Lecture 7 - Filtration

Filtration is an ancient technology for cleaning water

- sand and gravel filters used in India as early as 2000 BC

- Romans dug channels next to lakes to use natural filtration

- French began commercializing filtration around 1750 on small scale

- Filtration for municipal supply systems began in England and Scotland around 1800

  - First modern slow sand filtration system in London in 1829

- Rapid filtration began in US in 1880s

  - First municipal plant with coagulation and filtration in Somerville, NJ in 1885

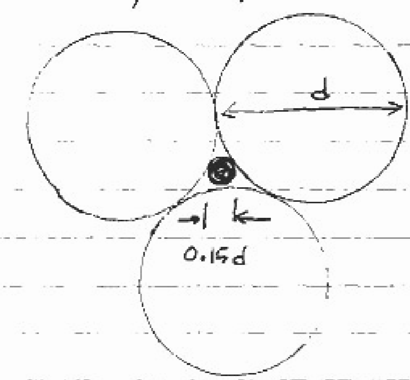
- Surface Water Treatment Rule 1989 - first regulation requiring widespread filtration throughout US

Comparison of filter media with suspended sediment

Filter media

Sand	800 μm
All media	400 - 1500 μm

In uniform medium of spherical particles of diameter d, a particle of diameter 0.15 d will pass thru' pores



Size of suspended matter:

Soil	1 - 100 μm
Cryptosporidium oocysts	5
Bacteria	0.3 - 3
Viruses	0.005 - 0.01
Floc particles	100 - 2000
Visible particle (w/ 20-20 vision)	37 μm
Giardia	8 - 12 μm

Engineered filter media strain particles no smaller than 30 to 80 μm depending on media type

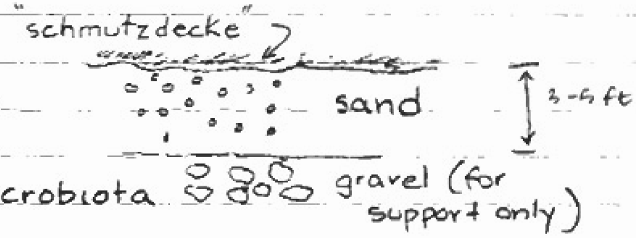
Types of granular media

Slow sand filters: oldest form of filters

fine sand loaded at low rates $0.05 - 0.2 \frac{m}{hr}$

treatment by physical straining and biological degradation

schmutzdecke is layer of organic material and microbiota



clean by scraping top layer every few weeks or months

simple operation, no chemicals

used rarely for municipal-scale plants
50 slow sand systems out of 50,000 water systems in U.S.

Usually used for small systems where simple operation is advantageous

Raw water turbidity must be < 50 NTU (usually <10 in practice)

NTU = nephelometric turbidity unit

Lakes 1-20 NTU
Rivers 10 - >4000 NTU
Required for finished water = 0.3 NTU
Most systems strive for < 0.1 NTU (non detectable)

Filter performance measured by effluent turbidity

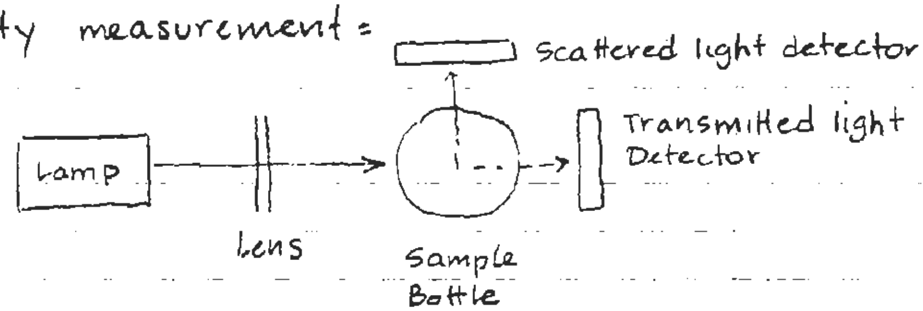
Turbidity measurement

Turbidity meter or
Turbidimeter

Measure of relative clarity of water
- indicates the presence of dispersed suspended solids like silt clay algae microorganisms organic matter

Not a direct measure of TSS but of interaction between light and suspended particles in water

Turbidity measurement =



Comparison of scattered and transmitted light done by nephelometer (or turbidimeter)

nephel - from Greek word for cloudy

Turbidity reported in NTU nephelometric turbidity units

(called FNU formazin nephelometric units outside US)

Instrument is calibrated with suspensions of formazin polymer

Rapid filtration

Much more common in U.S. Replaced slow sand filters in 20th century

Much higher loading rates than slow sand filters – ~100 X typically 5-15 m/hr

Media are coarser, more uniform (often multiple)

Removal is not by physical straining on surface as primary mechanism

Conceptually, rapid filtration is like sedimentation

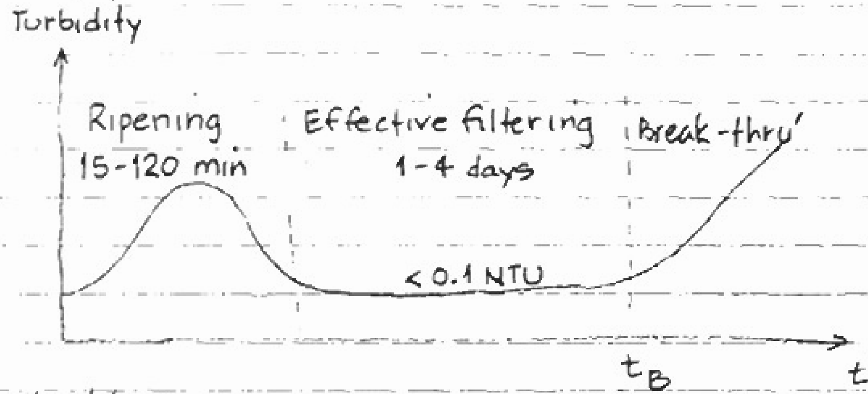
Particles need pre-treatment with a coagulant to destabilize electrical charge

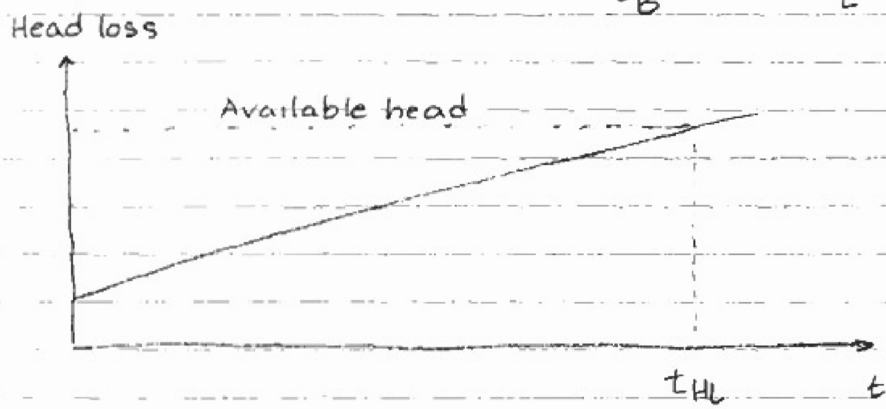
Destabilized particles adhere to grains in filter medium and are removed

Depth filtration – removal through entire depth of bed occurs (bed depth 2-6 ft)

Turbidity of outflow changes with time

Head loss in filter increases with time as filter clogs and gets lower hydraulic conductivity





Lesser of t_B or t_{HL} indicates time to end the filter run

At end of filter run, filter is "backwashed"

Strong flow sent back through porous medium, mobilizing grains, and washing solids off of medium

Rapid filters may be: See photo pg 8

single media (usually sand)

dual media (usually sand and anthracite
anthracite = hard coal)

multi-media sand, anthracite, garnet,
ilmenite, granular activated carbon
(GAC)

Granular media are sieved and washed to make a more uniform grain-size distribution (see chart, pg 9)

Measured by Uniformity Coefficient $UC = \frac{d_{60}}{d_{10}}$

Effective size, $ES = d_{10}$ = grain size diameter at which 10% of the media by weight are smaller

Chart on pg 10 shows properties of media

Other filters:

Pressure filters - similar to rapid filter, but in closed vessel under high pressure

Precoat filters - diatomaceous earth formed as cake on a filter screen or porous plate

continuous feed of diatomaceous earth renews filter surface, prevents clogging

Please see Figure 11-4 in MWH, J. C. Crittenden, R. R. Trussell, D. W. Hand, K. J. Howe, and G. Tchobanoglous, 2005. *Water Treatment: Principles and Design*, Second Edition. John Wiley & Sons, Hoboken, New Jersey.

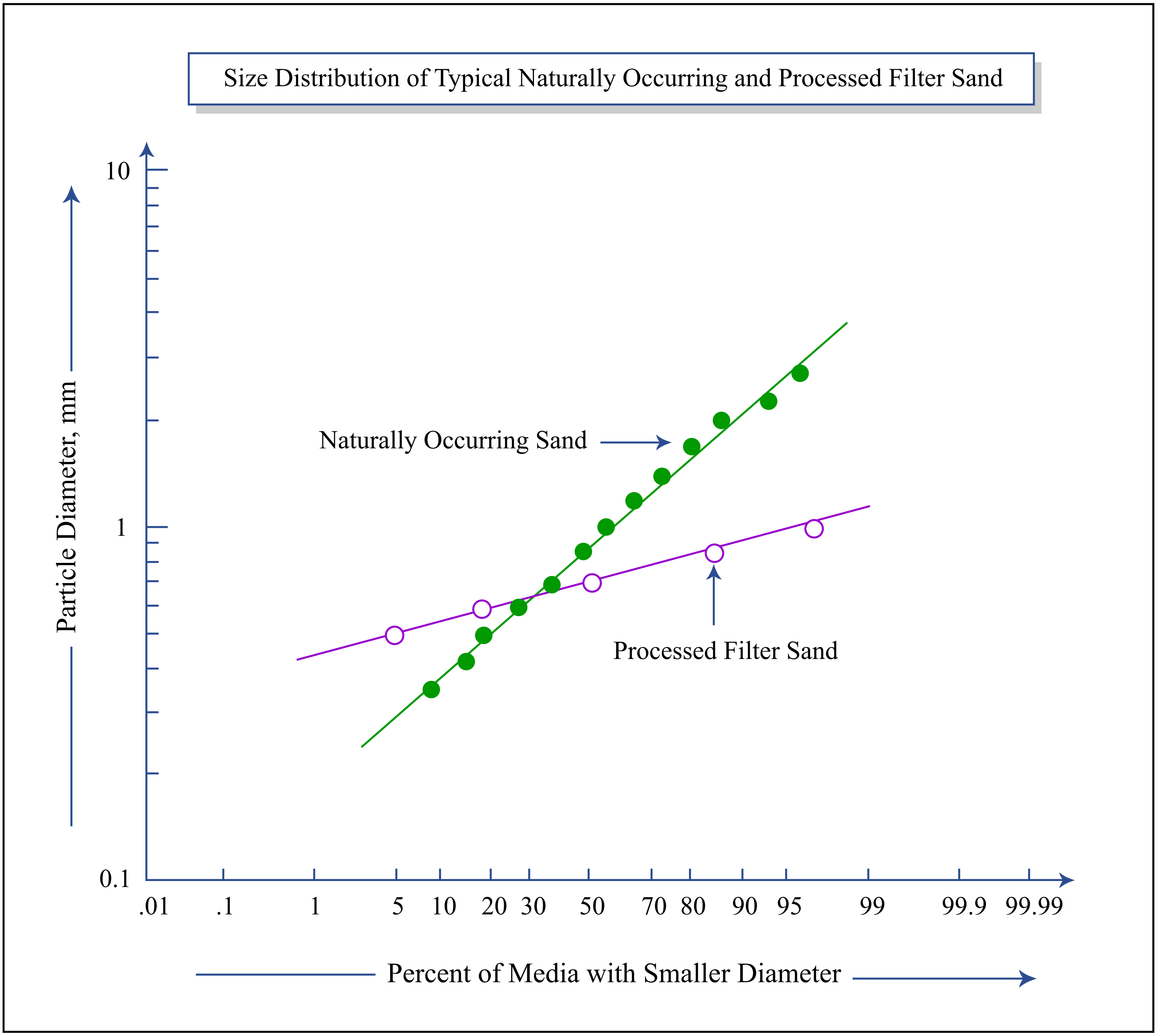


Figure by MIT OCW.

Adapted from: MWH, J. C. Crittenden, R. R. Trussell, D. W. Hand, K. J. Howe, and G. Tchobanoglous. *Water Treatment: Principles and Design*. 2nd ed. Hoboken, NJ: John Wiley & Sons, 2005, p. 881.

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Typical properties of filter media used in rapid filters*

PROPERTY	UNIT	GARNET	LLMENITE	SAND	ANTHRACITE	GAC
Effective Size, ES	mm	0.2 - 0.4	0.2 - 0.4	0.4 - 0.8	0.8 - 2.0	0.8 - 2.0
Uniformity Coefficient, UC	UC	1.3 - 1.7	1.3 - 1.7	1.3 - 1.7	1.3 - 1.7	1.3 - 2.4
Density, ρ_ρ	g/mL	3.6 - 4.2	4.5 - 5.0	2.65	1.4 - 1.8	1.3 - 1.7
Porosity, ε	%	45 - 58	Not available	40 - 43	47 - 52	Not available
Hardness	Moh	6.5 -7.5	5.6	7	2 - 3	Low

* = Not Available

Figure by MIT OCW.

Adapted from: MWH, J. C. Crittenden, R. R. Trussell, D. W. Hand, K. J. Howe, and G. Tchobanoglous. *Water Treatment: Principles and Design*. 2nd ed. Hoboken, NJ: John Wiley & Sons, 2005, p. 882.

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Flow through filter beds

Flow regime defined by Reynolds number

$$Re = \frac{\rho_w V_f d}{\mu_w}$$

ρ_w - fluid density
μ_w - fluid dynamic viscosity
d - media grain diameter
V_f - filtration rate [L/T]
(also called superficial velocity

$$V_f = \frac{Q}{A_p}$$

Q = flow rate through filter
A_p = plan area of filter

Note: velocity within filter (i.e. between media grains) is higher

Four regimes:

1. Darcy flow or creeping flow $Re \lesssim 1$

   viscous flow governed by Darcy's law:

$$V_f = K \frac{h_L}{L}$$

K = hydraulic conductivity [L/T]
h_L = head loss across filter [L]
L = depth of granular media [L]

slow sand filtration, slower rates of rapid filtration in Darcy flow

2. Forchheimer flow $1 \lesssim Re \lesssim 100$

Laminar flow influenced by both viscous and inertial forces

Inertial forces arise as fluid accelerates and decelerates in twists, turns, expansions, and contractions of media void space

Backwashing – $3 \leq Re \leq 25$

High-rate rapid filtration may be Forchheimer flow

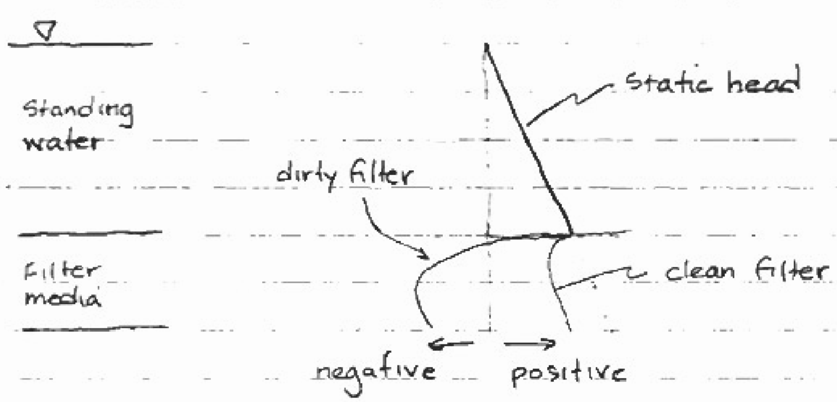
Head loss given by:

$$\frac{h_L}{L} = K_1 V_f + K_2 V_f^2$$

3. Transition flow $100 \lesssim Re < 600-800$
4. Fully turbulent $Re > 600-800$

These flow regimes not encountered in filtration

Head distribution in filter: (see pg 13)



Negative pressure can cause air to come out solution – cause filter binding

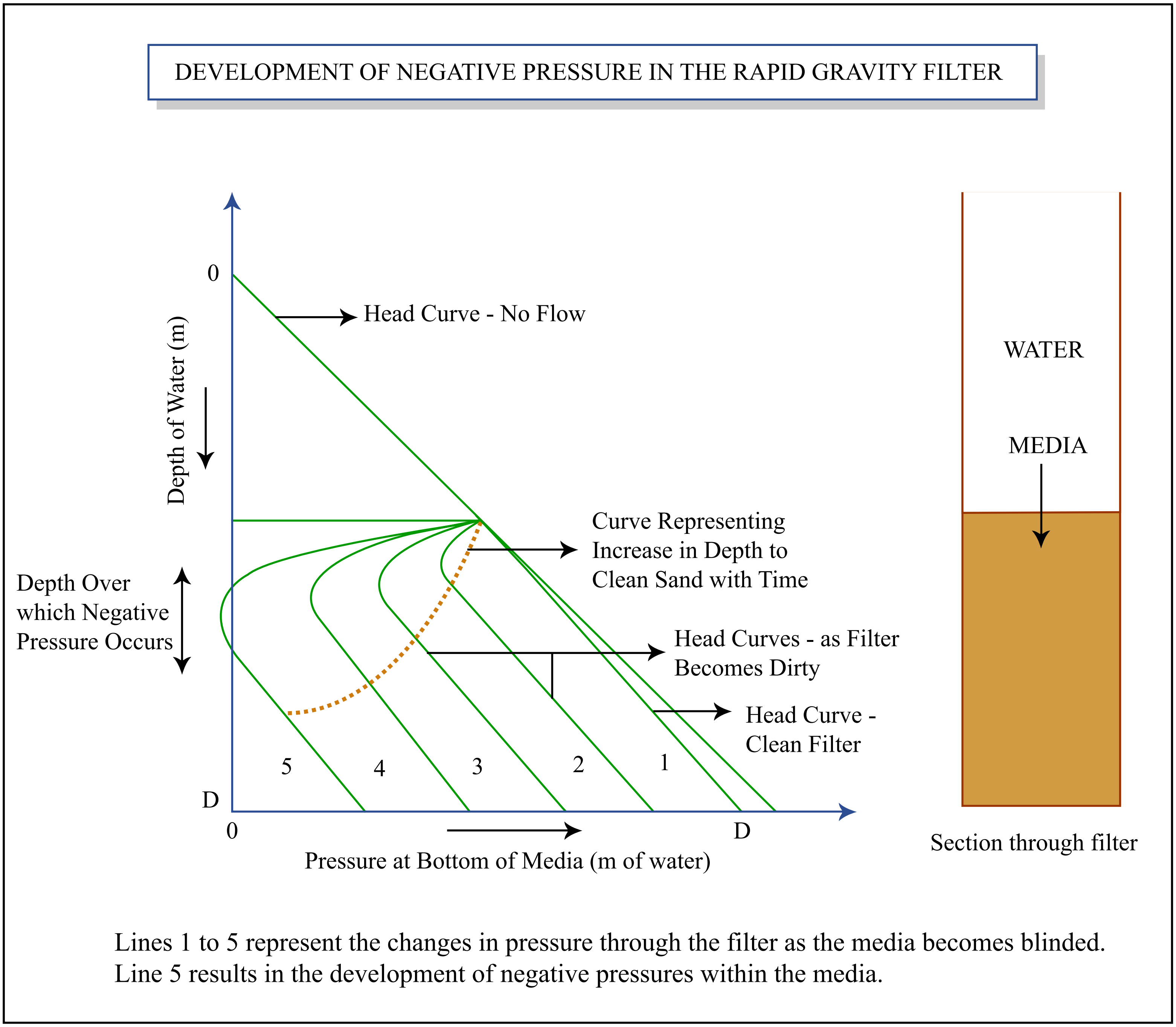


Figure by MIT OCW.

Adapted from: Binnie, C., M. Kimber, and G. Smethurst. *Basic Water Treatment*. 3rd ed. Cambridge, UK: Royal Society of Chemistry, 2002.

Filtration theory (for rapid filtration)

Fundamental aspects

Straining is not important removal mechanism

Particles adhere to media grains and are removed

Each grain is a collector

Water must be pre-treated to destabilize negatively-charged particles

In depth filtration, particles are removed according to the relation proposed by Iwasaki in 1937:

$$\frac{\partial C}{\partial z} = -\lambda C$$

i.e. first-order removal with depth

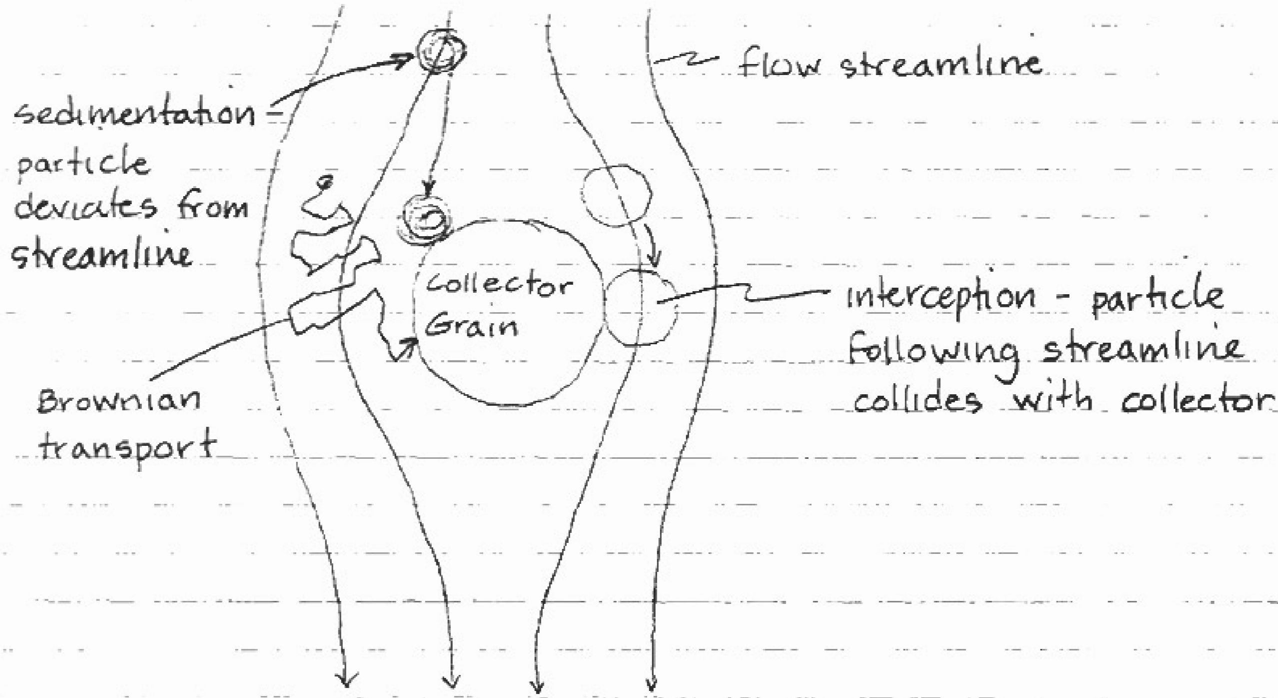
- C = concentration or number of particles per unit volume M/L^3 or L^{-3}
- z = depth into filtration bed (zero at surface) $[L]$
- λ = filtration coefficient $[L^{-1}]$

More detailed phenomenological models verify this relationship

Models assume:

- Spherical particles and spherical media
- Effects of angular media on hydrodynamics ignored
- λ assumed constant with time
- Constant porosity and grain dimension with time

Transport mechanisms:



Efficiency of particle collection depends on:

Transport efficiency = $\eta = \dfrac{\text{particles contacting collector}}{\text{particles approaching collector}}$

Attachment efficiency $\alpha = \dfrac{\text{particles adhering to collector}}{\text{particles contacting collector}}$

For isolated single collector

Mass flow approaching collector $= V_f C \left(\frac{\pi}{4} d_c^2\right)$

V_f = filtration rate (Q/A_p)
C = particle conc.
d_c = collector particle diameter

Mass capture by single collector is:

$$\eta \alpha V_f C \left(\frac{\pi}{4} d_c^2\right)$$

For filter as a whole, need to consider number of collectors:

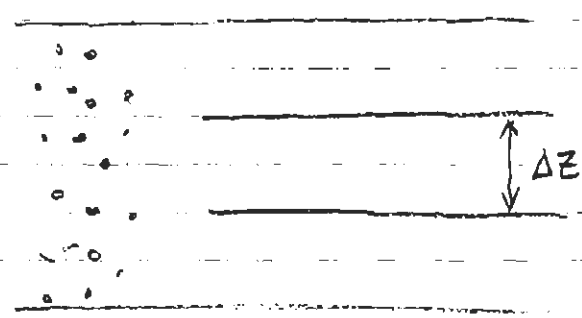
$$\text{Number of collectors} = \frac{(1-n) A_p \, \Delta z}{(\pi/6) d_c^3}$$

n = bed porosity = $\dfrac{\text{volume of voids}}{\text{total volume}}$

$\simeq$ 0.4 to 0.5 for engineered media

Δz = unit thickness of bed

Particle mass balance over Δz in bed:



Mass removed = mass in − mass out ± reactions (assumed zero)

$$\left[\eta \alpha v_f C \left(\frac{\pi}{4} d_c^2\right)\right]\left[\frac{(1-n) A_p \, \Delta z}{(\pi/6) d_c^3}\right] = Q C_z - Q C_{z+\Delta z}$$

Mass removed by single collector — Number of collectors in Δz

$$= v_f A_p \left(C_z - C_{z+\Delta z}\right)$$

As $\Delta z \to 0$

$$\frac{dC}{dz} = -\frac{3(1-n)\eta \alpha}{2 d_c} C = -\lambda C$$

$$\frac{C_{out}}{C_{in}} = \exp\left(-\frac{3(1-n)\eta\alpha}{2d_c} L\right)$$

L = bed thickness

Function of

α - Chemistry (pre-treatment with coagulants)

L/d_c - Design parameter for bed

(Rule of thumb $1000 < L/d_{10} < 2000$)

n - porosity

η - single collector efficiency

Models for η

$$\eta = \eta_I + \eta_G + \eta_D$$

η_I — interception

η_G — gravity

η_D — diffusion (Brownian motion)

Yao et al. 1971:

$$\eta_I = \frac{3}{2}\left(\frac{d_p}{d_c}\right)^2$$

d_p = particle diameter

$$\eta_G = \frac{(\rho_p - \rho_w) g d_p^2}{18 \mu V_f}$$

based on Stoke's Law for creeping flow

$$\eta_D = 0.9\left(\frac{KT}{\mu d_p d_c V_f}\right)^{2/3}$$

based on Einstein (1905) on Brownian motion

K = Boltzmann's constant

T = Absolute temp.

Note:

$$\eta_I \propto d_p^2$$

$$\eta_G \propto d_p^2$$

} Big particle interception

$$\eta_D \propto \frac{1}{d_p^{2/3}}$$

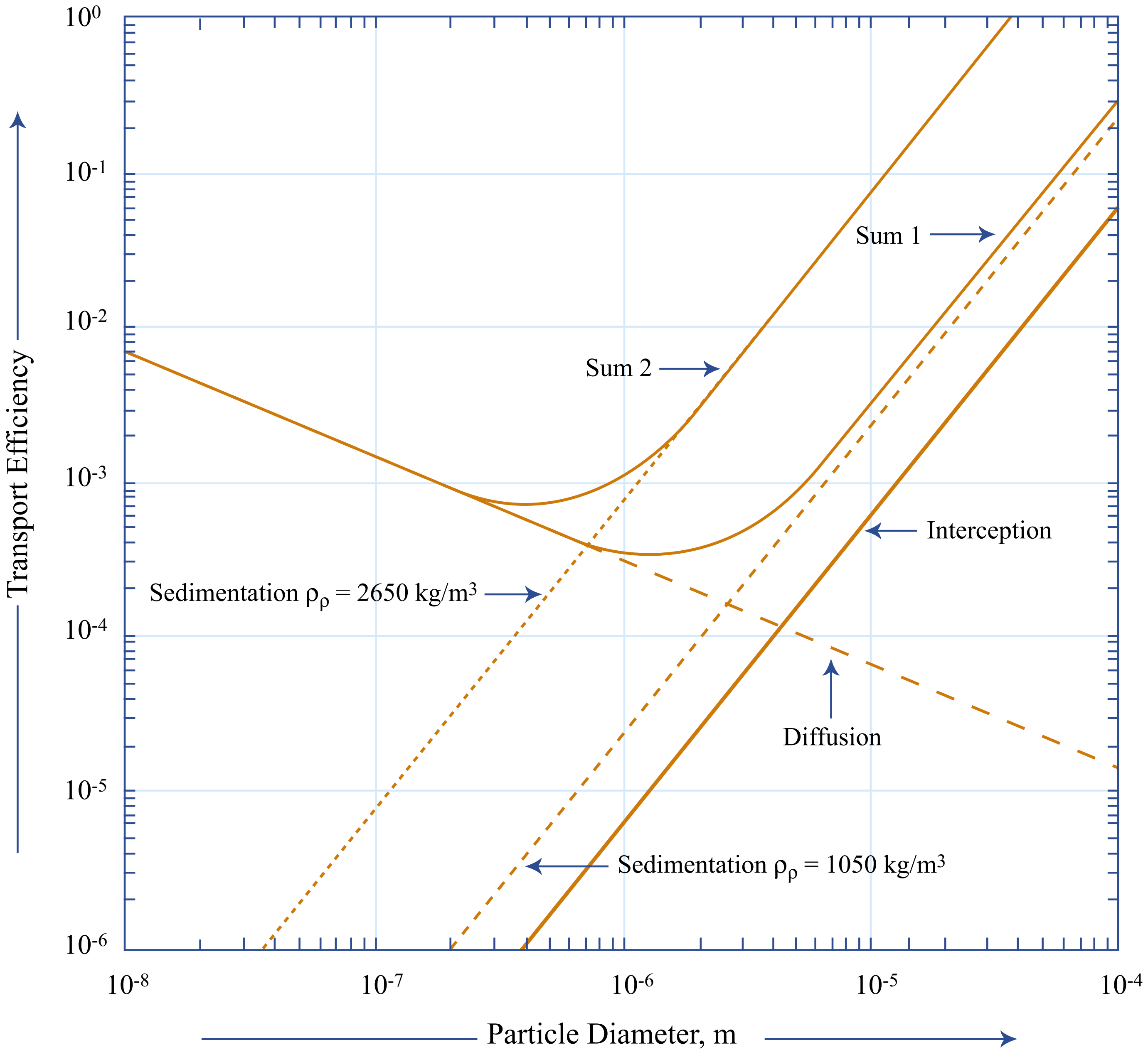
– Small particle interception

Net effect of particle capture (according to theory) shows in Figure on pg 19

Comparison of experimental data with model on pg 20 shows significant differences but preservation of correct trend – i.e. poorer removal at $d_p = 1\ \mu m$

More sophisticated models account for altered hydrodynamic drag when particles approach, Van der Waals forces (Rajagopalan and Tien, 1976), and better prediction of chemical effects (Tobiason and O'Melia, 1988)

Multi-media filters offer somewhat different performance in single filter. Improve performance of overall filter – Figure pg 21 shows performance of 45 cm of anthracite over 25 cm of sand. With $\alpha = 0.1$, removal by sand compensates for poor removal by anthracite



Influence of Particle Size and Density on Filtration Transport Efficiency (d_c = 0.5 mm, v = 5 m/h, and T = 25°C)

Figure by MIT OCW.

Adapted from: MWH, J. C. Crittenden, R. R. Trussell, D. W. Hand, K. J. Howe, and G. Tchobanoglous. *Water Treatment: Principles and Design*. 2nd ed. Hoboken, NJ: John Wiley & Sons, 2005, p. 912.

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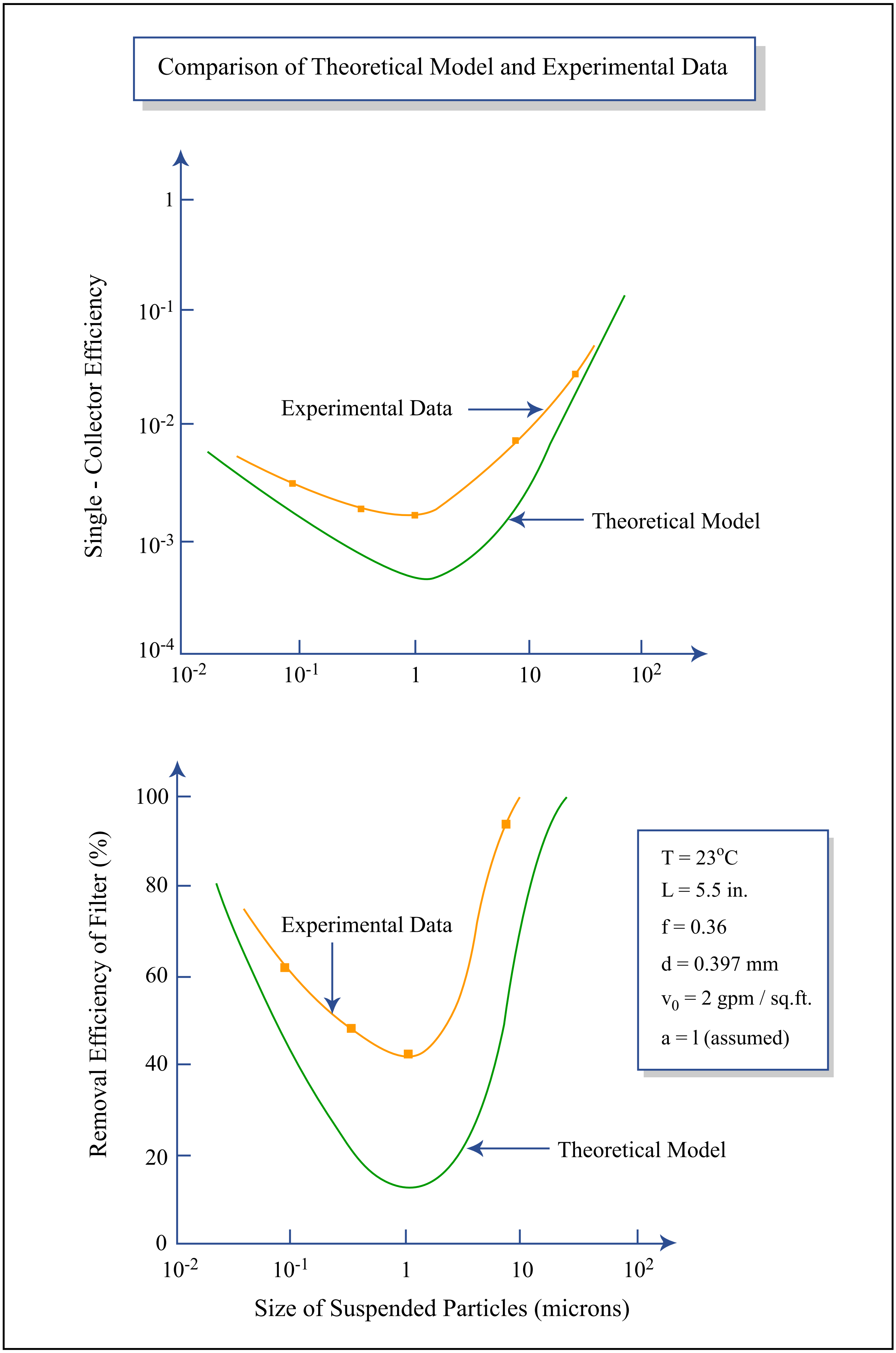


Figure by MIT OCW.

Adapted from: Yao, K.-M., M. T. Habibian, and C. R. O'Melia. "Water and Waste Water Filtration: Concepts and Applications." *Environmental Science & Technology* 5, no. 11 (November 1971): 1105-1112.

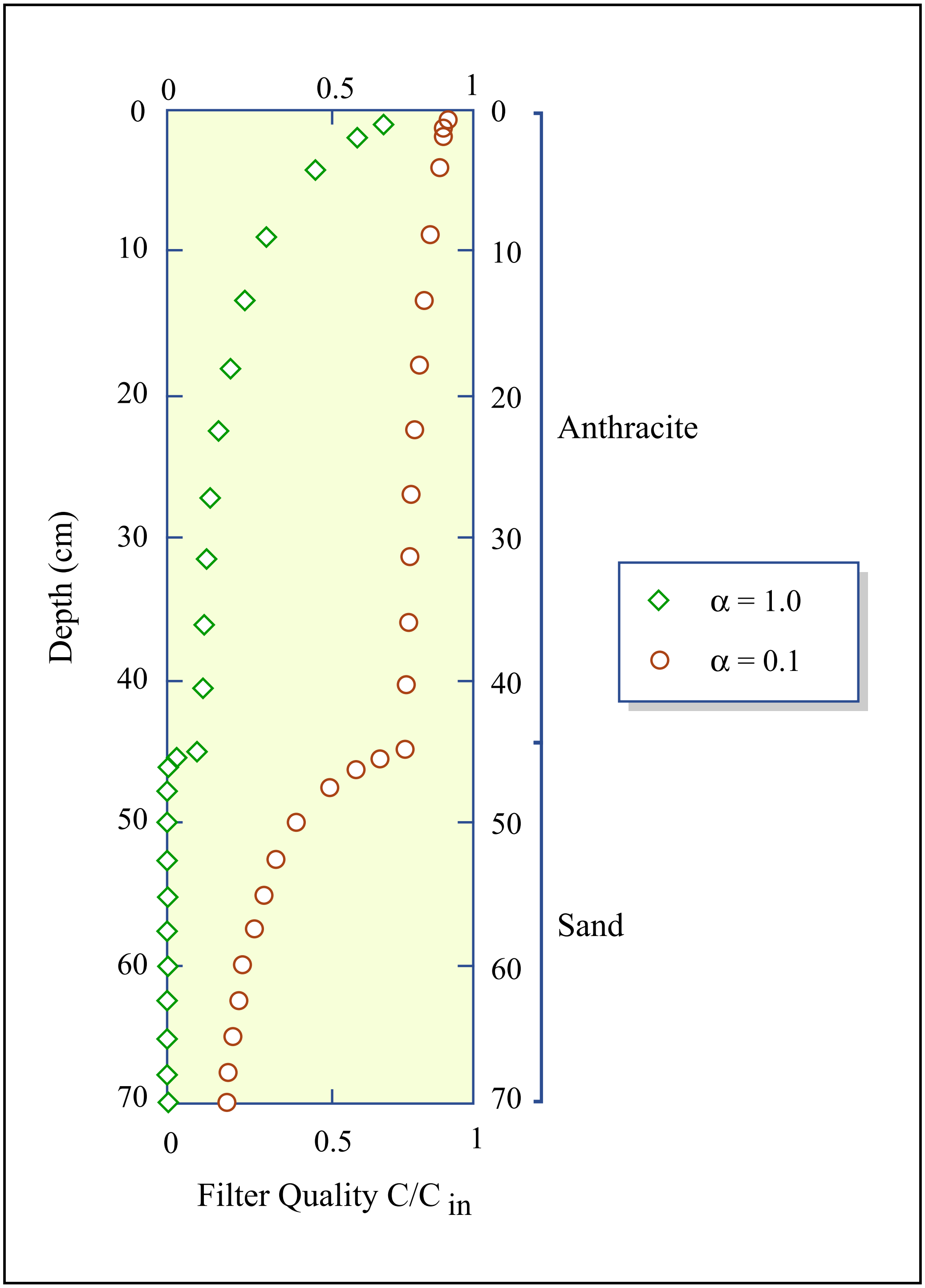


Figure by MIT OCW.

Adapted from: O'Melia, C. R., and J. Y. Shin. Removal of particles using dual media filtration: modeling and experimental studies." *Water Science and Technology: Water Supply* 1, no. 4, (2001): 73-79.

Conclusions

Rapid filtration requires pre-treatment (coagulation) to create favorable chemistry for particle capture

Particles larger than 1 μm are captured by sedimentation and interception

Particles smaller than 1 μm are captured by diffusion

Most difficult particles to capture are about 1 μm in size

Dual media provide better capture than single media

Design requires consideration of mixing, coagulation, flocculation, and filtration

Textbook, slides to follow illustrate typical installations

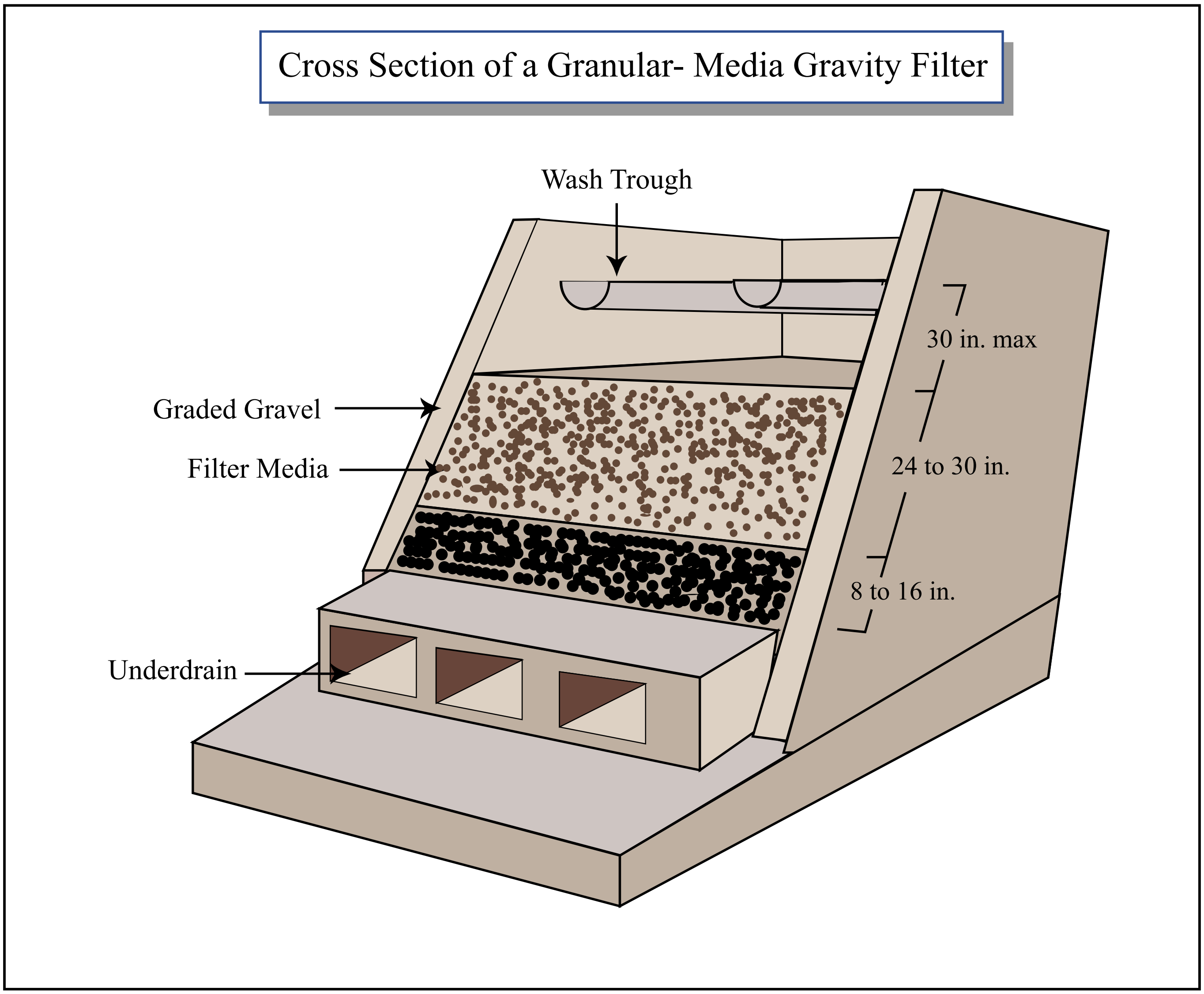
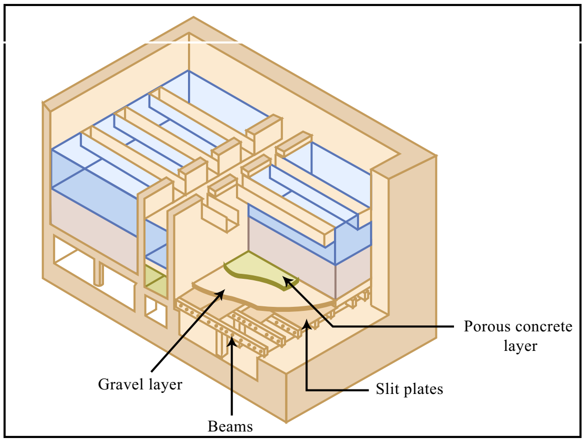
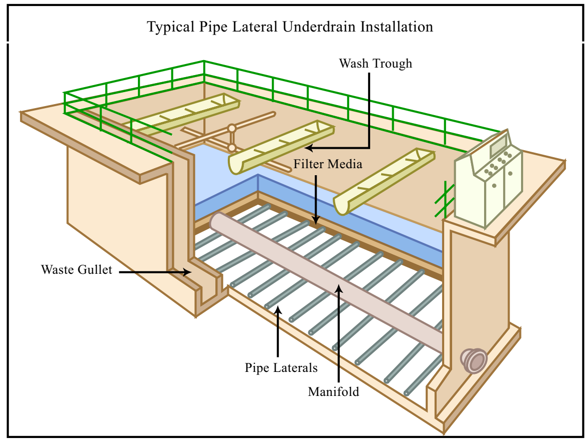


Figure by MIT OCW.

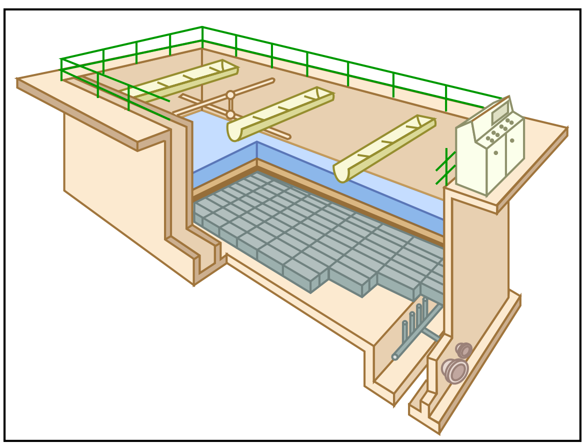
Adapted from: Binnie, C., M. Kimber, and G. Smethurst. *Basic Water Treatment*. 3rd ed. Cambridge, UK: Royal Society of Chemistry, 2002.

Source: JSIM, 2001. Database on Japanese Advanced Environmental Equipment, The Underdrain System for Rapid Filter and GAC Adsorption Filter. Japan Society of Industrial Machinery Manufacturers. http://nett21.gec.jp/JSIM_DATA/WATER/WATER_6/html/Doc_307.html. Accessed February 21, 2005.





Source: F.B. Leopold Company, 2003. Filtration, The Process, Underdrain Types. http://www.fbleopold.com/water/filtration/underdrain.htm. Accessed February 21, 2005.

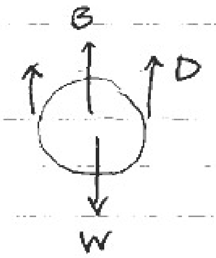


Figures by MIT OCW.

Source: F.B. Leopold Company, 2003. Filtration, The Process, Underdrain Types. http://www.fbleopold.com/water/filtration/underdrain.htm. Accessed February 21, 2005.

Backwash hydraulics

same force balance as sedimentation:



except drag D arises from upflowing backwash water flowing past media grain

Need to determine backwash flow so that
$D \geq W - B$

Viewed another way, the upflow velocity must exceed the settling velocity of the media grain:

$$V > V_s = \left[\frac{4}{3} \left(\frac{\rho_1 - \rho}{\rho} \right) \frac{gd}{C_D} \right]^{1/2}$$

For transition range turbulence

$$C_D = \frac{24}{\mathbb{R}e} + \frac{3}{\sqrt{\mathbb{R}e}} + 0.34$$

$$\mathbb{R}e = \frac{V_s d}{\nu}$$

solve iteratively for V_s

Fluidization will expand bed $\quad \frac{L_E}{L_F} = \frac{1 - n_F}{1 - n_E}$

E - expanded   F - fixed
L - bed depth
n - porosity - can be computed by empirical formulas