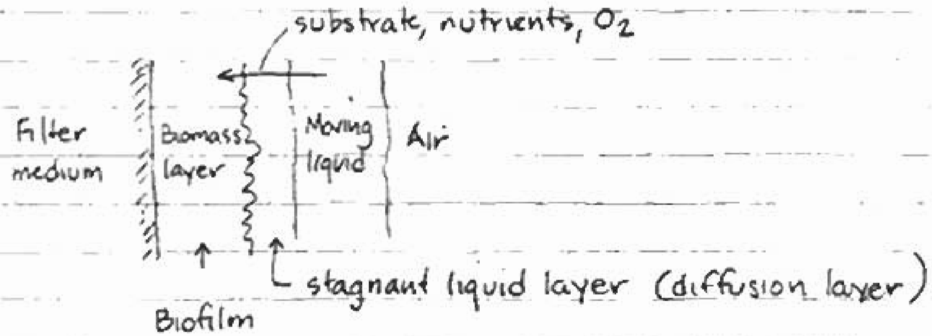
Lecture 19 - Attached Growth Processes

Whereas activated sludge is a "suspended growth" process, trickling filters and rotating biological contactors are "attached growth" processes.

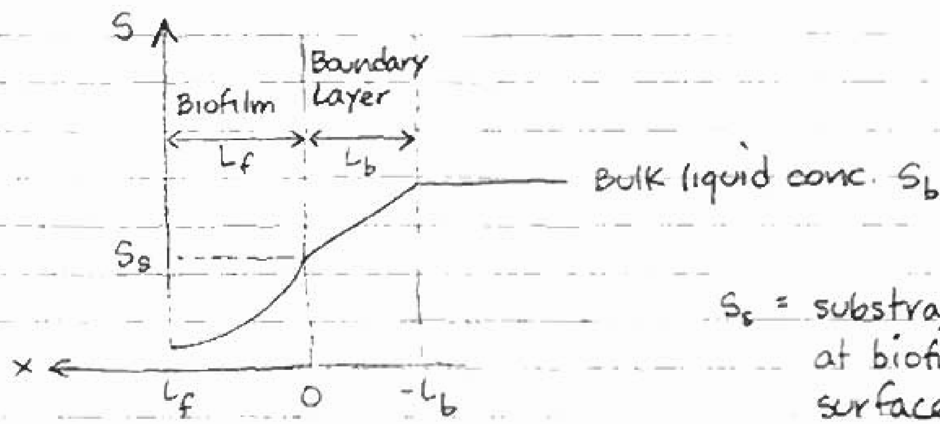
Wastewater trickles over medium

Bacteria grow on medium, creating biofilm:



10 μm to 10 mm thick

Substate conc:



S_s = substrate conc. at biofilm surface

Substrate, O_2, nutrients diffuse across stagnant boundary layer

Reactions are diffusion-limited - rate is limited by how much material diffuses through

Rate of substrate flux into biofilm:

$$r_{sf} = -D_w \frac{dS}{dx} = -D_w \frac{(S_b - S_s)}{L_b} \qquad (1)$$

r_{sf} = rate of substrate surface flux $\left[\frac{M}{L^2 \cdot T}\right]$

D_w = molecular diffusion coefficient for substrate in water $[L^2/T]$ (varies with substrate!)

dS/dx = substrate conc. gradient $[M/L^3 \cdot L]$

S_b = substrate conc. in bulk liquid $[M/L^3]$

S_s = substrate conc. at biofilm surface $[M/L^3]$

Within biofilm, rate of movement is

$$r_{bf} = -D_e \frac{dS}{dx} \qquad (2)$$

r_{bf} = rate of substrate flux $[M/L^2 \cdot T]$

D_e = effective molecular diffusion coeff in biofilm $(< D_w)$ $[M^2/T]$

Within biofilm, substrate is utilized for biological growth:

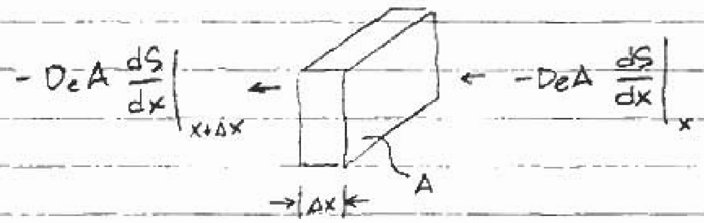
$$r_{su} = \frac{\mu_{max} S X}{Y (S + K_s)} \qquad (3)$$

r_{su} = rate of substrate utilization per unit vol. $[M/L^3 \cdot T]$

other notation same as in previous lectures

Mass balance for biofilm under steady-state:

Consider increment of Δx within biofilm:



$$\text{Change in mass} = 0 = - D_e A \left.\frac{dS}{dx}\right|_x + D_e A \left.\frac{dS}{dx}\right|_{x+\Delta x} - \Delta x A \left(\frac{\mu_{max} S X}{Y (K_s + S)} \right)$$

Divide by A and Δx:

$$D_e \frac{d^2 S}{dx} - \frac{\mu_{max}}{Y} \frac{SX}{K_s + S} = 0 \qquad (4)$$

Boundary conditions

At media surface, flux is zero:

$$D_e \frac{dS}{dx} = 0 \quad \text{at} \quad x = L_f \qquad (5)$$

At biofilm surface, flux is same as through boundary layer:

$$D_w \left.\frac{dS}{dx}\right|_{x=0} = D_e \left.\frac{dS}{dx}\right|_{x=0}$$

$$= \frac{D}{L_b} (S_b - S_s) \qquad (6)$$

Solution assuming $S \ll K_s$ (i.e. low concentrations)

$$D_e \frac{d^2S}{dx^2} - \frac{\mu_{max}}{Y} \frac{SX}{K_s} = 0 \qquad (7)$$

first-order decay

Solution is:

$$S = S_s \frac{\cosh((L_f - z)/\tau_1)}{\cosh(L_f/\tau_1)} \qquad (8)$$

$\tau_1 = \sqrt{D_e K_s Y / \mu_{max} X}$ = biofilm depth dimension [L]

Figure 4.2 from Rittman and McCarty, 2001. Environmental Biotechnology: Principles and Applications on page 5 shows solution

$L_f/\tau_1 > 1$ is a deep biofilm - substrate does not penetrate far

$L_f/\tau_1 \ll 1$ is a fully penetrated biofilm

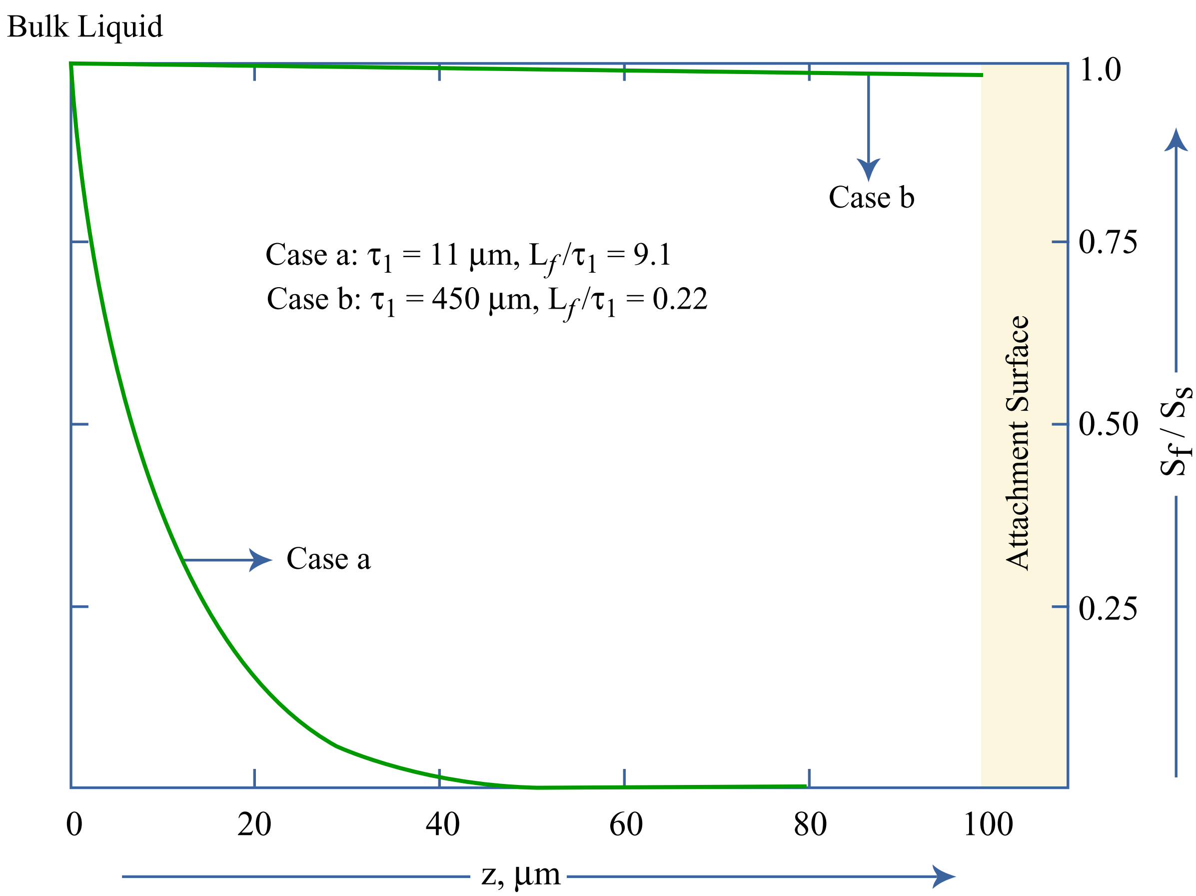
Rittman and McCarty give advice on parameter estimation as well as other solutions

$X \approx 40{,}000$ mg/L (vs 2,000 in AST)

$D_e \approx 0.8 D_w$

$L_f < 30\ \mu m \rightarrow$ "thin" biofilm

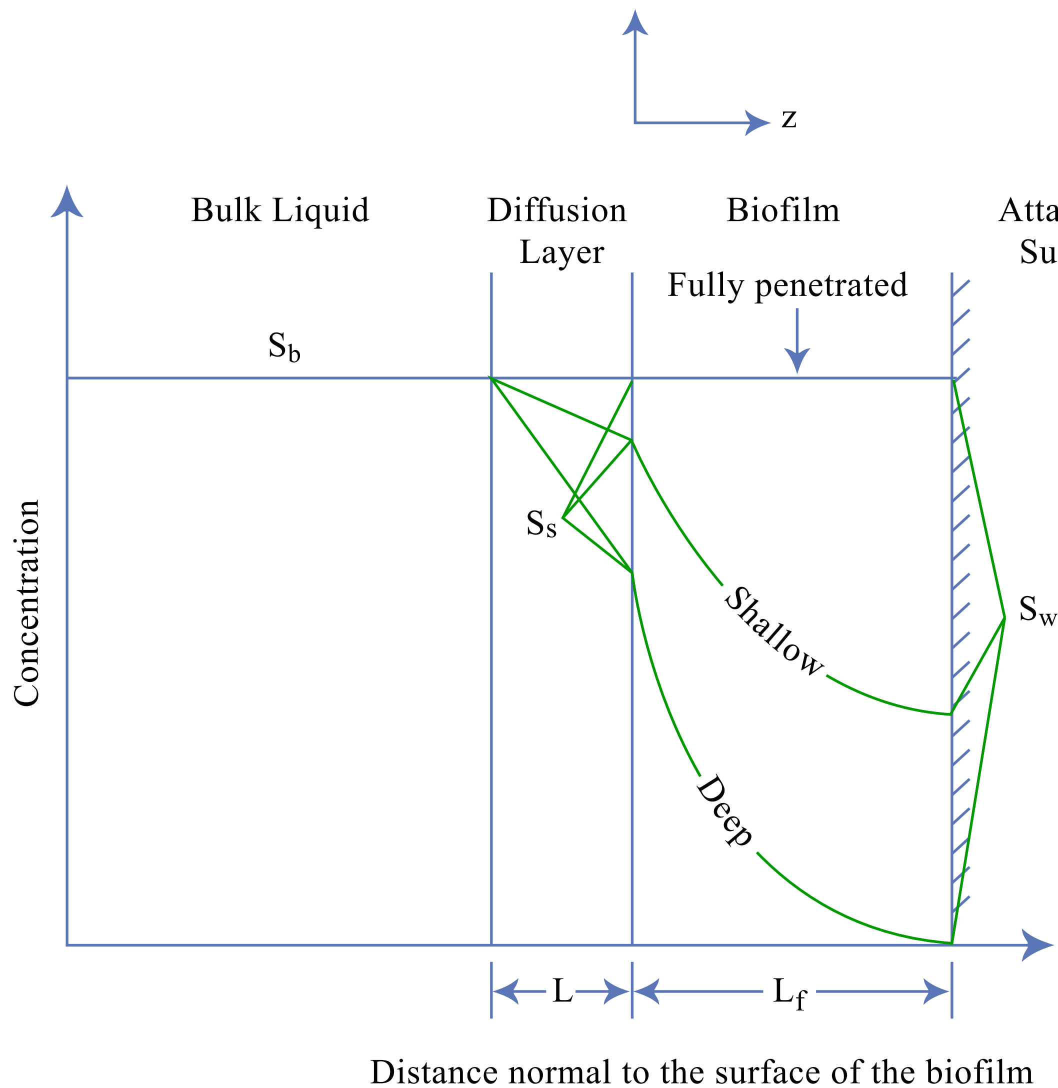
Page 6 shows deep, shallow, and fully penetrated conc distributions



Substrate concentration profiles for characteristic deep (case a) and nearly fully penetrated (case b) biofilms. The ratio L_f/τ determines if the biofilm is deep. Many values of k_1, D_f, and X_f can give the same τ_1 value, and Rittman and McCarty (2001) illustrate how this affects J_1.

Figure by MIT OCW.

Adapted from: Rittman, Bruce E., and Perry L. McCarty. *Environmental Biotechnology: Principals and Applications*. New York, NY: McGraw-Hill, 2001.



Characteristic Substrate Concentration Profiles within a Biofilm

Figure by MIT OCW.

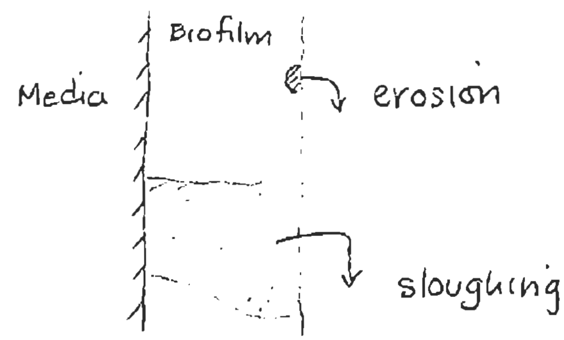
Adapted from: Suidan, M. T., B. E. Rittman, and U. K. Traegner. "Criteria establishing biofilm-kinetic types." *Water Research* 21, no. 4 (April 1987): 491-498.

Within the biofilm, this mass balance applies:

$$\frac{d\,(X_f dz)}{dt} = Y\,\mu_{max}\,\frac{S_f}{S_f + K_s}\,X_f dz - k_{loss}\,X_f dz \qquad (9)$$

dz = unit thickness of biofilm [L]
S_f = substrate conc within biofilm [M/L³]
X_f = biomass conc within biofilm [M/L³]
k_{loss} = overall loss rate for biofilm [1/T]

Biofilms lose mass constantly by erosion of small pieces and sloughing of large sections:



Can be generally captured as 1st-order process

Equation (9) can be integrated over full thickness of biofilm ($\int_0^{L_f} dz$) and set to steady-state conditions ($d/dt = 0$) to get, with substitutions (see Rittman & McCarty, 2001, pg. 214):

$$X_f L_f = \frac{JY}{k_{loss}} \qquad (10)$$

Biofilm thickness is thus:

$$L_f = \frac{JY}{X_f k_{loss}} \qquad (11)$$

equilibrium between cell growth due to inflowing substrate (JYX_f) and cell loss (k_{loss})

Modeling a biofilm reactor requires simultaneous solution of -

Substrate equation	(Eq. 4)
Flux into biofilm	(Eq. 6)
Biomass in biofilm	(Eq. 10)
Boundary conditions	(Eq 5 and 6)

Rittman and McCarty 2001 Figure 4.3 (pg 9) shows form of solution:

For $S_b < S_{b,min} = K_S \dfrac{k_{loss}}{Y\mu_{max} - k_{loss}}$ $\qquad J \to 0$

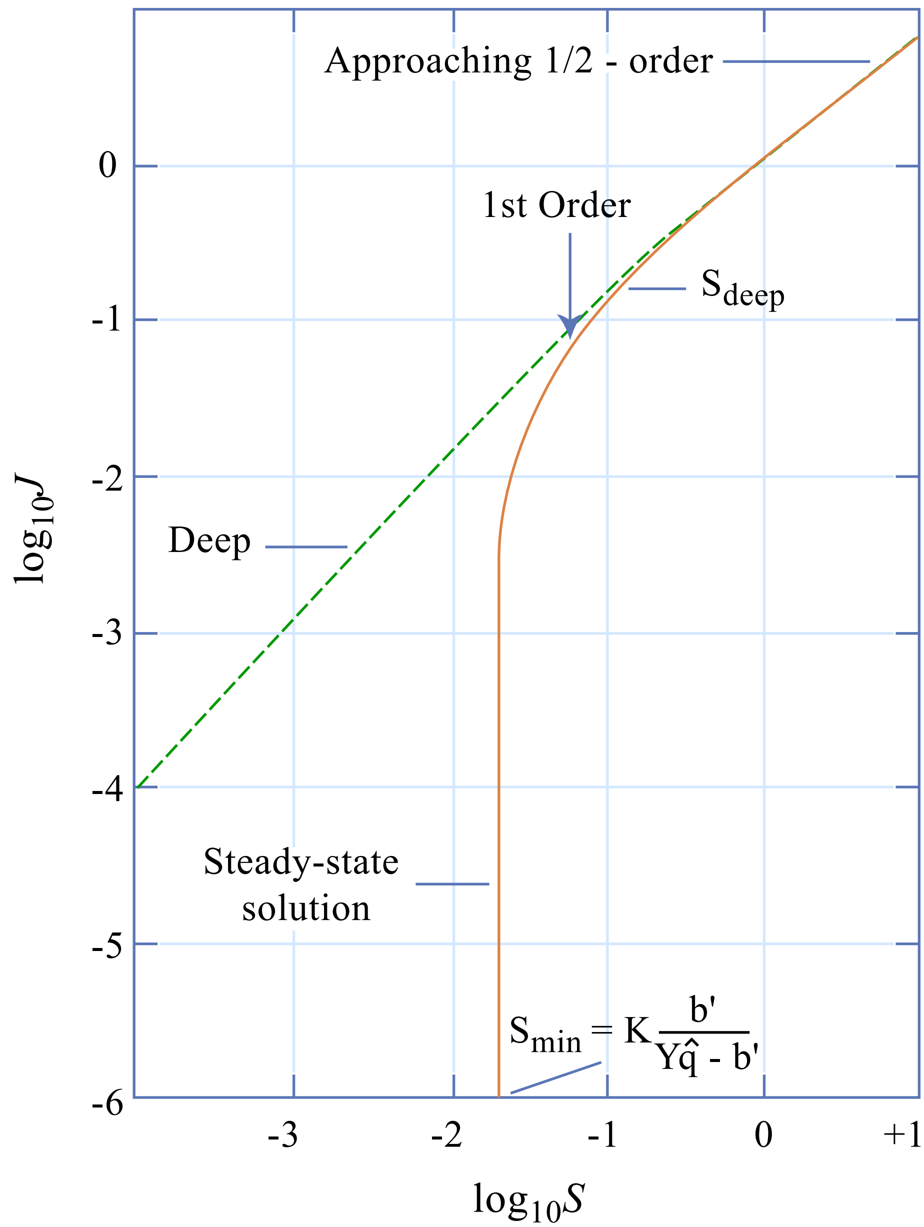
i.e. below a certain minimum substrate concentration, there is no biofilm

For $S_b \gg S_{b,min}$, biofilm is "deep"

$S_f \approx 0$ in inner biofilm

$J \propto S^{1/2}$ "half-order kinetics"

We look at applying these concepts to biofilm reactor design after first looking at the traditional biofilm reactor — the trickling filter



Typical response of a steady-state biofilm to changes in *S*. For this example, $S_{min} = 0.0204\ mg/cm^3$. *S* has units mg/cm^3, and *J* has units mg/cm^2-d.

Figure by MIT OCW.

Adapted from: Rittman, B. E., and P. L. McCarty. *Environmental Biotechnology: Principles and Applications*. Boston, MA: McGraw-Hill Higher Education, 2001.

Biofilms are the means of treatment in trickling filters and rotating biological contactors (RBCs)

Trickling "filters" are not actually filters

Tank with rock packing (historically) or plastic packing (now more common)
Wastewater is sprayed on top of packing, and trickles down getting biofilm treatment in the process - Page 11

Technology has been in use since early 1900s
Plastic packing since 1950s - higher loading rates and deeper tanks made possible

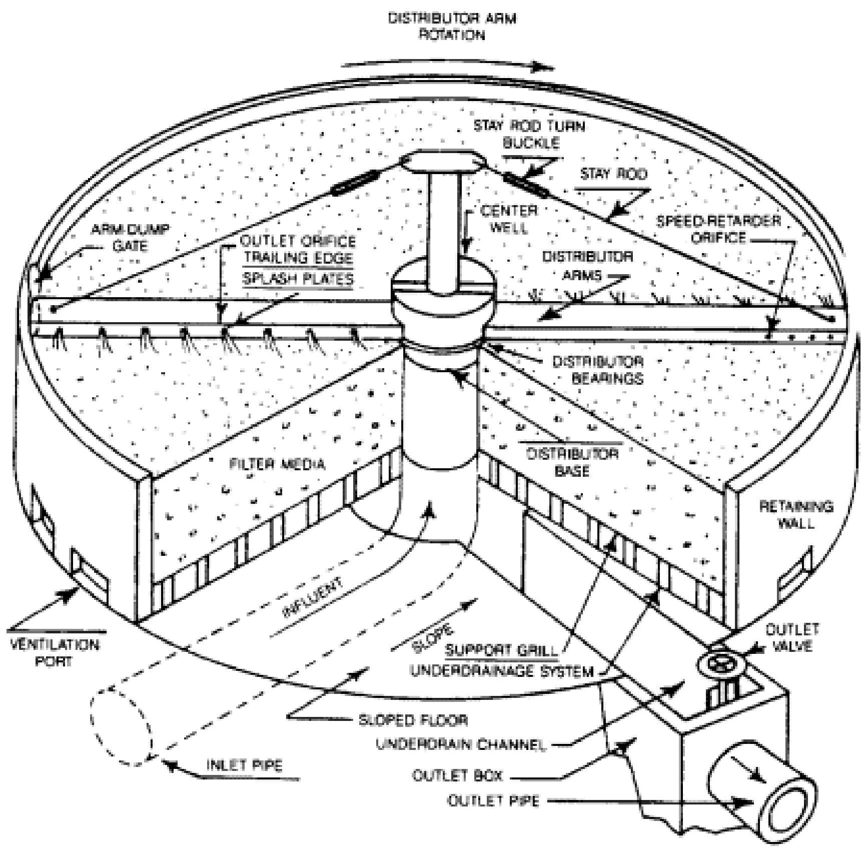
Page 11 shows view of trickling filter
Wastewater distributed by rotating spray arm (distributor)
Spray arm is pushed by jet action of sprays - Page 12

Advantages: (over AST)
- less energy needed
- simpler operation
- no bulking sludge problems
- better sludge thickening
- less O&M
- withstands shock toxic loads

Disadvantages:
- poorer effluent quality
- sensitive to low temp
- produces odors
- sloughing events can create lots of sludge in short time
- filter flies (psychoda)
- nitrogen removal is difficult

Most of these can be overcome with better design

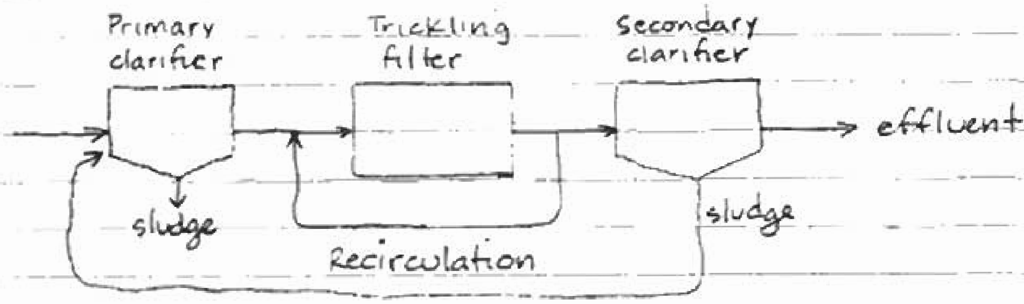
Trickling filter



Source: U.S. EPA, 2000. Wastewater Technology Fact Sheet: Trickling Filters. Report No. EPA 832-F-00-014. Office of Water, U.S. Environmental Protection Agency, Washington, D.C. September 2000.

Image courtesy of Lakeside Equipment.
Image Source: http://www.lakeside-equipment.com/Large_Photos/trickle_large.htm.

Typical configuration



Recirc is used during low-flow periods (nighttime) to ensure biofilms don't dry out

Secondary clarifier sludge is usually sent to primary clarifier for re-settling and disposal

Other configurations include 2 stages, roughing filter before AST

Types of filters

Low-rate or standard-rate
- Rock filters - 1 to 3 m deep
- Loading rates - 2 to 20 lb BOD5 / 1000 ft^2·day
  - 0.08 to 0.32 kg BOD5/m^2·day
- Efficiency - 90-95% BOD removal
  - 12-25 mg BOD5/L in effluent

High-rate
- Rock or plastic packing - 1 to 2 m deep
- Loading - 20 to 60 lb BOD5/1000 ft^2·day
  - 0.32 to 1.0 kg BOD5/m^2·day
- Efficiency - 85-90% BOD removal
  - 20-30 mg BOD5/L

Super-rate (used as roughing filter before add'l treatment)
- Synthetic packing
- Loading - 50 to 380 lb BOD5/1000 ft^2·day
  - 0.8 to 6.0 kg BOD5/m^2·day

Filter is equipped with underdrain system much like rapid sand filter - see Figure 17.8 from Reynolds and Richards, 1995 on page 15

Design

Equations on page 7 established a minimum bulk-liquid substrate conc for successful operation

Trickling filters usually operate at 100 to 1000 times that conc - generally enough to create deep biofilms

BOD loading ranges over 2 to 10 $\frac{\text{kg BODu}}{1000\ m^2 \cdot d}$

Although biofilm phenomena are at the root of treatment, most design formula are largely empirical and ignore details of biofilms

Eckenfelder proposed an overall kinetic formula as:

$$-\frac{1}{X}\frac{dS}{dt} = kS \qquad (12)$$

= specific rate of substrate removal

k = empirical rate constant $[L^3/(M_{cells} \cdot T)]$

S = bulk liquid substrate conc. (dropping subscript b from earlier)

Integrate over height of filter to get:

$$S_{out} = S_{in}\, e^{-k\bar{X}t} \qquad (13)$$

$\bar{X}$ = average cell mass in filter $[M_{cells}]$

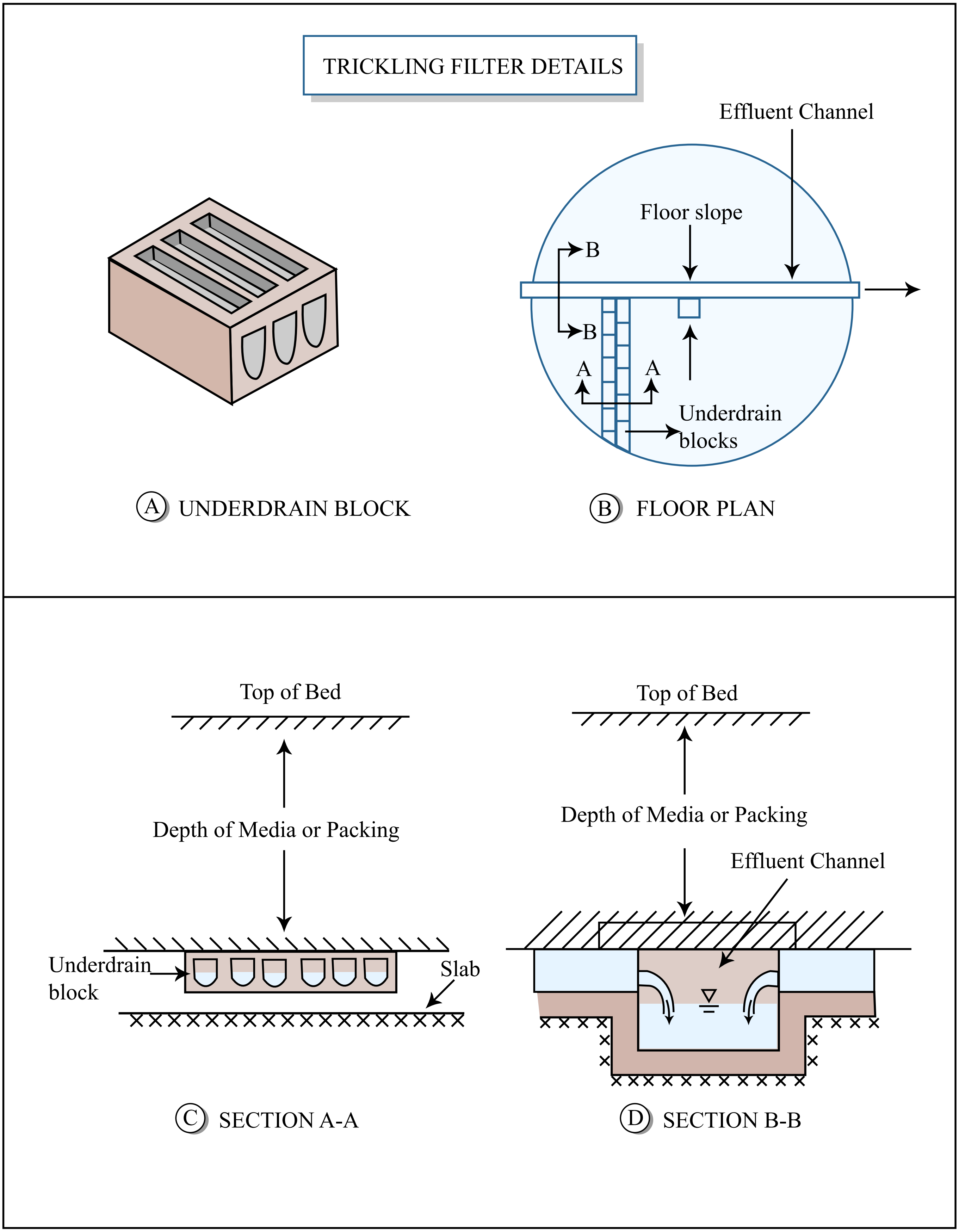


Figure by MIT OCW.

Adapted from: Reynolds, T. D., and P. A. Richards. *Unit Operations and Processes in Environmental Engineering*. 2nd ed. Boston, MA: PWS Publishing Company,1996, p. 543.

Assume: $\bar{X} \propto A_s$ specific surface area in filter $\left(\frac{\text{surface area}}{\text{volume}}\right)$

$$t = CD/Q_L^n$$

C, n = empirical constants $n \approx 0.5$
D = filter bed depth $[L]$
Q_L = loading rate $[L^3/L^2 \cdot T]$

$$\therefore \quad S_{out} = S_{in} \exp\left\{-\frac{K' A_s D}{Q_L^n}\right\} \qquad (14)$$

k' = empirical constant $= kC\frac{\bar{X}}{A_s}$

Further empirical modifications of this basic equation have been done. The design equation in most common use is the "modified Velz equation":

$$S_{out} = \frac{S_{in}}{(R+1)\exp\left\{\frac{k_{20} A_s D\, \theta^{T-20}}{[Q_L(R+1)]^n}\right\} - R} \qquad (15)$$

R = recirculation ratio (recycle flow rate divided by influent flow rate) $[-]$
k_{20} = filter treatability constant at 20° C $[(L^3/T)^{1/2}/L^2]$
A_s = packing specific surface area $[L^2/L^3]$
θ = temp. correction factor = 1.035
Q_L = hydraulic loading rate $[L^3/L^2 \cdot T]$
n = factor for filter packing (usually 0.5)

For rock towers, Nat'l Reseach Council (1946) formula:

$$E = \frac{100}{1 + 0.4432\sqrt{W_1/\forall F}} \qquad (16)$$

E = BOD removal efficiency (%)
W_1 = BOD loading rate (kg/d)
$\forall$ = filter packing volume (m^3)
F = recirculation factor

$$= \frac{1+R}{(1+R/10)^2}$$

R = recycle ratio = $\frac{Q_R}{Q}$ (usually 0 to 2)

Rotating biological contactors

Plastic discs rotated through tank of wastewater serve as medium for biofilm growth
(see pictures pg 18 & 19)

Developed in Germany in 1960s
Initially plagued by operational problems - now solved

Advantages: Low energy
Limited operator need
Short retention times
Handle flow variations
Low sludge production

Disadvantages: Sensitive to temp.
Shaft bearings and mechanical drive units must be maintained

Please point your browser to this link for an image of Rotating Biological Contractors (RBCs):
http://www.gmcanada.com/inm/gmcanada/english/about/MissionGreen/Daily/Oct06/O11.jpg

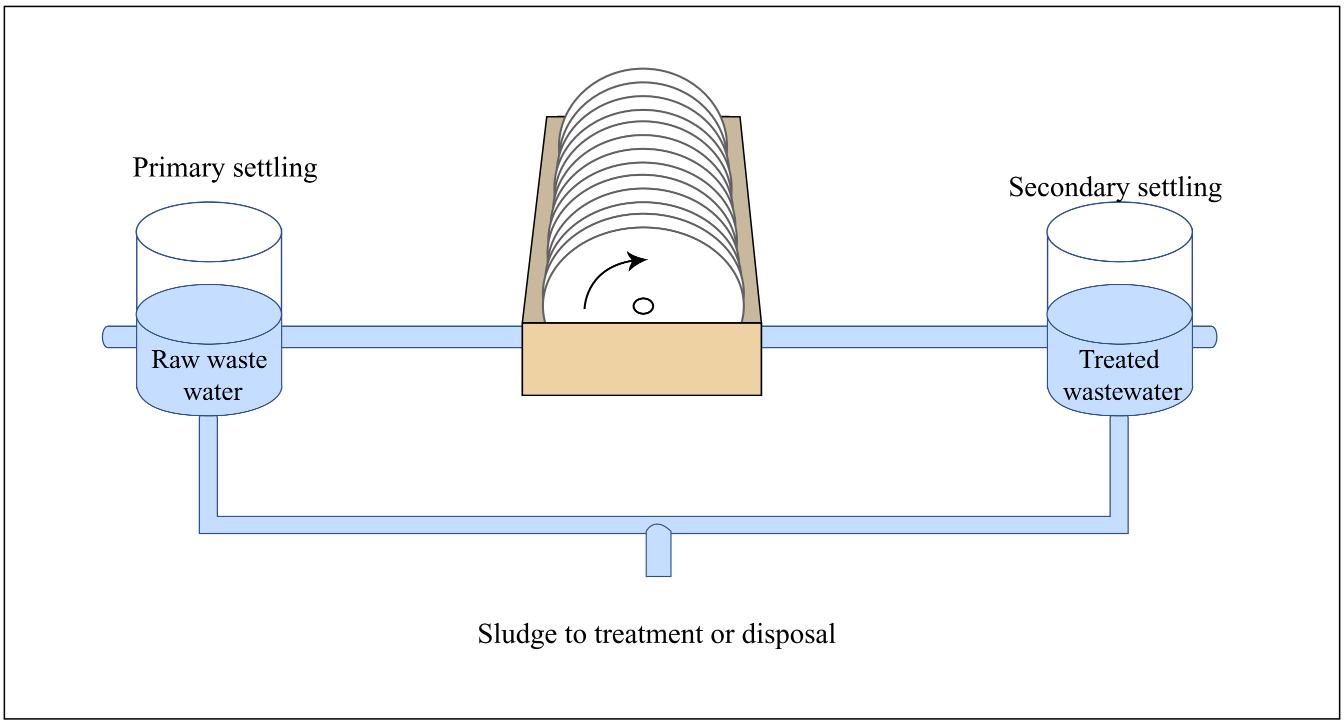


Figure by MIT OCW.

Adapted from Gonzalez, J. F. *Wastewater Treatment in the Fishing Industry*.

Final notes:

Biofilms are everywhere

A search on biofilm yields literature from
- wastewater treatment
- chemical engineering
- environmental water quality
- medicine
- dentistry (plaque on teeth is a biofilm)

Biofilms contribute to suspended media treatment

Polprasert has improved models of facultative lagoons by accounting for biofilm activity

(Water Science & Technology Vol 31 No 12 pp 119-128 1995
J. Env'l Engineering-ASCE Vol 124 No 9 pg 838 1998)