ◆ 1.7×10^6 yd³ clay (MBDS)
- ◆ 1.1×10^6 yd³ silt (CAD cells)

Confined Aquatic Disposal Cells

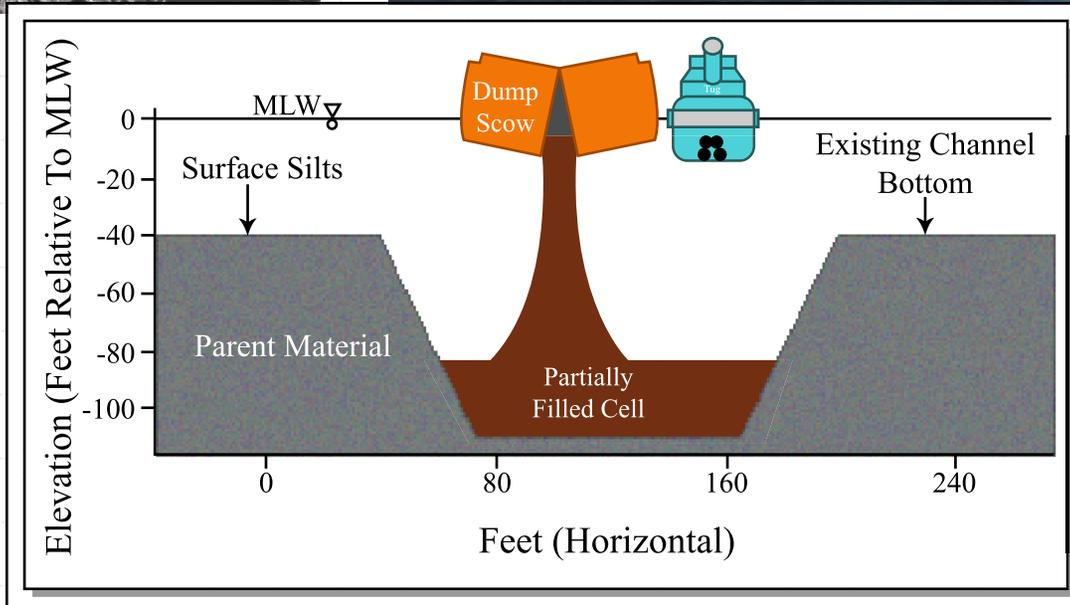


Figure by MIT OCW.

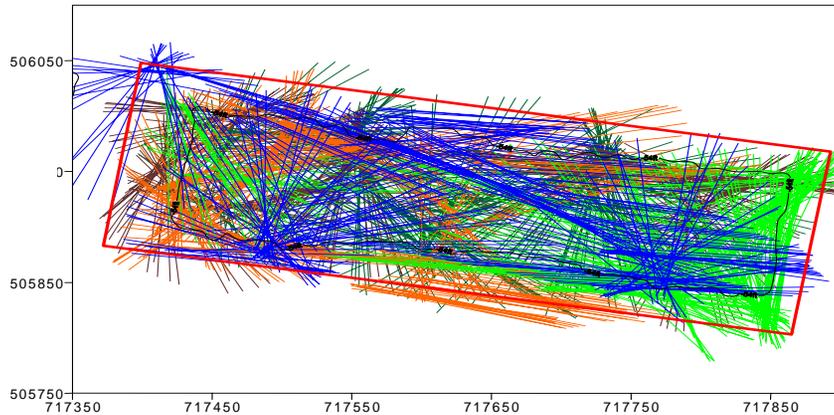
Dredge buckets



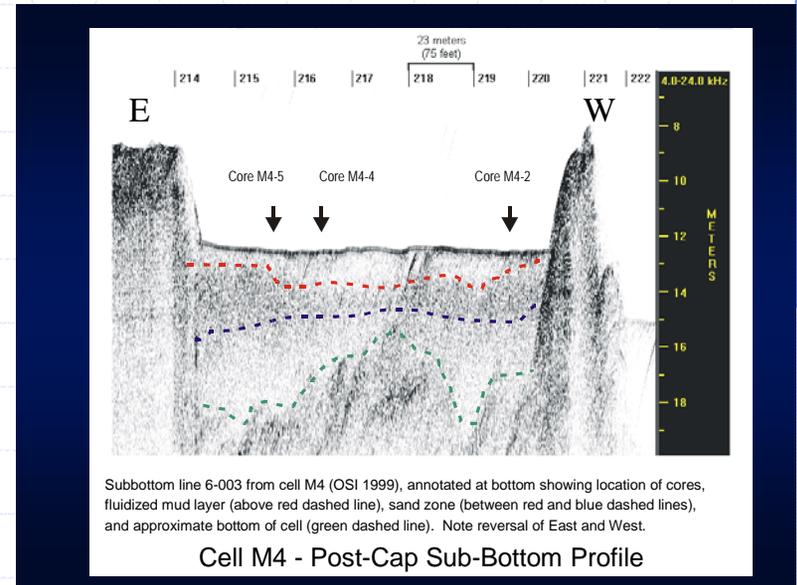
Environmental

Clam shell

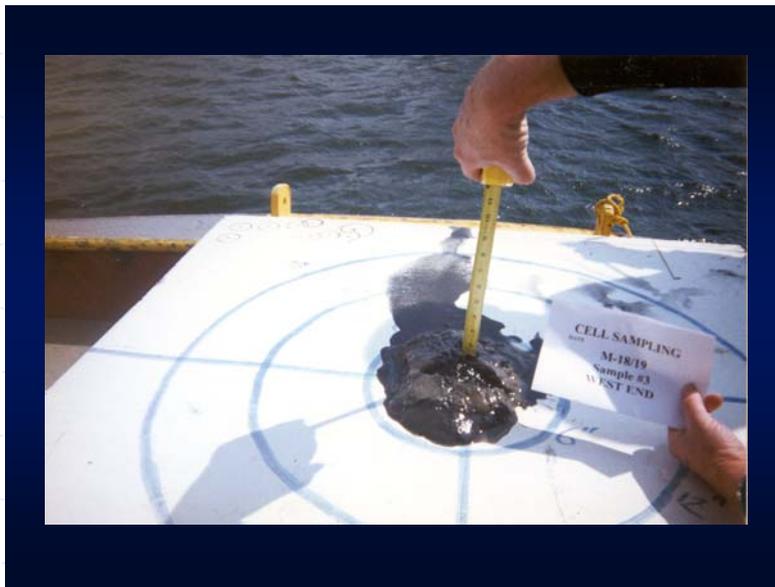
CAD Challenges



Hitting target



Verifying CAP integrity



Waiting for sufficient consolidation

Additional Issues

- ◆ Containing dredged and capping material (during descent & upon impact)
- ◆ Time of disposal (environmental windows to allow migrating fish passage)
- ◆ Residual silt (should you “rake all the leaves?”)
- ◆ Open cells (exposure to uncapped material)