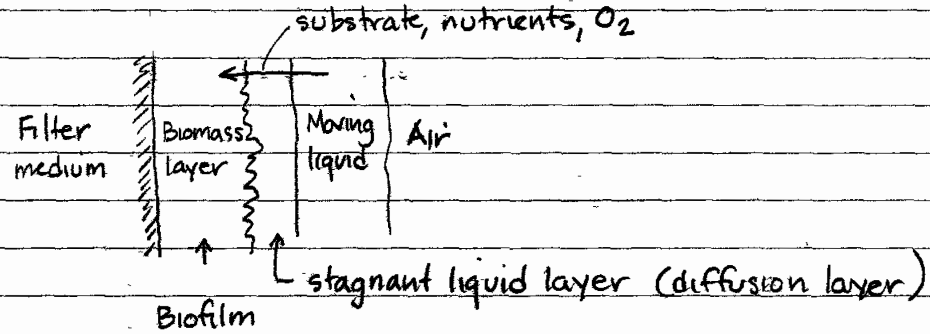
Lecture 21 – Trickling filters

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

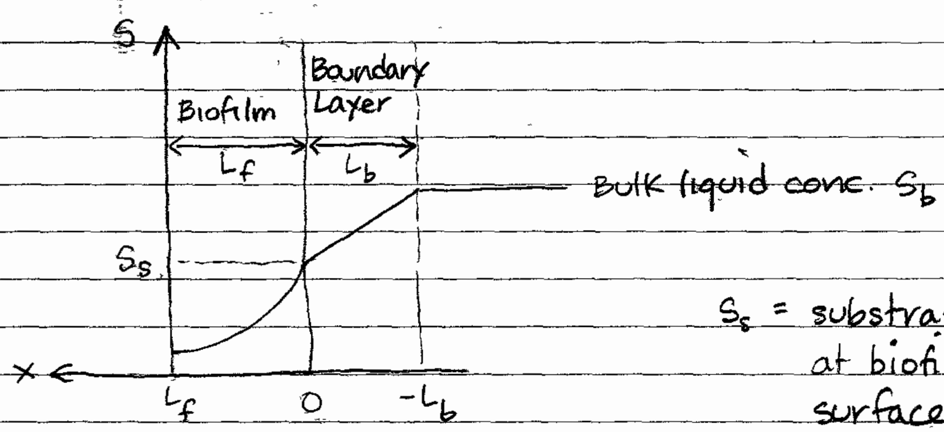
Wastewater trickles over medium

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:

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

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

D_W = molecular diffusion coefficient for substrate in water $[L^2/T]$

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

$$r_{bf} = -D_e \frac{dS}{dx}$$

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:

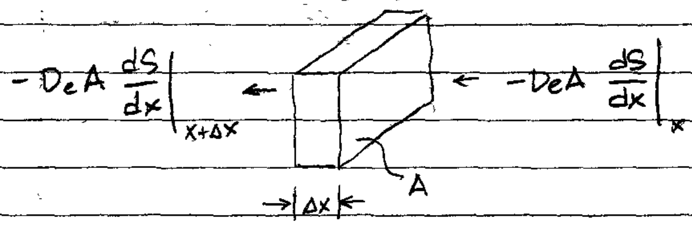
$$r_{su} = \frac{\mu_{max} S X}{Y (S + K_s)}$$

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

other notation same as in Lectures 16 & 17

Mass balance for biofilm under steady-state:

Consider increment of Δx within biofilm:



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

Divide by A and Δx:

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

Boundary conditions

At media surface, flux is zero:

$$D_e \frac{dS}{dx} = 0 \quad \text{at } x = 0$$

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

$$D_w \frac{dS}{dx}\Big|_{x=0} = D_e \frac{dS}{dx}\Big|_{x=0}$$

Solution assuming $S \ll K_s$

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

↑ first-order decay

Solution is :

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

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

Figure 4.2 from Rittman and McCarty, 2001. Environmental Biotechnology: Principles and Applications. on page 10 shows solution

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

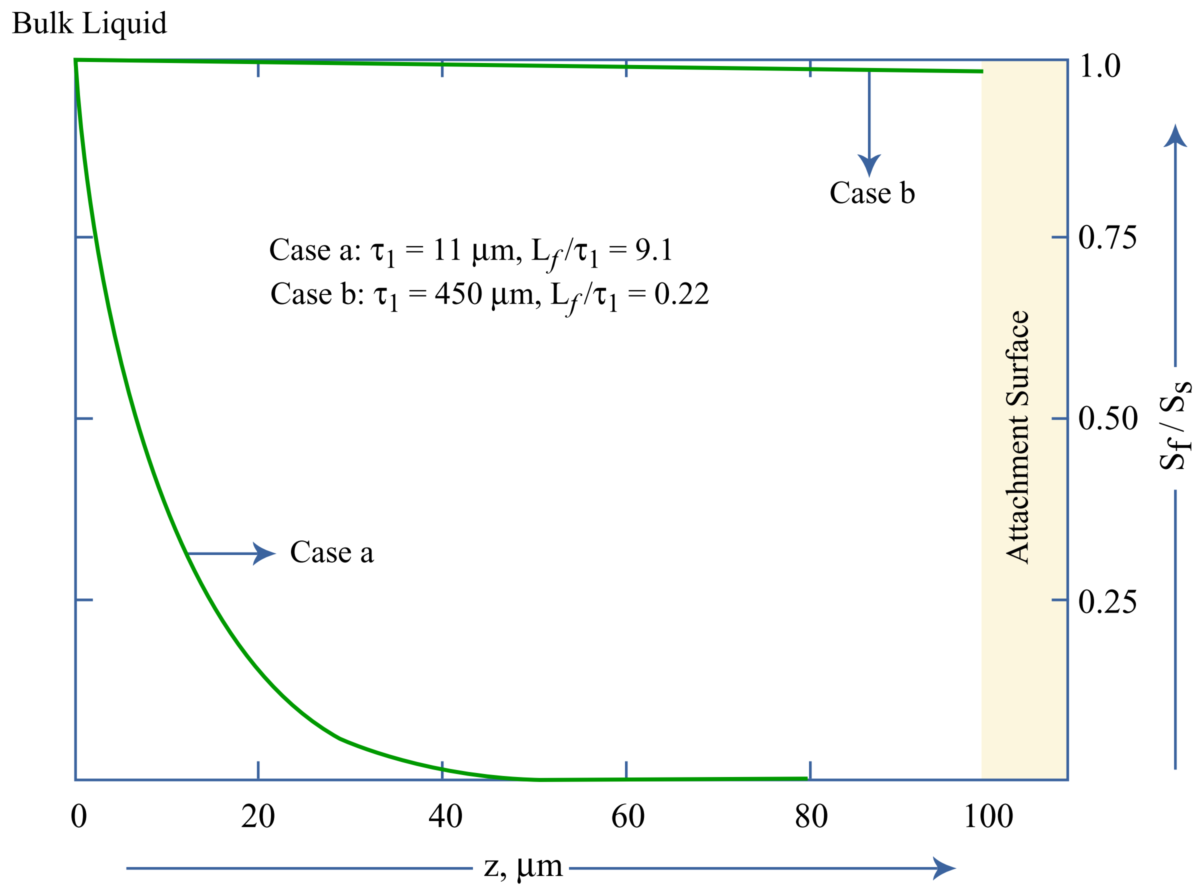
$L_f/\tau_1 \ll 1$ is a fully penetrated biofilm

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

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

$D_e \approx 0.8\, D_W$

$L_f < 30\ \mu m$ → "thin" biofilm



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.

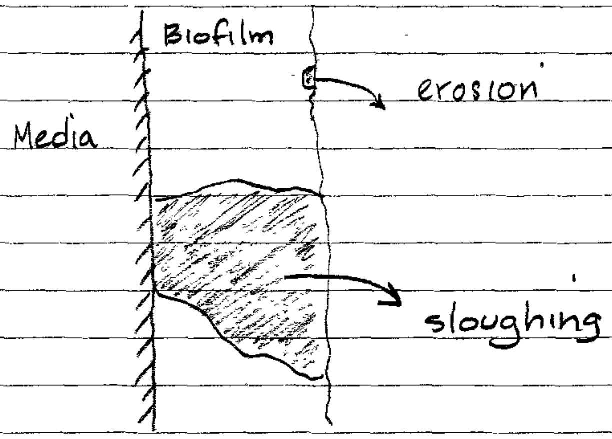
Solution of equation for $S \ll K_s$ in terms of flux:

$$J = \frac{D_e S_s \tanh(L_f / \tau_1)}{\tau_1}$$

J varies greatly with diffusion coefficient, rapidity of cell growth in biofilm, and thickness of biofilm

substrate may be limited by:
- reaction rates within biofilm or bulk liquid concentration - substrate limitation
- diffusion rates across stagnant liquid - surface flux limitations

Biofilms lose mass constantly due to erosion of small pieces or sloughing of large sections:



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

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

Page 13 shows view of trickling filter
Wastewater distributed by rotating spray arm (distributor)
Spray arm is pushed by jet action of sprays – Page 14

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

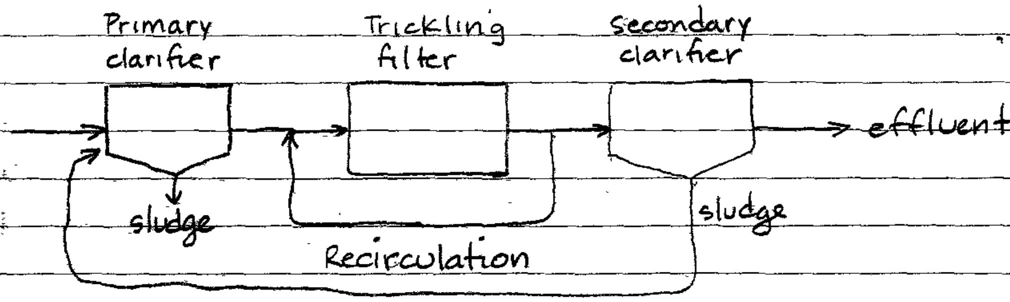
Disadvantages:
- poorer effluent quality
- sensitive to low temp.
- produces odors
- sloughing events can create lots of sludge in short time
- filter flies (psychoda)
- nitrogen removal is difficult

Most of these can be overcome with better design

Please point your browser to the following link to view a trickling filter image:
http://projects.andassoc.com/tomscreek/alternative/trickling_filters.htm

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 $ft^2 \cdot$ day
  - 0.08 to 0.32 Kg BOD5/ $m^2 \cdot$ 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 $ft^2 \cdot$ day
  - 0.32 to 1.0 Kg BOD5/ $m^2 \cdot$ 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 $ft^2 \cdot$ day
  - 0.8 to 6.0 Kg BOD5/ $m^2 \cdot$ day

Filter is equipped with underdrain system much like rapid sand filter – see Figure 17.8 from Reynolds and Richards, 1995 on page 17

Design

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

Kinetic equation for overall filter by Eckenfelder:

$$-\frac{1}{X}\frac{dS}{dt} = kS \quad \text{specific rate of substrate removal}$$

k = empirical rate constant $[L^3/M\,\text{cells}\cdot T]$

Integrate over tower to get:

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

$\bar{X}$ = average cell mass conc in tower

Assume $\bar{X} \propto A_s$ surface area in tower packing

Also contact time, $t = CD/Q_L^n$

C, n – empirical constants
D – depth of bed $[L]$
Q_L – loading rate $[L^3/L^2]$

$$\therefore \quad S_{out} = S_{in} \exp -\{KA_s^m D/Q_L^n\} = S_{in}\, e^{-KD/Q_L^n}$$

m – empirical const.
K – tower const determined by pilot studies

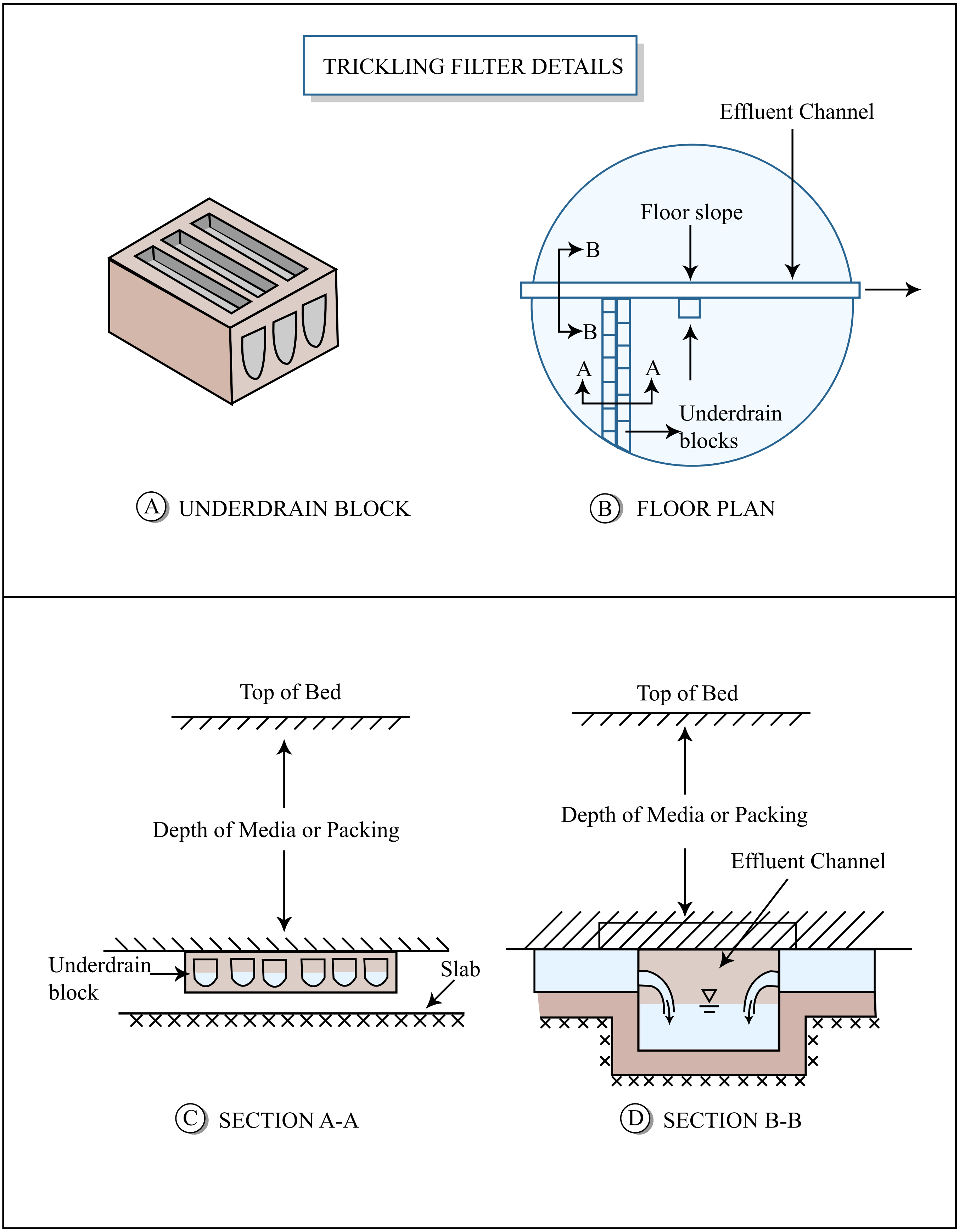


Figure by MIT OCW.

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.

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

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

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 picture, pg 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

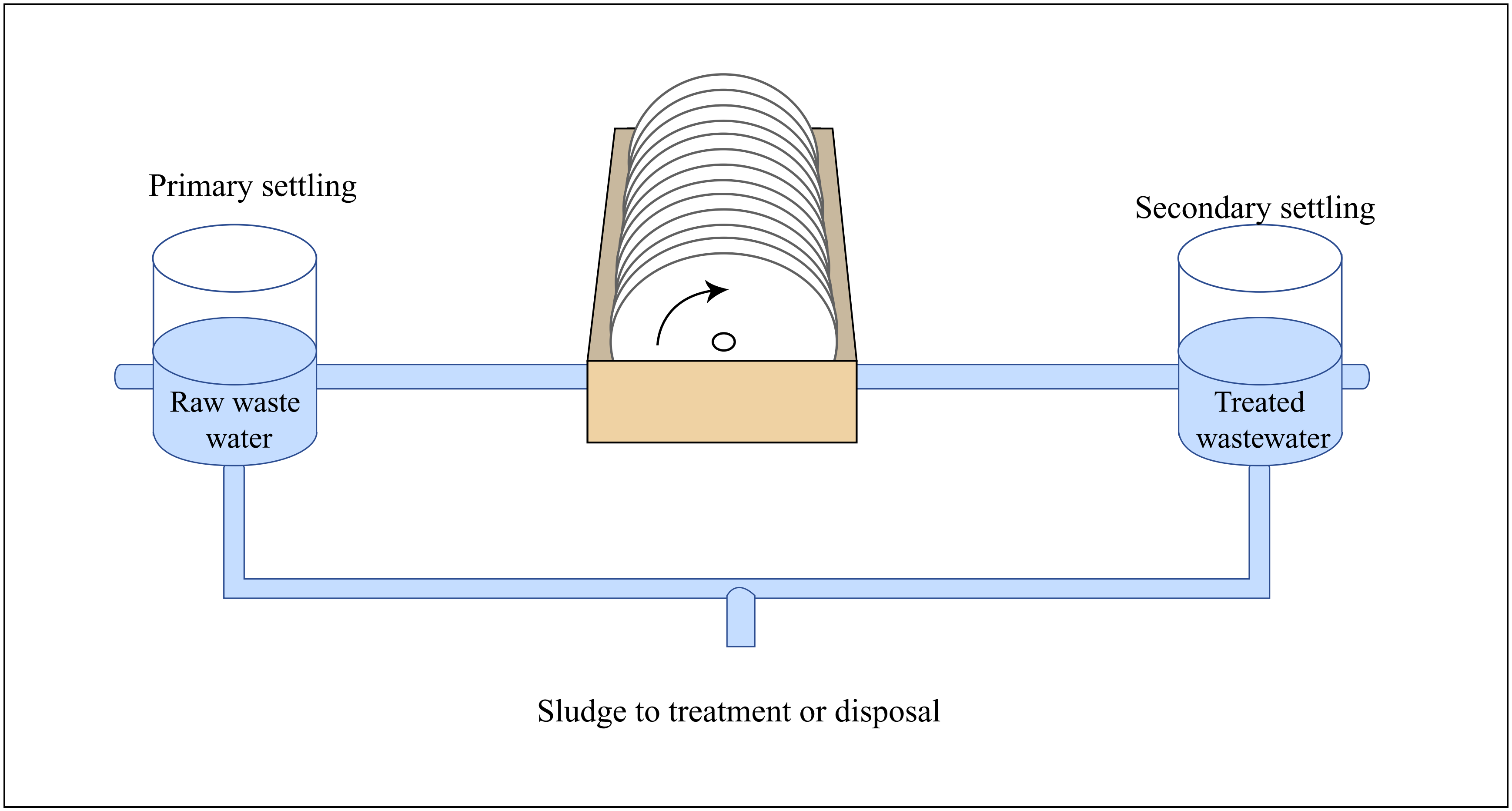


Figure by MIT OCW.

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