CornellEngineering

Civil and Environmental Engineering

CEE 4540

Sustainable municipal drinking water treatment

Instruction: YuJung Chang

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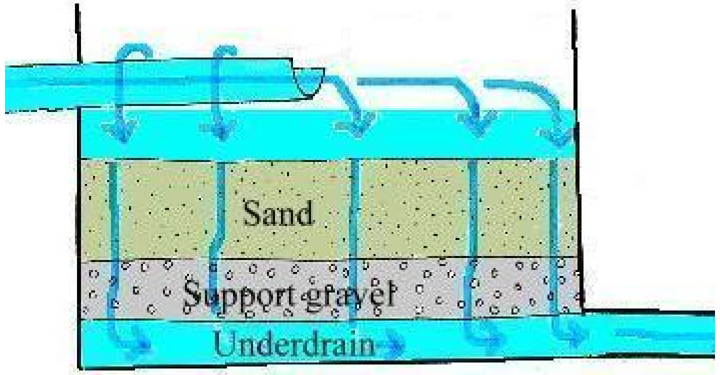
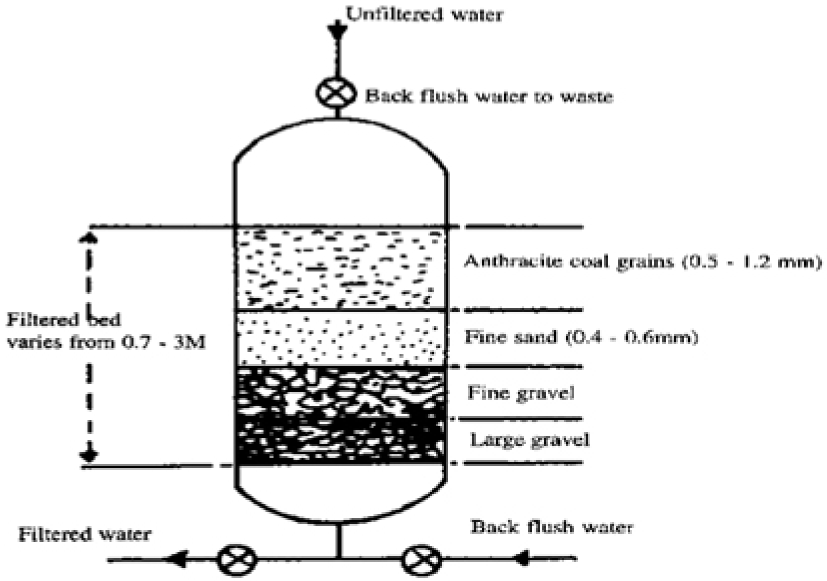
Class #7 09/19/2018 2:55 – 4:10pm

Filtration: A Physical Process for the Removal of Solids

- Strainers (MF/UF)
- Bag Filters
- Cloth Filters
- Cartridge Filters (NF/RO)
- Media Filters
  - Single media filter
  - Multimedia filter
- Membrane Filters
  - Microfiltration (MF)
  - Ultrafiltration (UF)



Filter Basin



Pressurized Filter Vessel

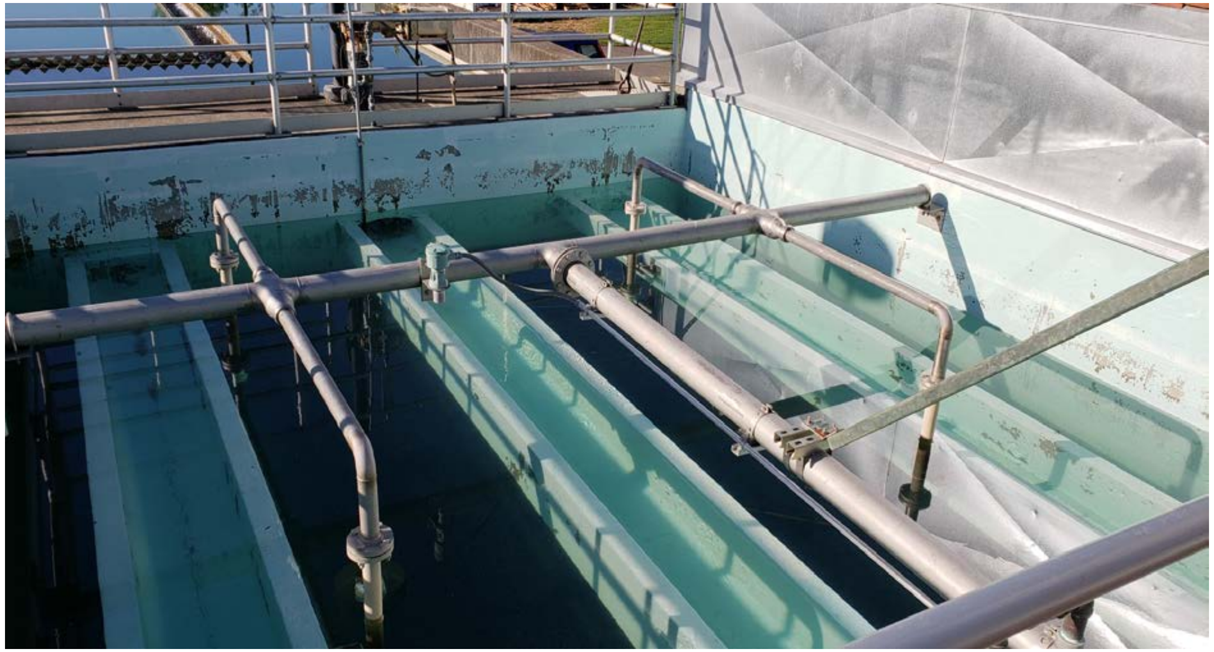
Grants Pass Site Visit on 9/19/2018

- Designed Capacity: 20 MGD
- Limited to mostly 12 – 13 mgd due to pumping constraint

Sedimentation Basins

Outdoor Filters

- Occasional flocs carry over



Primary Objective for Filtration: Public Health Protection

Pathogenic bacteria, viruses and protozoa in water and Supply represent potential risks to public health.

Bacteria

(*E.coli*)

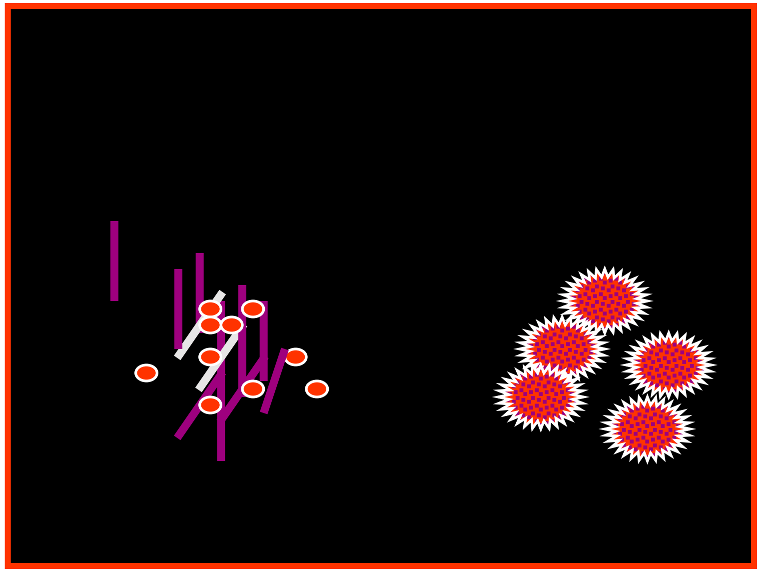
Viruses

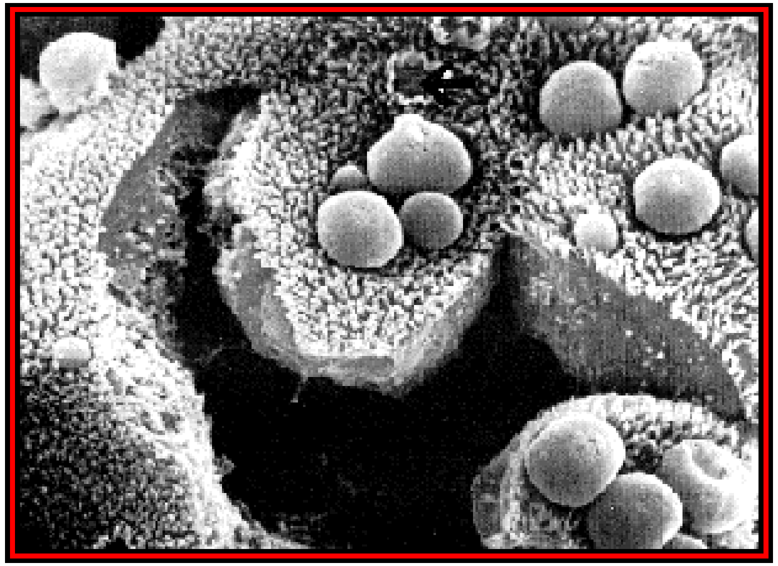
(Hepatitis, Polio)

Protozoa

(*Giardia*)

(*Cryptosporidium*)





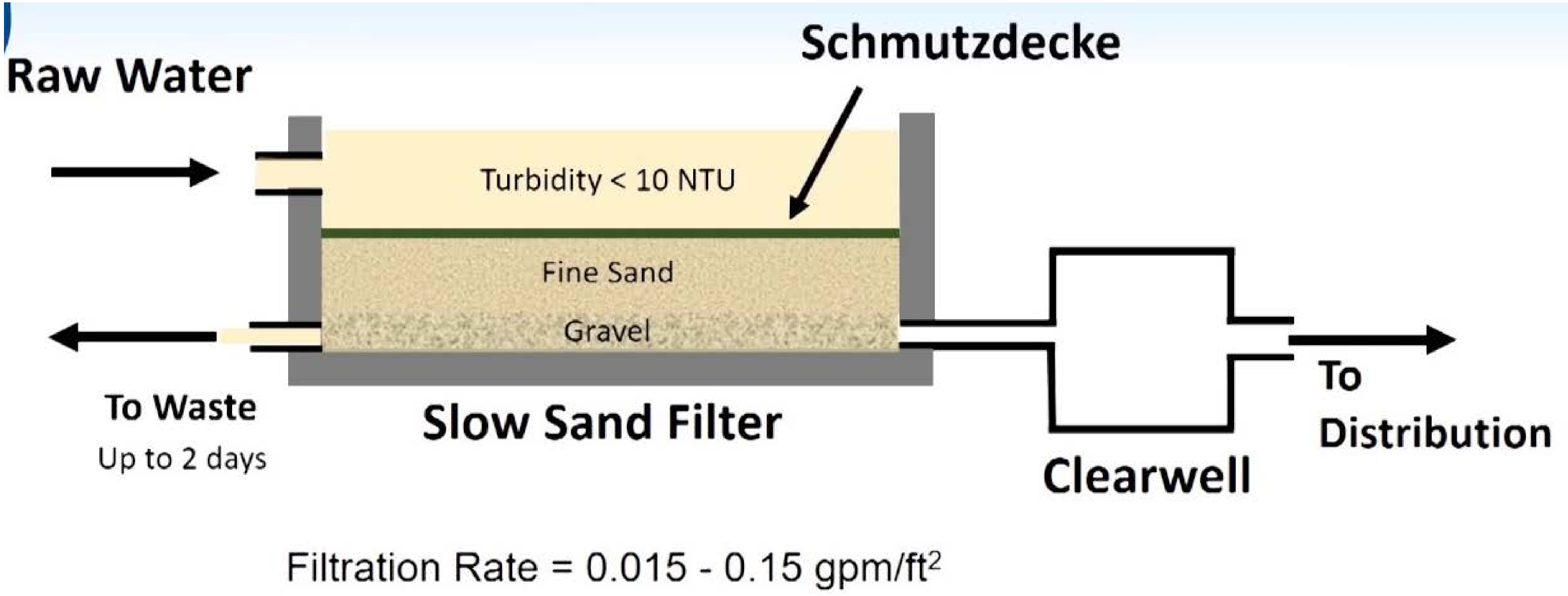
Filtration with Sand…..

- Filtration through sand is the oldest and universally, most accepted method through out the world
- 98 – 99% of bacteria are removed along with other impurities through filtration
- Filtration technologies evolved through the past century significantly
  - Slow Sand
  - Rapid Sand
  - Demetrious Earth
  - Cartridge
  - Membranes

Rapid Filtration vs. Slow Sand Filtration

- Developed in 1804 in Scottland
- A Slow Sand Filter (SSF) utilizes a very thin layer of “deposits” (a.k.a Schmutzdecke) that consist of inert sand/silt, organics, and biomass to remove particulate in the feed water
- Filtration Rate is very low; but requires very low level of operation and no chemical is needed
- A well-designed and properly maintained SSF can effectively removes turbidity and pathogenic organisms through various biological, physical and chemical processes in a single treatment step.

- Filtration rate is about 0.0015 – 0.15 gpm/ft2; much lower than that for conventional sand filters
- Requires feed water turbidity < 10 NTU



Treatment Mechanisms of a Slow Sand Filter

- Physical: Mechanical straining & sedimentation
- Chemical: Oxidation of organic matter by aerobic bacteria
- Biological: Occurs through the “Vital Layer” and the degradation efficiency of a slow sand filter depends on the “Vital Layer”
- Vital Layer is a slimy biological layer known as “Schmutzdecke”
- The layer is slimy & gelatinous. It consists of threadlike algae and numerous forms of live plankton, diatoms, and bacteria
- Vital layer is the most critical component of a slow sand filter

Operation Sequence of a Slow Sand Filter

- Filtration Stage
  - Filtration stage usually lasts for a few months and the head loss gradually builds up over time
  - Filtration stage is terminated when the head loss is about equal to the available head (3 – 6 ft). Note turbidity in the effluent usually does not breakthrough even when head loss is high.
- Regeneration Stage
  - The filter is drained
  - About 1 – 2 cm of the media surface is scrapped off (usually include the Schmutzdecke), hydraulically cleaned, and stock piled onsite
  - Fiter-to-waste is provided until the new Schmutzdecke is ripen.
  - When the media depth reached a minimum level (~ 50 cm) the stock piled sand can be used to rebuild the slow sand filter

Advantages and Limitations of Slow Sand Filters

– Advantages
  - Simple construction
  - Very low chemicals required
  - Effective for pathogen removal (3 – 4 log for bacteria and 2 – 3 log for E.coli)

– Limitations
  - Requires large land space
  - While initial cost is low, maintenance cost could be much higher than rapid sand filter
  - Very low flow rate
  - No control on the growth and effectiveness of the Schmutzdecke
  - Feed water quality must be very good (< 10 NTU)
  - Sensitive to feed water quality changes

Rapid Sand Filter

- First rapid sand filter was installed in USA
- RSF gained considerable popularity through the world for its ease of construction, simple operation, and reliability
- It is considered the “default” filtration technology in industrialized countries and is adopted by developing world as well.
- Sand, or Media filters can be operated in open/gravity driven basins or in enclosed pressurized filters.

Advantages of Rapid Sand Filter

- Occupies less space
- Filtration rate is much higher than slow sand filters (40 – 50 times)
- Washing the media is easy
- Flexible in operations
  - Variable flow rate
  - Adjust water quality
  - Can shut down for a period of time

Disadvantages of Rapid Sand Filter (compared to slow sand)

- Requires pretreatment
  - Coagulation/flocculation/sedimentation
- Requires chemicals and energy to operate (higher operation costs)
- Requires higher level of operation skills
- Reduction of bacterial count is less than slow sand filters

Media Filters

- Filtration is done through passing water through Filter Media
- Media means gravels, sand, or GAC/Anthracite

Fine Sand

Corse Sand

Gravels

Granular Activated Carbon

Anthracite

Media Filters

- Filtration through “Filter Media”
- Media means gravels, sand, or GAC/Anthracite

Fine Sand

Corse Sand

Gravels

Garnet

Garnet

Mono Media Filters

- A filter that uses only one type of filter media, usually the coarse sand
- Mono media filters are usually deep bed filtration (> 8 ft)

Fine Sand

Coarse Sand

Gravels

Garnet

Garnet

Media Used for Filtration

- These medias can be loaded into concrete filter basins or pressure filter vessels

Fine Sand

Coarse Sand

Gravels

Garnet

Garnet

Multi-Media Filter

– Filter consists of more than one type of media
  - A: Fine Sand + Corse Sand + Gravels
  - B: Fine Sand + Corse Sand + Garnet Sand
  - C: Anthracite + Corse Sand + Gravels
  - D: GAC + Corse Sand + Gravels

A B C D

Example of a Multimedia Filter Bed

- Composition of a 60” (5 ft) multimedia filter bed

Material	Layer	Particle Size
Anthracite coal	28”	1-1.2 mm
Silica sand	15”	0.4-0.5 mm
High-density sand	5”	0.2-0.3 mm
Garnet gravel	3”	90-100 % 0.476 mm 0-10% 1.41 mm
Silica gravel	3”	1/4” – 1/8”
Silica gravel	3”	1/2” – 1/4”
Gravel	3”	3/4“ – 1/2”

Media Effective Size

– Media Effective Size: Measure of the size of granular media; the size at which 10 percent of the media has a smaller diameter (d10) as determined by a sieve analysis. (90% of the media is larger than the sieve size)

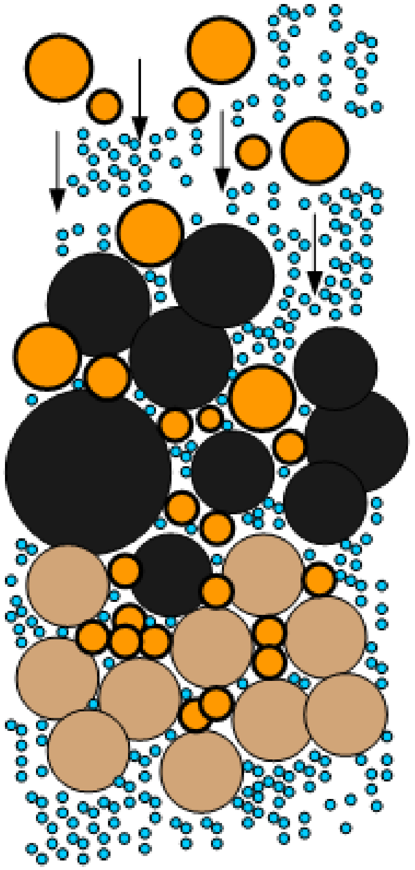
Sieve Mesh Chart			
APERTURE SIZE			
B.S.S(410/1969)	A.S.T.M. (11-70)	I.S. (469/1972)	MICRONS
4	5	4.00mm	4000
5	6	3.35mm	3353
6	7	2.80mm	2812
7	8	2.36mm	2411
8	10	2.00mm	2057
10	12	1.70mm	4000
12	14	1.40mm	1405
14	16	1.18mm	1204
16	18	1.00mm	1204
18	20	0.850mm	850
22	25	0.710mm	710
25	30	0.600mm	600
30	35	0.500mm	500
36	40	0.425mm	420
44	45	0.355mm	355
52	50	0..300mm	300
60	60	0.250mm	250
72	70	0.212mm	210
85	80	0.180mm	180
100	100	0.150mm	150
120	120	0.125mm	120
150	140	0.106mm	105
170	170	0.090mm	90
200	200	0.075mm	75
240	230	0.063mm	63
300	270	0.053mm	53
350	325	0.045mm	45
400	400	0.037mm	37
500	500	0.025mm	25

Uniform Coefficient for Filter Media

- UCF measures the uniformity of granular media
- UCF is the ratio of the 60th percentile (d60) to the 10th percentile (d10) media sizes as determined by a sieve analysis.
- UCF assure filter medias are in similar sizes; resulting in uniform space between media and therefore higher loading rate

$$\mathrm{UC} = \frac{d_{60}}{d_{10}} \qquad (11\text{-}1)$$

where UC = uniformity coefficient, dimensionless
d_{10} = 10th percentile media grain diameter, mm
d_{60} = 60th percentile media grain diameter, mm



Typical Ranges of Uniform Coefficient for Filter Media

Table 11-2

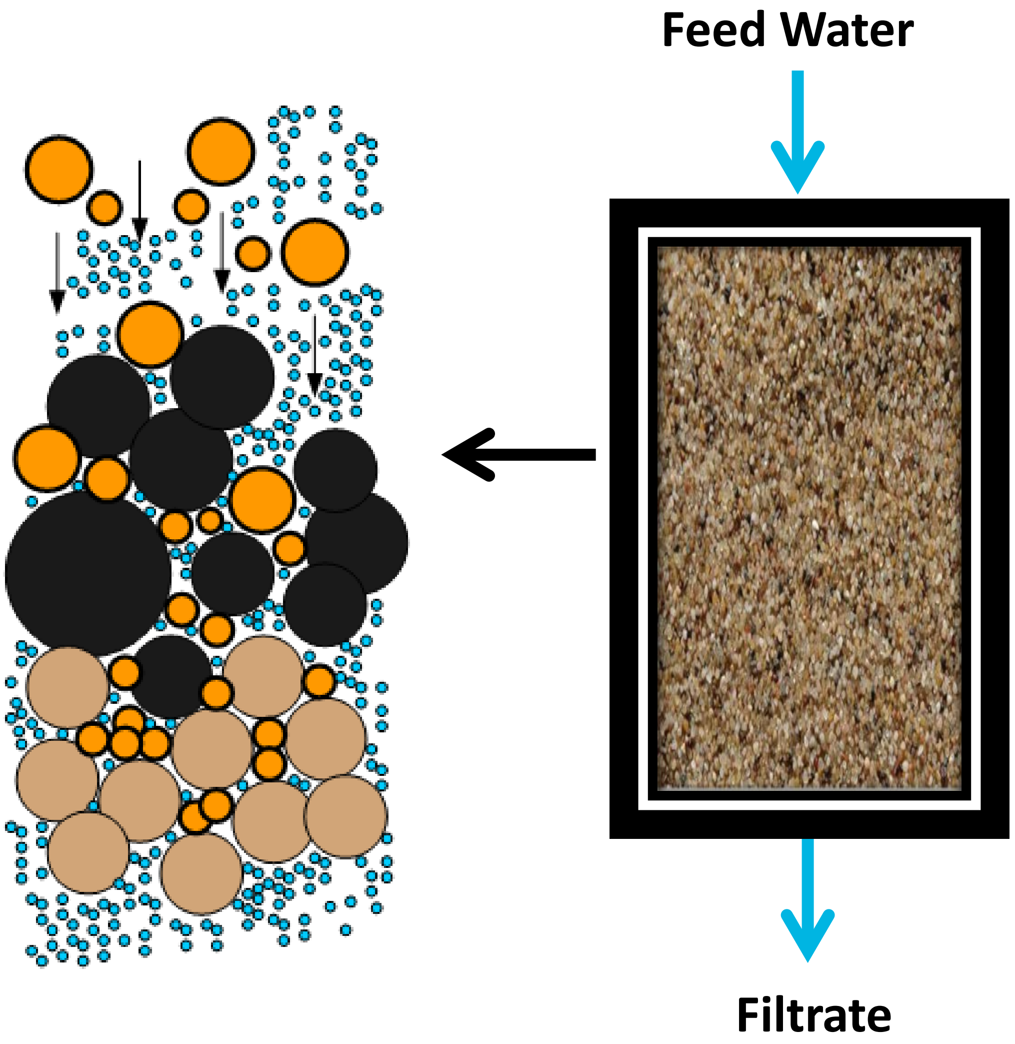
Typical properties of filter media used in rapid filters[a]

Property	Unit	Garnet	Ilmenite	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_p	g/mL	3.6–4.2	4.5–5.0	2.65	1.4–1.8	1.3–1.7
Porosity, ε	%	45–58	N/A	40–43	47–52	N/A
Hardness	Moh	6.5–7.5	5–6	7	2–3	Low

[a]N/A = not available.

Filtration Mechanism for Media Filter

- Sizes of particles in water (especially settled water) are much, much smaller than the void space between filter medias
- Therefore “straining” is NOT the mechanism that enable filters to capture and retain small particles from water
- Surface charge attraction and interception are the two primary filtration mechanism that allows media filters to retain particles.
- Water chemistry is very important in media filtration



Particle Removal Mechanisms by Media Filters

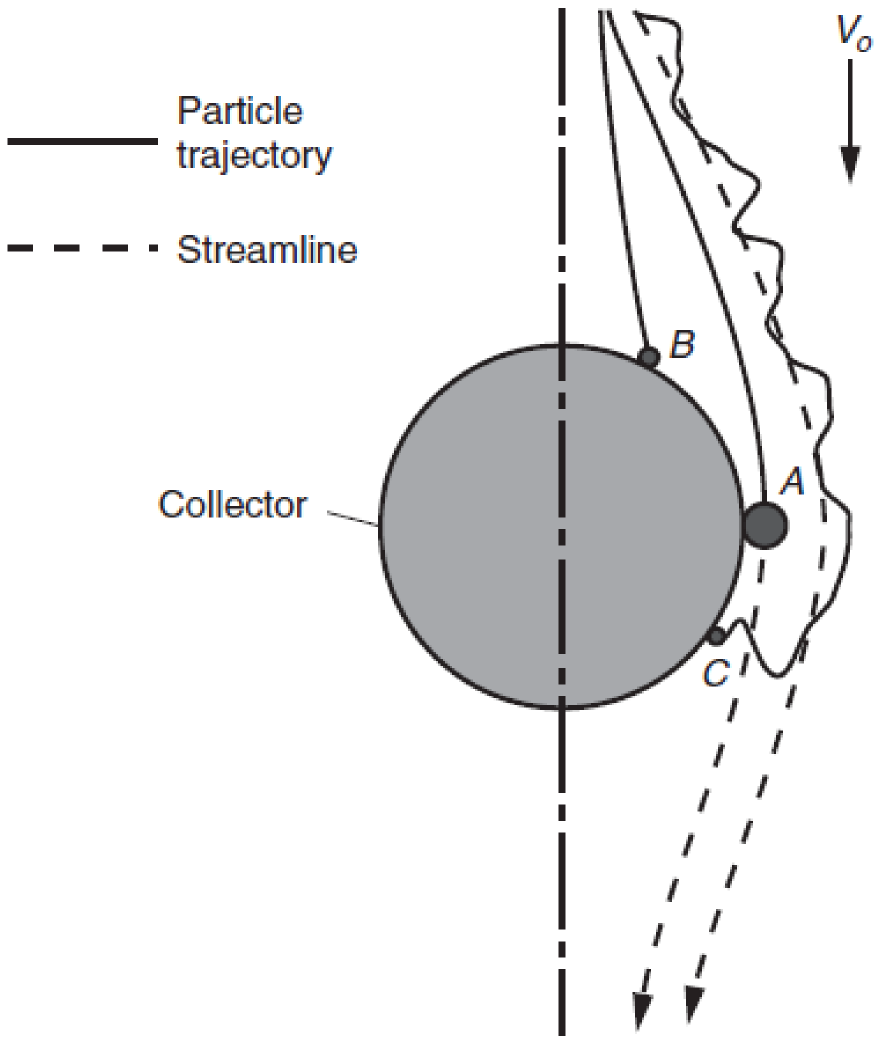
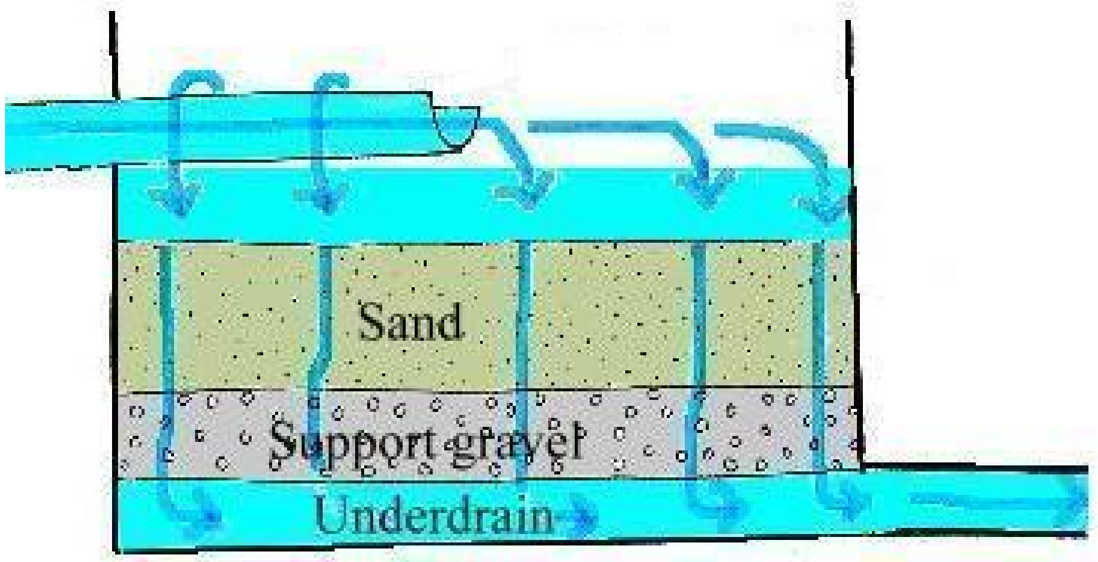
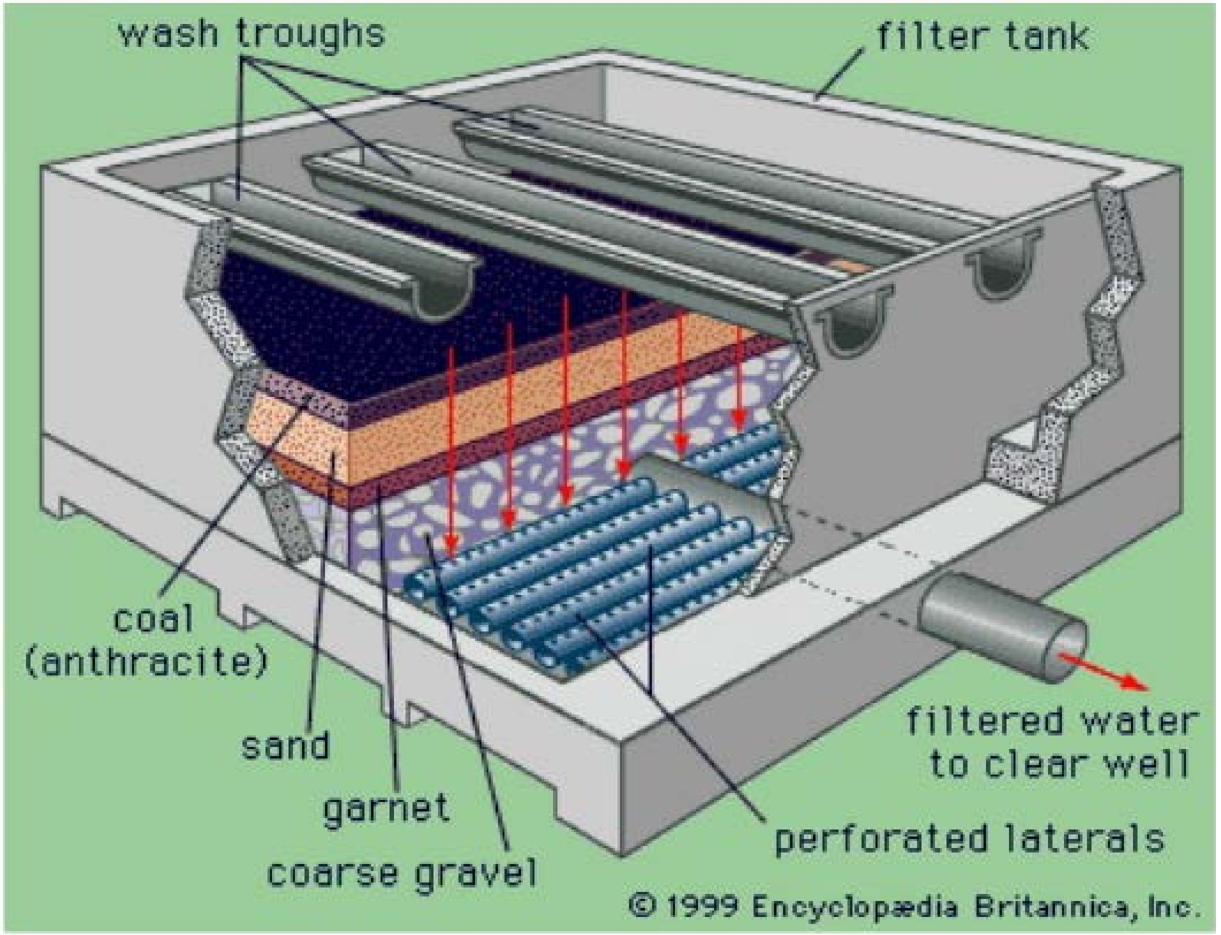


Figure 11-10
Particle transport mechanisms in fundamental filtration theory: (a) interception, particle A follows streamline but collides with the collector because of the proximity between the streamline and the collector; (b) sedimentation, particle B deviates from the streamline and collides with the collector because of gravitational forces; (c) diffusion, particle C collides with collector due to random Brownian motion.

Configuration & Key Elements of Multimedia Filter

- Filter Tank
- Media Bed
- Wash Troughs (for backwash waste)
- Under Drain
- Perforated laterals





Multi-media filter

Filter Box at Grants Pass

Typical Operation Cycles for Media Filters

- Filter to waste
- Filtration
- Surface Scouring (if equipped)
- Backwash
- Filter to waste

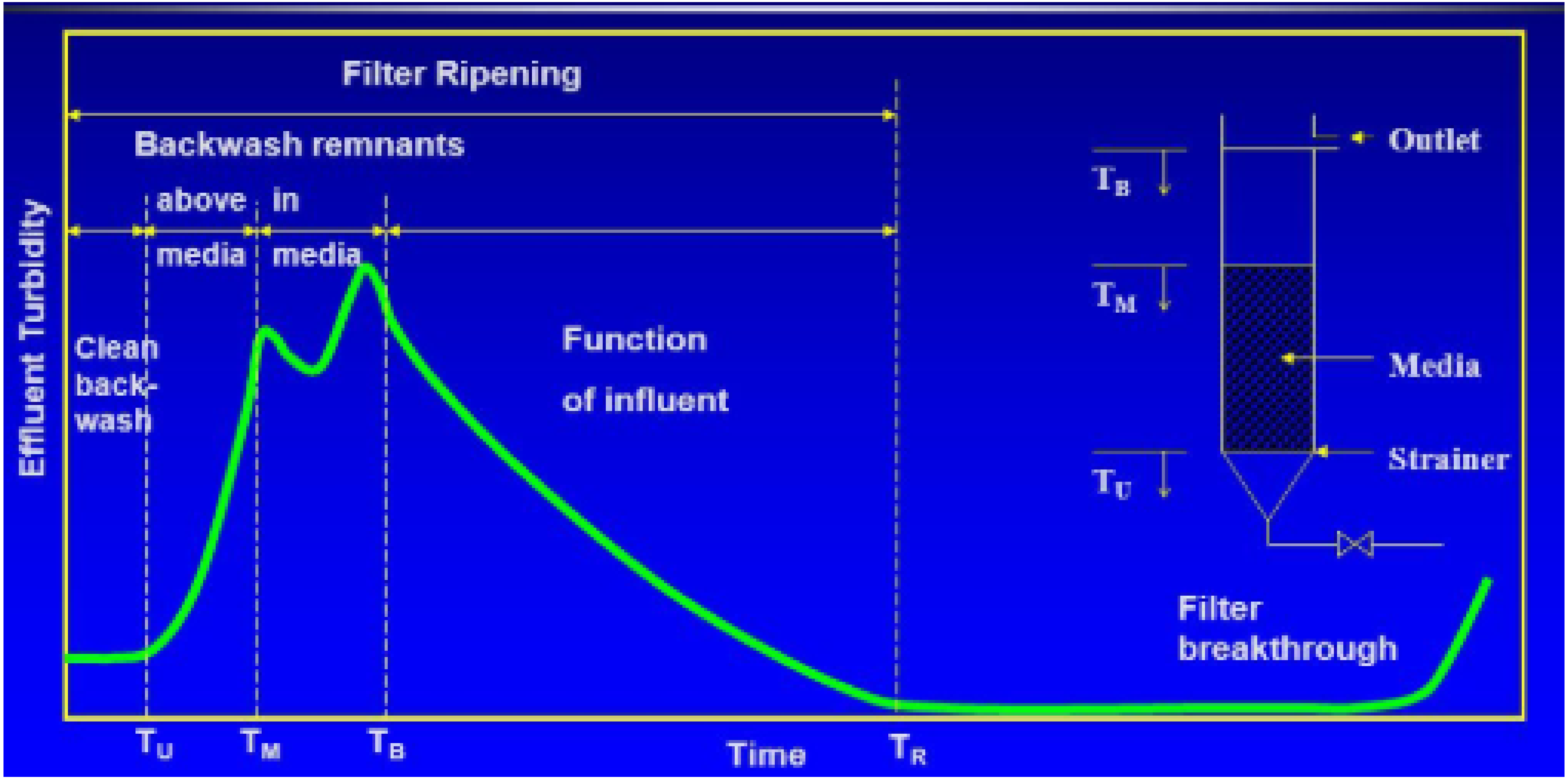
Key Terminologies in Media Filtration

- **Backwash:** Process for removing accumulated solids from a filter bed by reversing the water flow.
- **Air Scouring:** Optional feature during backwash in which air is introduced into filter underdrains along with backwash water; the vigorous scouring action helps clean deep-bed filters.
- **Contact Filtration:** Process train consisting of coagulation and filtration.
- **Depth Filtration:** Filtration mechanism in which particles accumulate throughout the depth of a granular filter bed by colliding with and adhering to the media. Captured particles can be many times smaller than the pore spaces in the bed.
- **Direct Filtration:** Process train consisting of coagulation, flocculation, and filtration. (No sedimentation)

Key Terminologies in Media Filtration (cont.)

- Filtration Rate: Key process variable; the superficial water velocity through the filter bed, calculated as the flow rate divided by the cross-sectional area of the bed. (gpm/ft2)
- Ripening: Process of granular media conditioning at the beginning of a filter run during which clean media captures particles and becomes more efficient at capturing additional particles. During ripening filter effluent water may not meet quality requirements and must be wasted; typically it is recycled to the head of the plant.

Turbidity within a Filtration Cycle



Key Terminologies in Media Filtration (cont.)

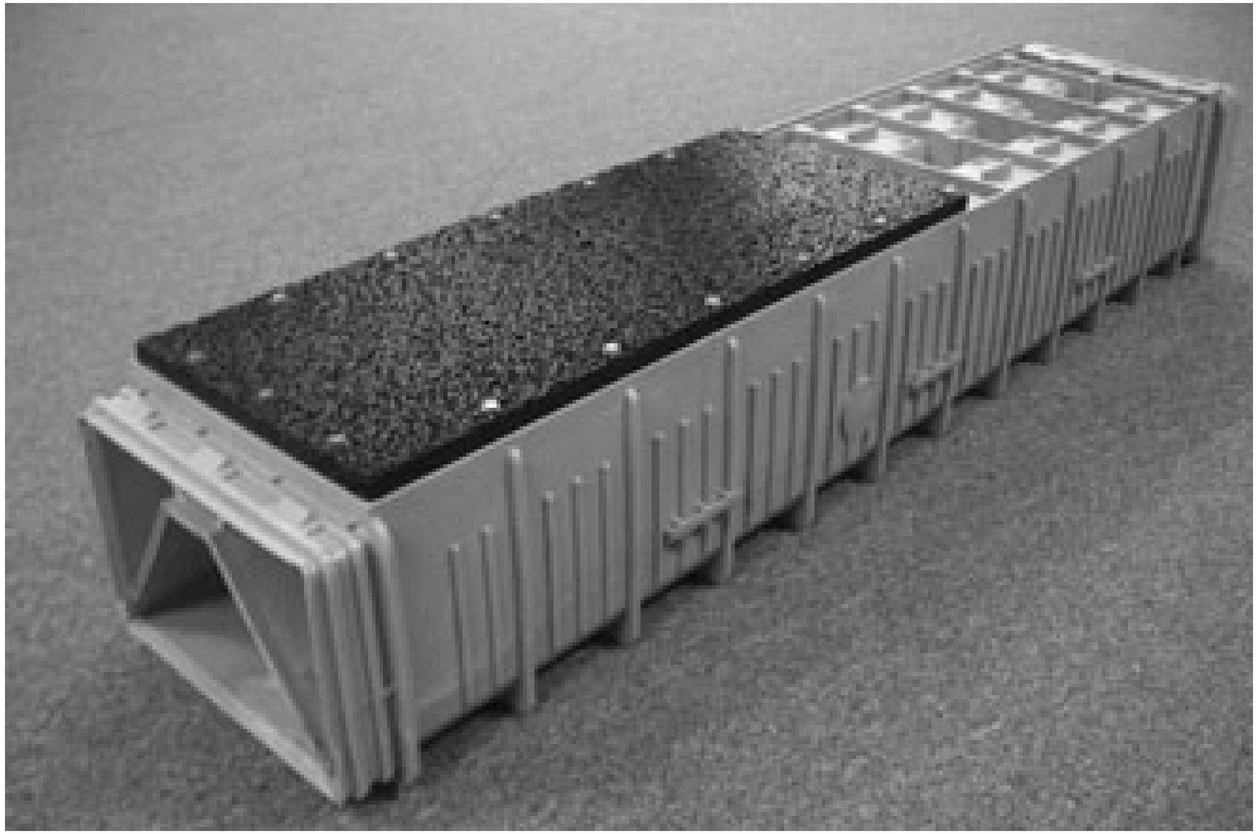
- Filter Breakthrough: Turbidity in the filtrate start increasing above the baseline
- Filter Run Time: Duration of filter operation between filter ripening and turbidity start increasing (filter breakthrough)
- Under Drain: Components installed at the base of a filter bed. Underdrains must support the media and evenly collect filter effluent and distribute backwash water (and air) to avoid channeling in the filter bed.

Underdrain at Grants Pass

– Leopold U-Block Underdrain

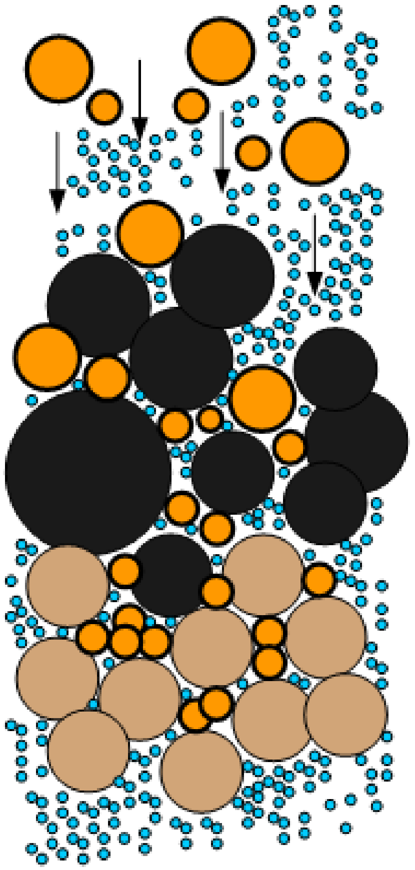
Underdrain at Grants Pass

- Leopold Underdrain with Cap
- Garnet and Gravels are not required with the Cap



Key Terminologies in Media Filtration (cont.)

- Channeling: a significant portion of water flows through certain pathways (with least resistance) and thereby reducing effectiveness of filtration efficiency
  - Much higher flowrate will create shearing/scouring force on media surface and thereby reduce solid retention (early breakthrough)
  - Usually caused by air binding and “mud balls”
- Air binding: Caused by release of dissolved gasses and air from water to form bubbles. These bubbles occupy void space of the filter media and drainage system. Usually it is caused by negative pressure within the filters; warm water temperature, and increased dissolved oxygen (DO) in water. It can be minimized by avoiding excess head loss, warming of water, control of algal growth and avoiding super saturation of air in water.



Comparisons between Rapid & Slow Sand Filter Design

Table 11-11
Comparison between rapid and slow sand granular filtration design criteria[a]

Process Characteristic	Slow Sand Filtration	Rapid Filtration
Filtration rate	0.08–0.25 m/h (0.03–0.10 gpm/ft^2)	5–15 m/h (2–6 gpm/ft^2)
Media effective size	0.15–0.30 mm	0.50–1.2 mm
Media uniformity coefficient	<2.5	<1.4
Bed depth	0.9–1.5 m (3–5 ft)	0.6–1.8 m (2–6 ft)
Required head	0.9–1.8 m (3–6 ft)	1.8–3.0 m (6–10 ft)
Run length	1–6 months	1–4 days
Ripening period	Several days	15 min–2 h
Pretreatment	None required	Coagulation
Dominant filtration mechanism	Straining, biological activity	Depth filtration
Regeneration method	Scraping	Backwashing
Maximum raw-water turbidity	10 NTU	Unlimited with proper pretreatment

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Class #8 09/24/2018 2:55 – 4:10pm

Typical Operation Cycles for Media Filters

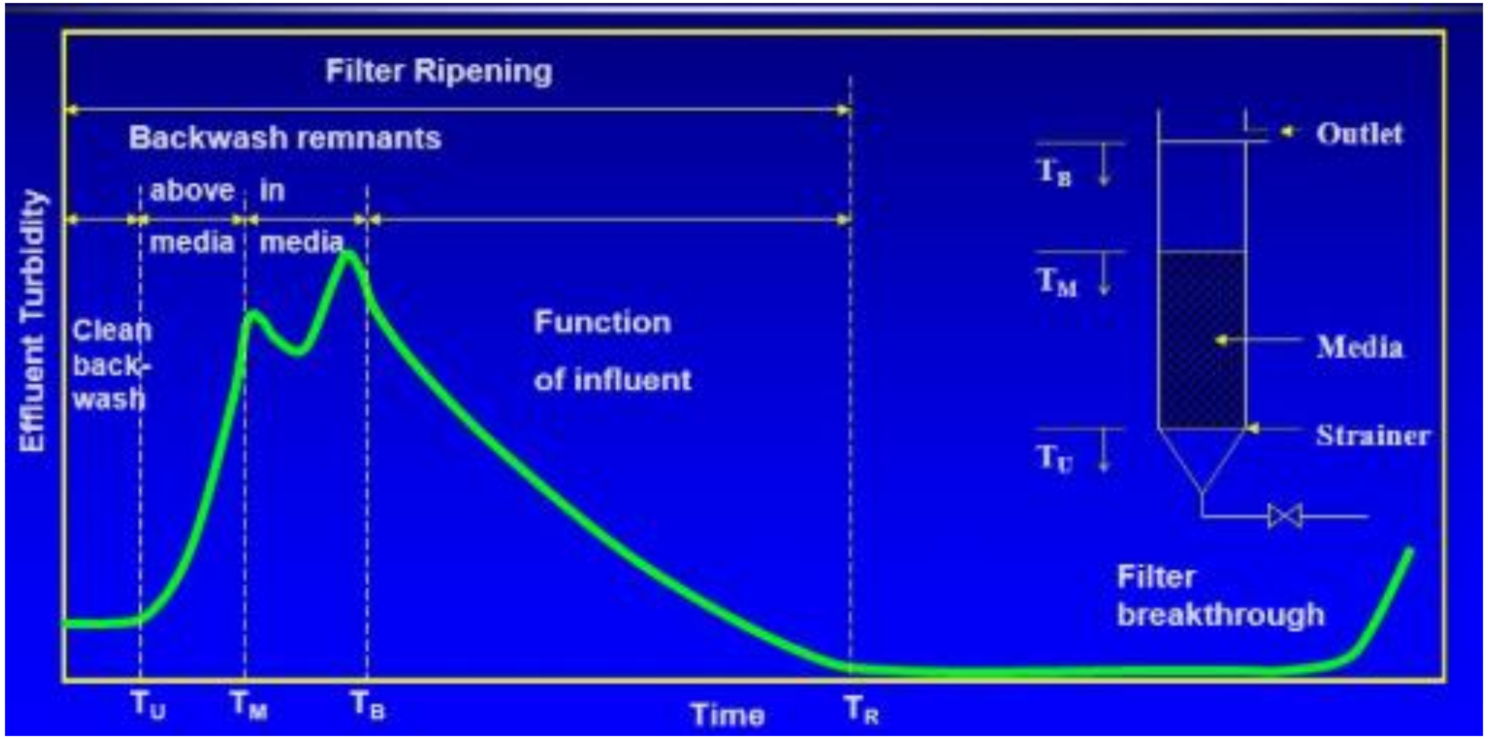
– Filter to waste (to make sure turbidity meets the treatment target)

– Filtration (producing water that meets the treatment target)

– Surface Wash with Air Scouring (if equipped)

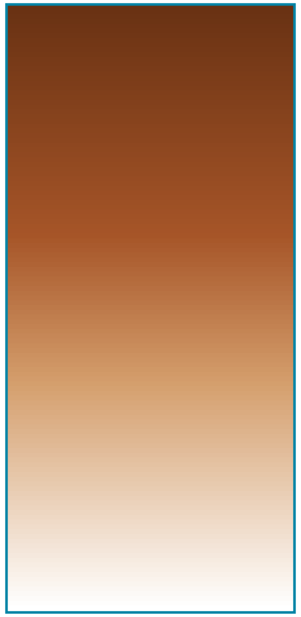
– Backwash

– Filter to waste

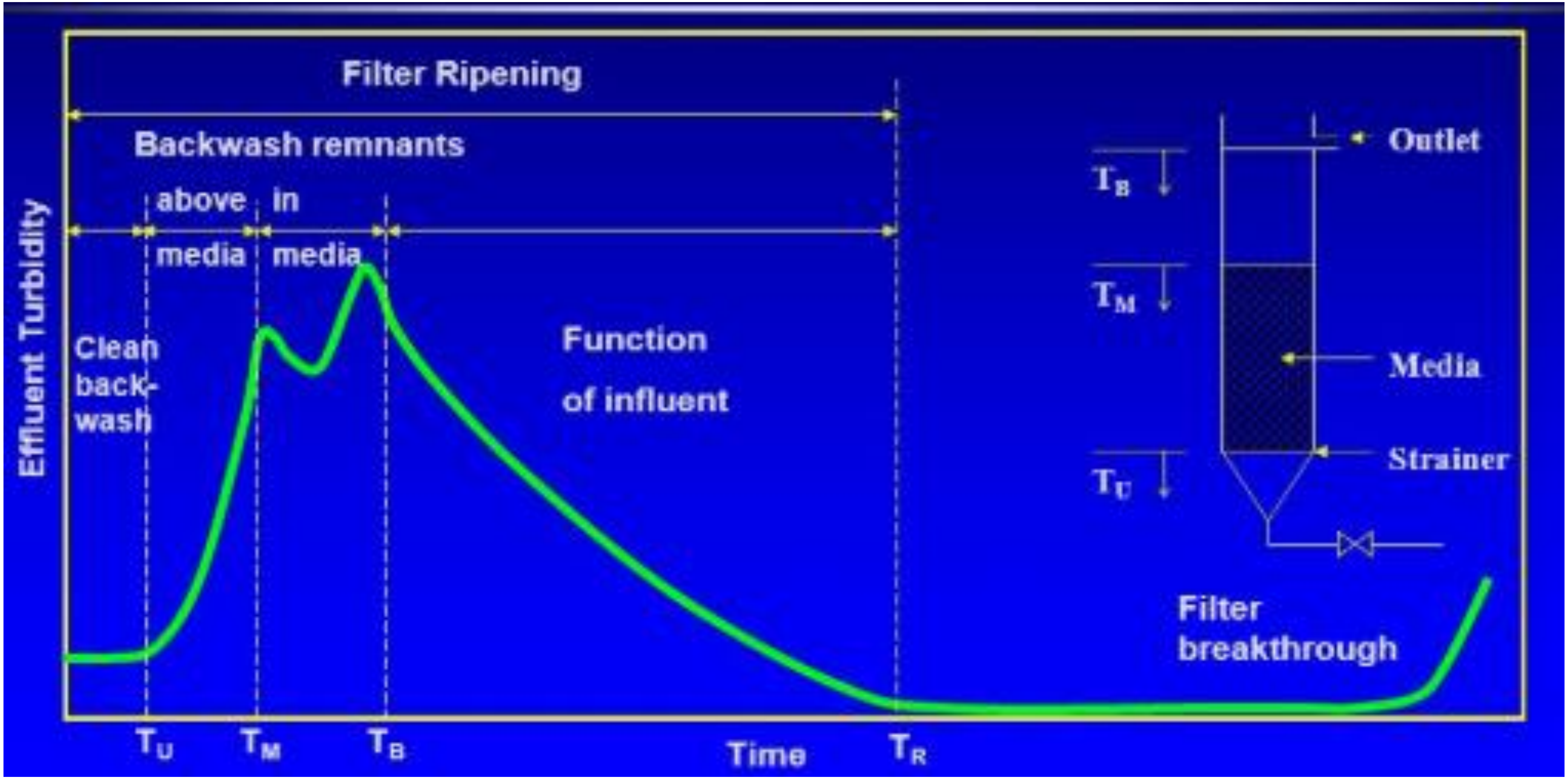


Turbidity in the Filter Immediately After Backwash

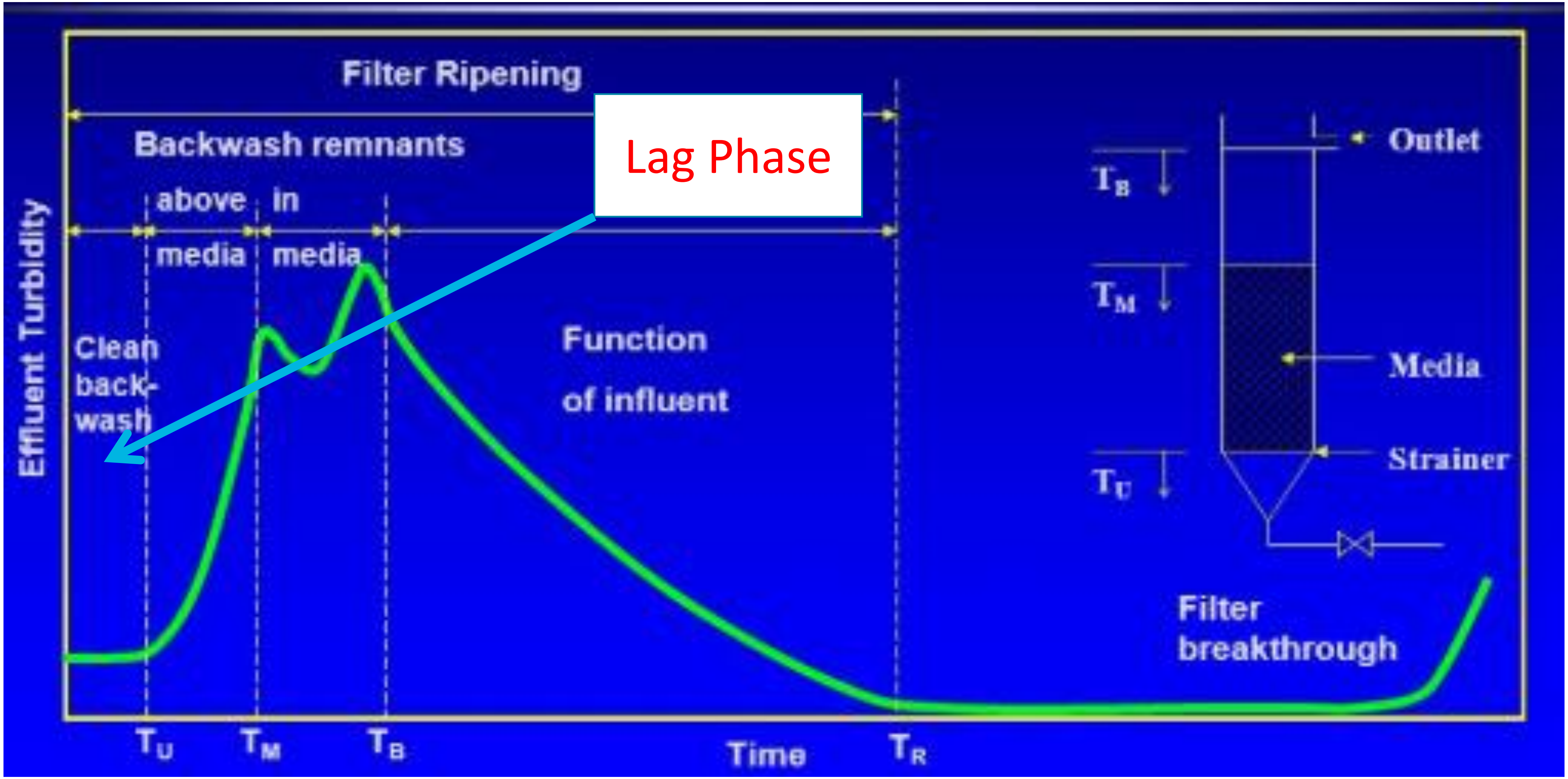
- When backwash pump stops, while most of the particles in the filter are removed, there are still particles left inside the filter, particularly close to the top of the surface
- Turbidity is lower at the bottom of the filter (mostly fresh backwash water, which is filtered water) and higher close to the filter surface (not all particles are removed by BW)
- Note the regulatory requirement on finished water turbidity is 0.3 NTU as maximum; but typical WTP control turbidity at 0.1 NTU or lower
- Water with a turbidity > 0.3 NTU is considered off-spec water



Turbidity Trend Immediately after Backwash is Completed



Turbidity within a Filtration Cycle



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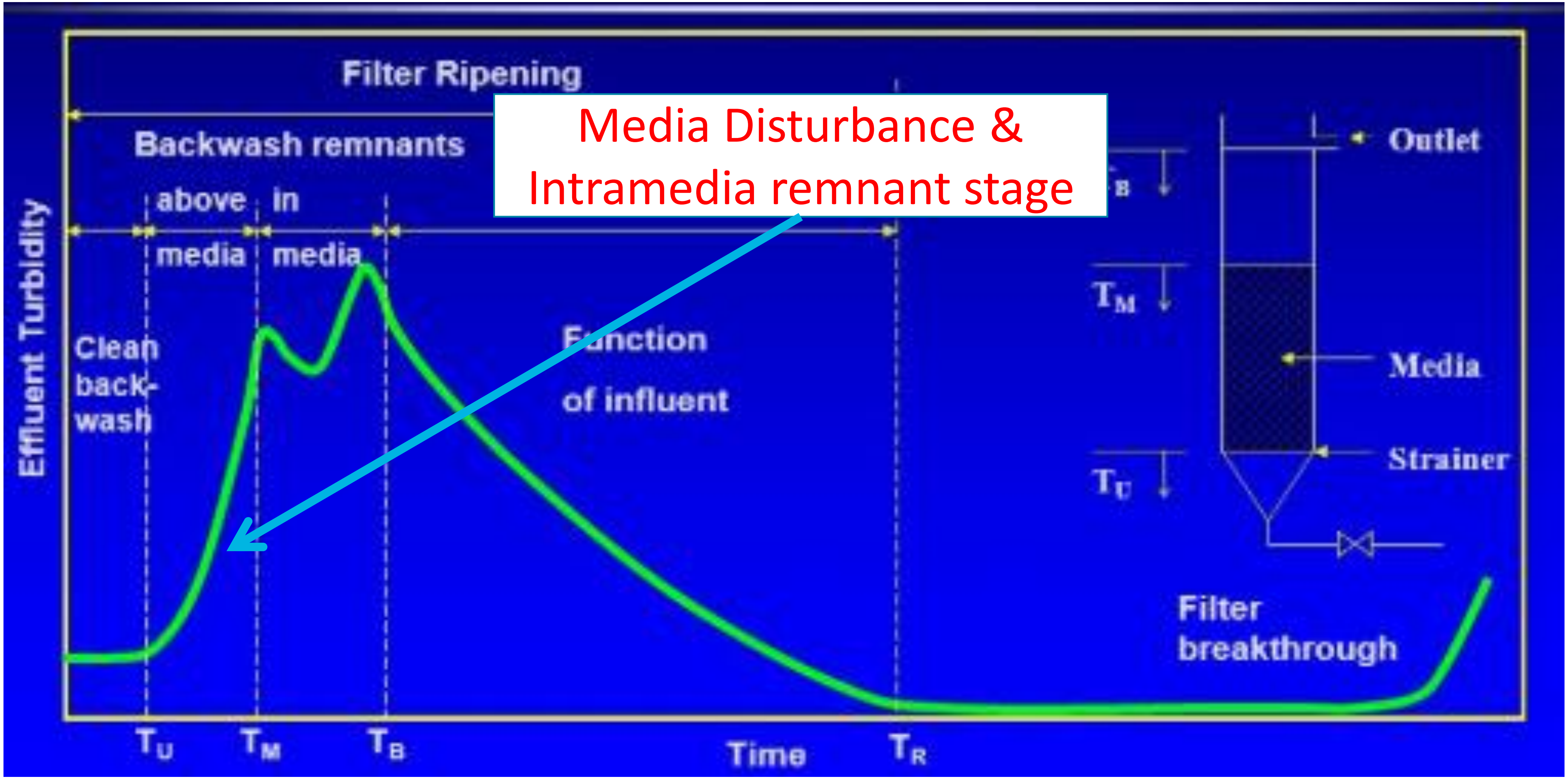
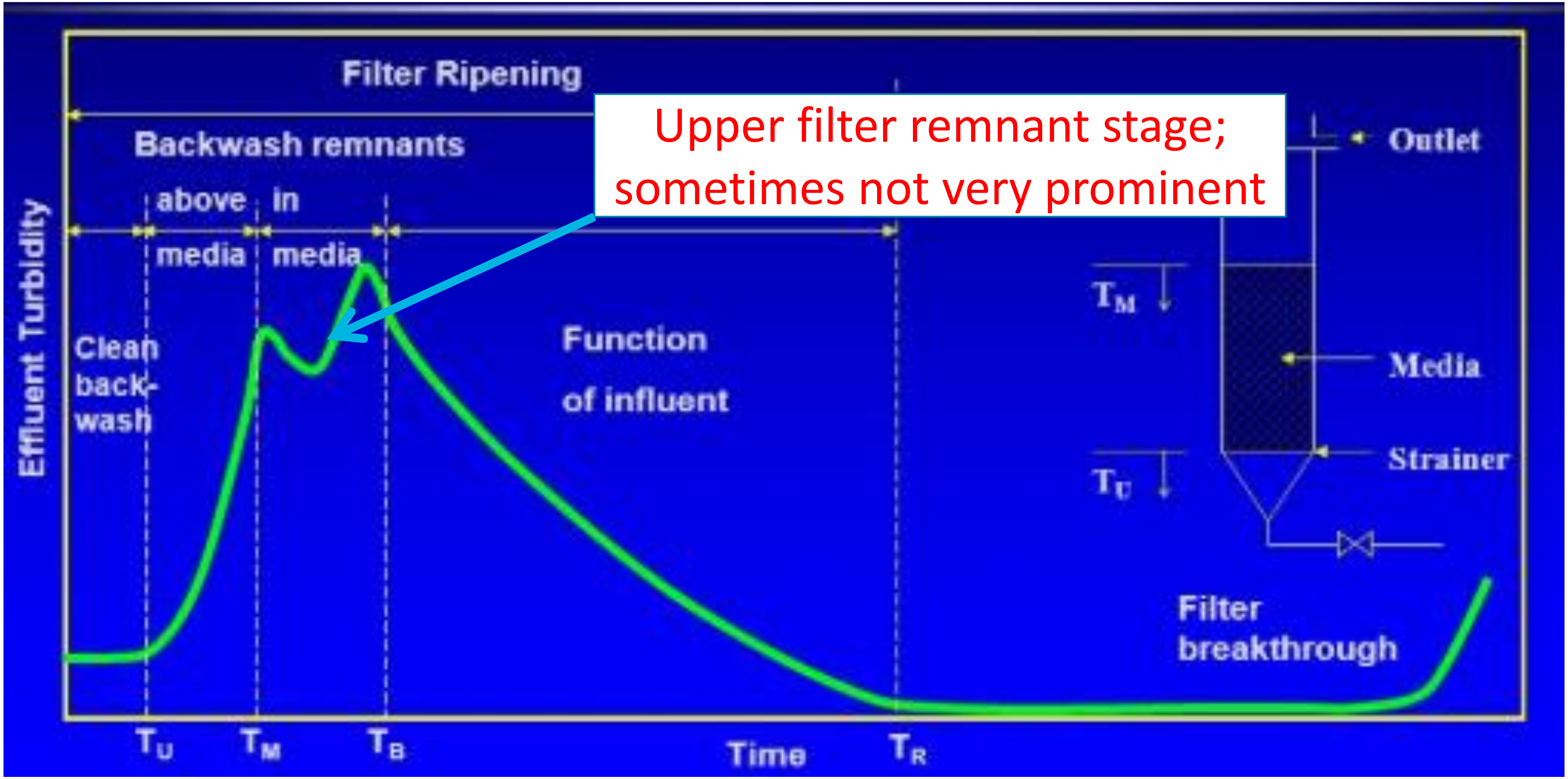
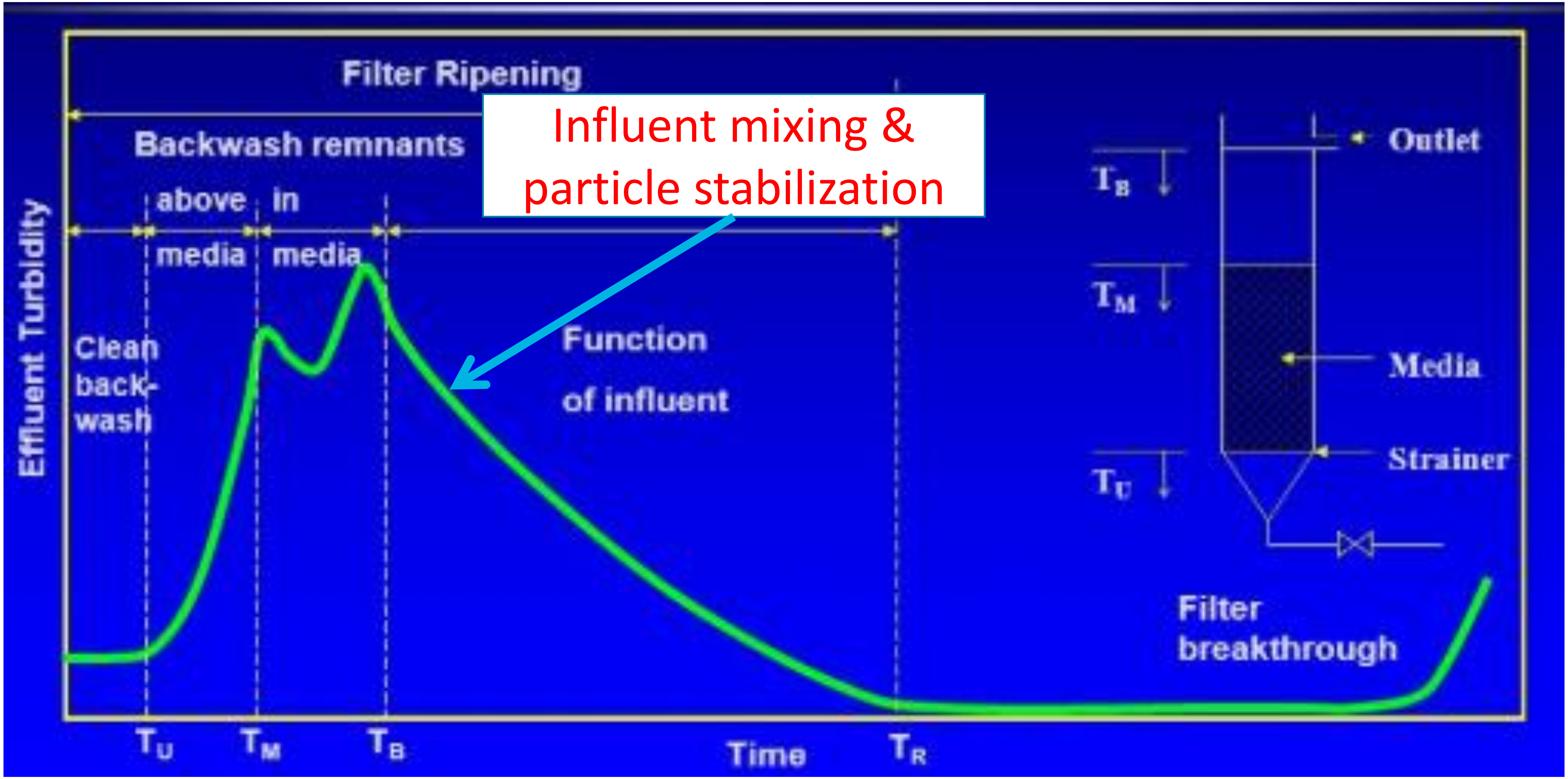


Turbidity within a Filtration Cycle



Upper filter remnant stage; sometimes not very prominent

Turbidity within a Filtration Cycle



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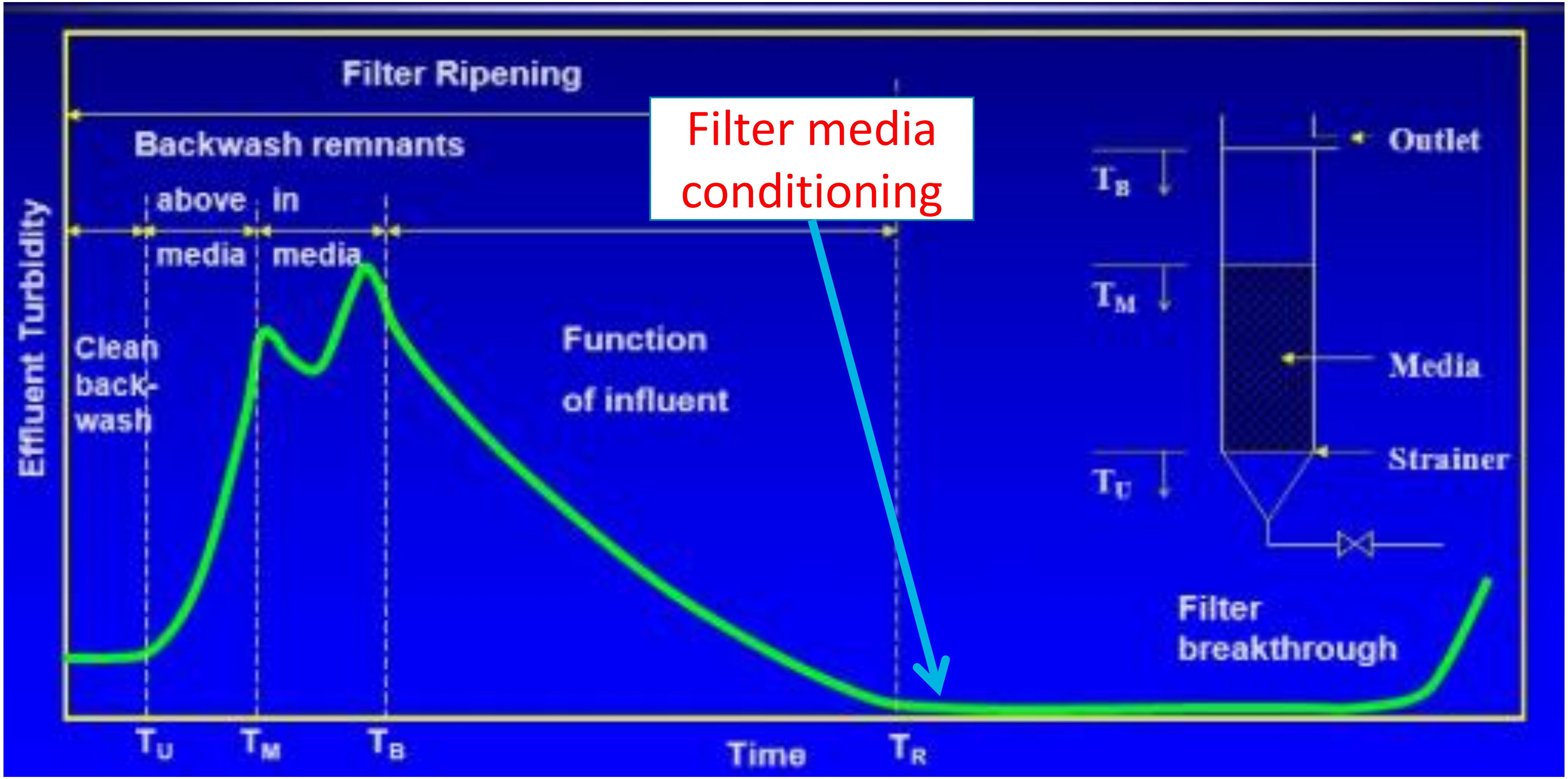

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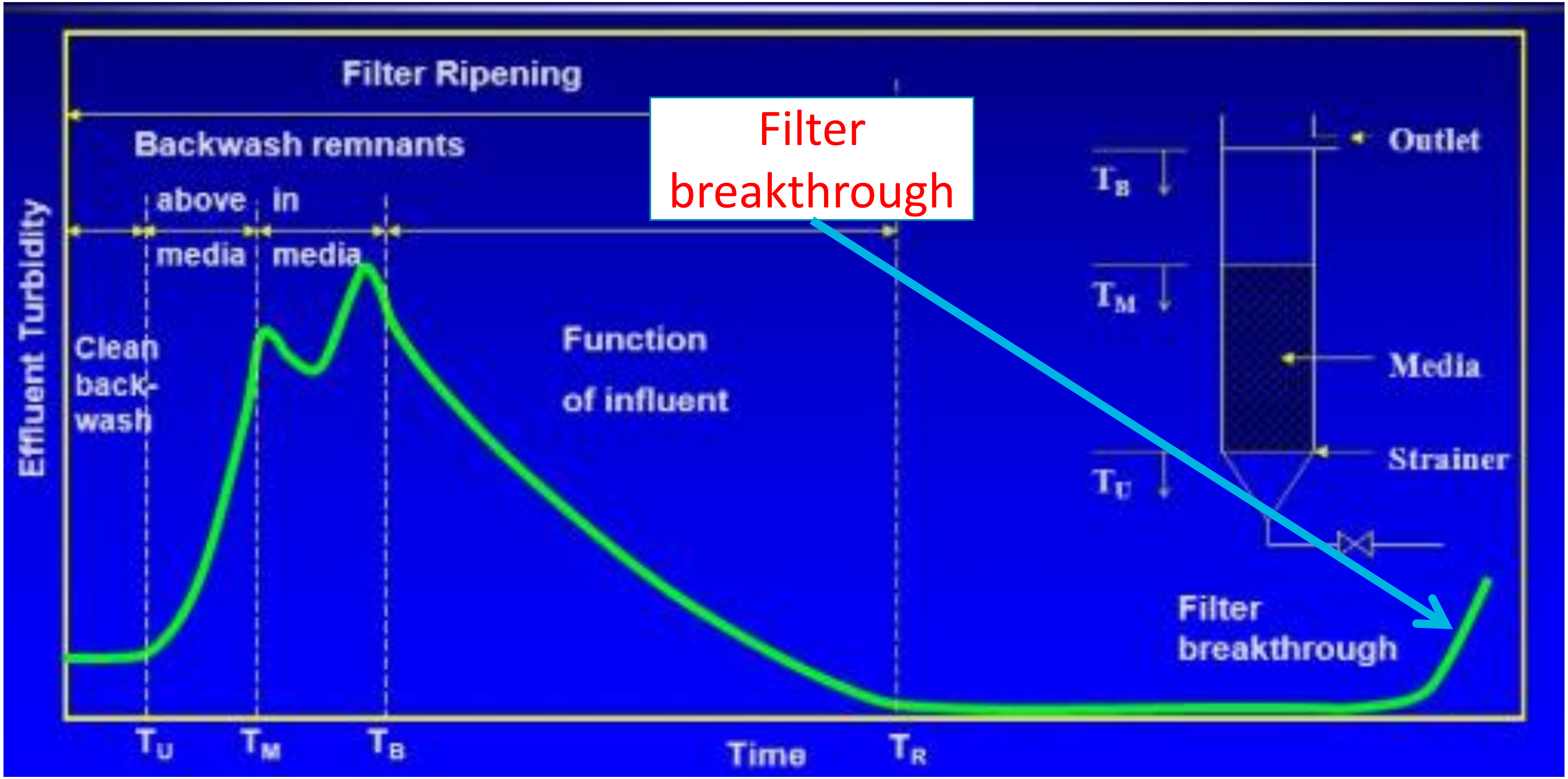
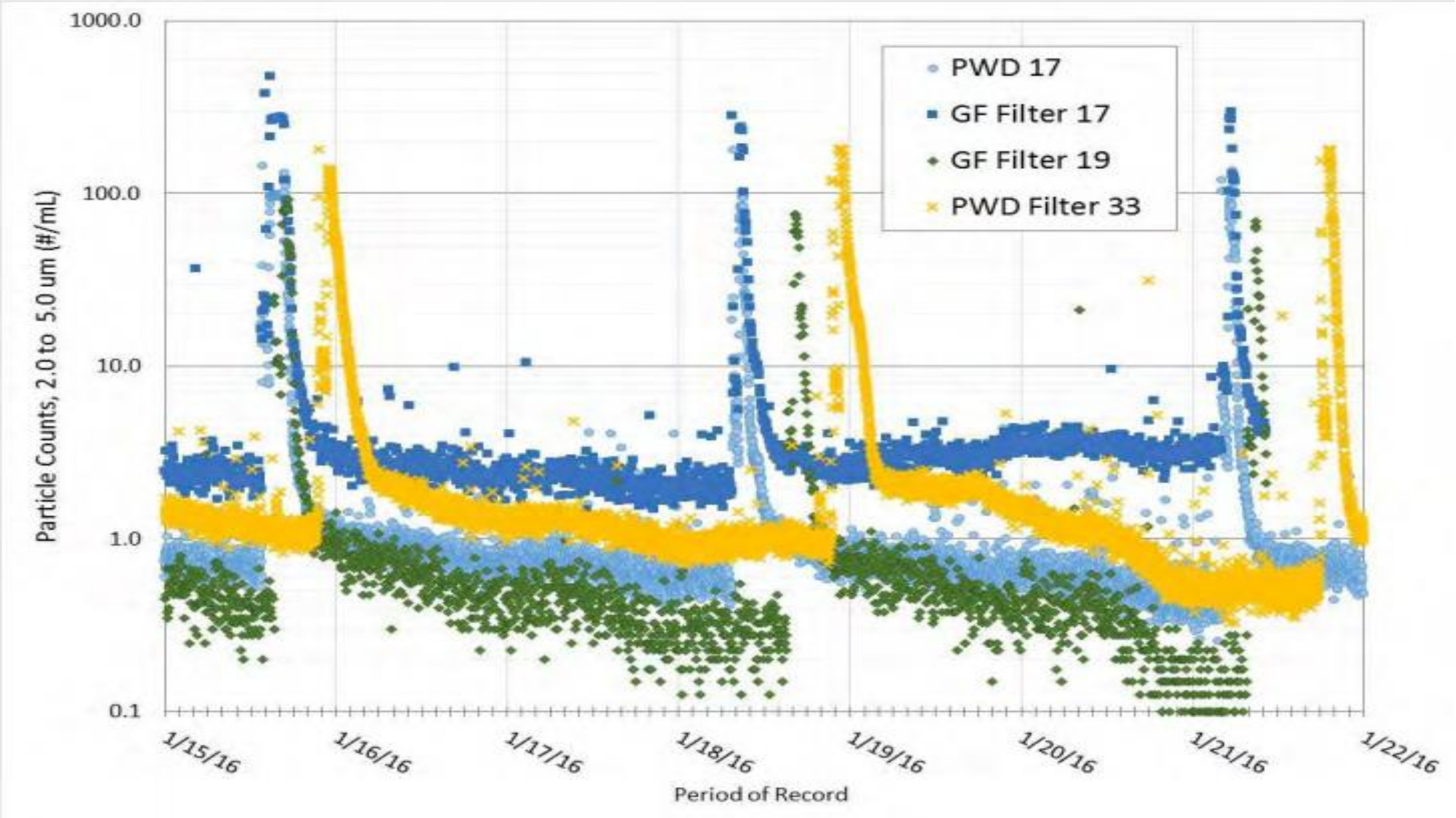
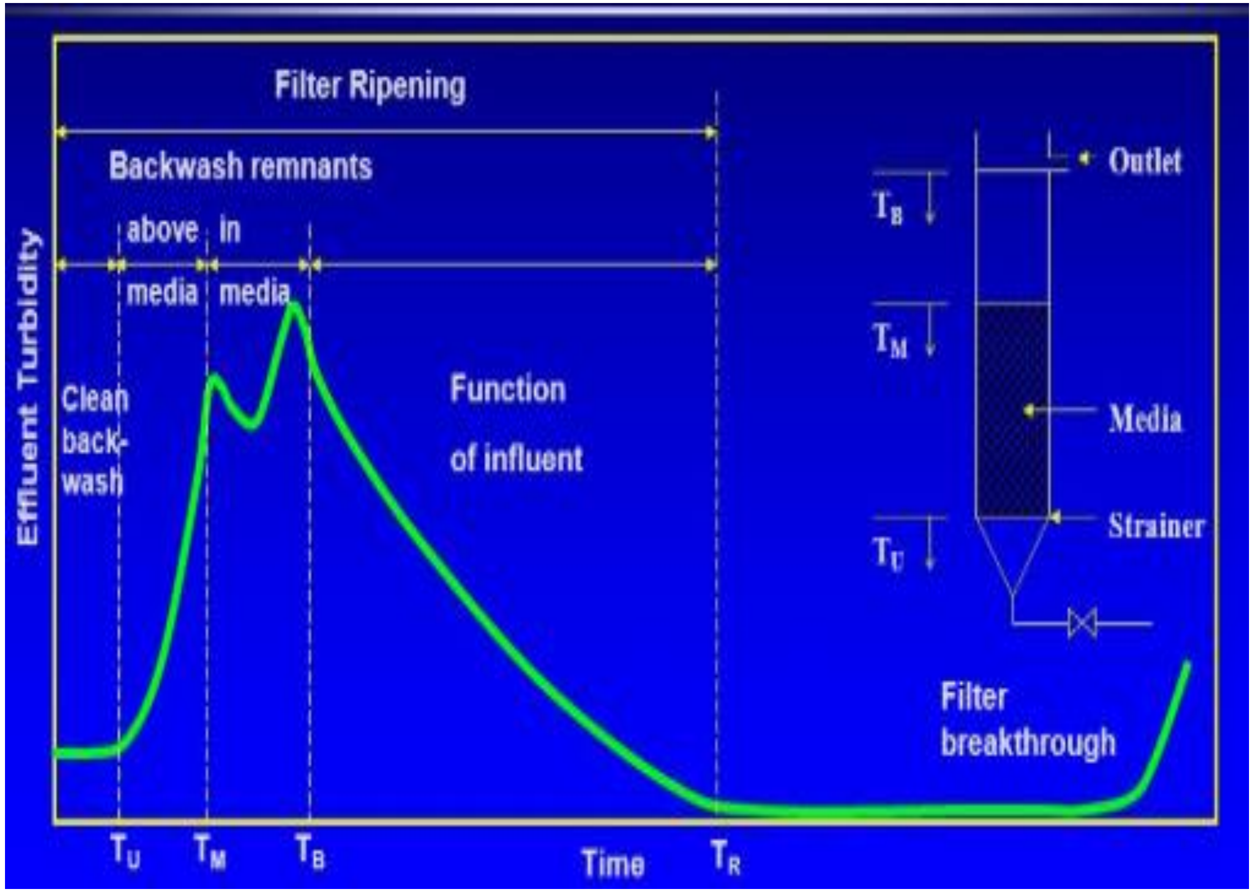


Typical Particle Count in Filter Effluent



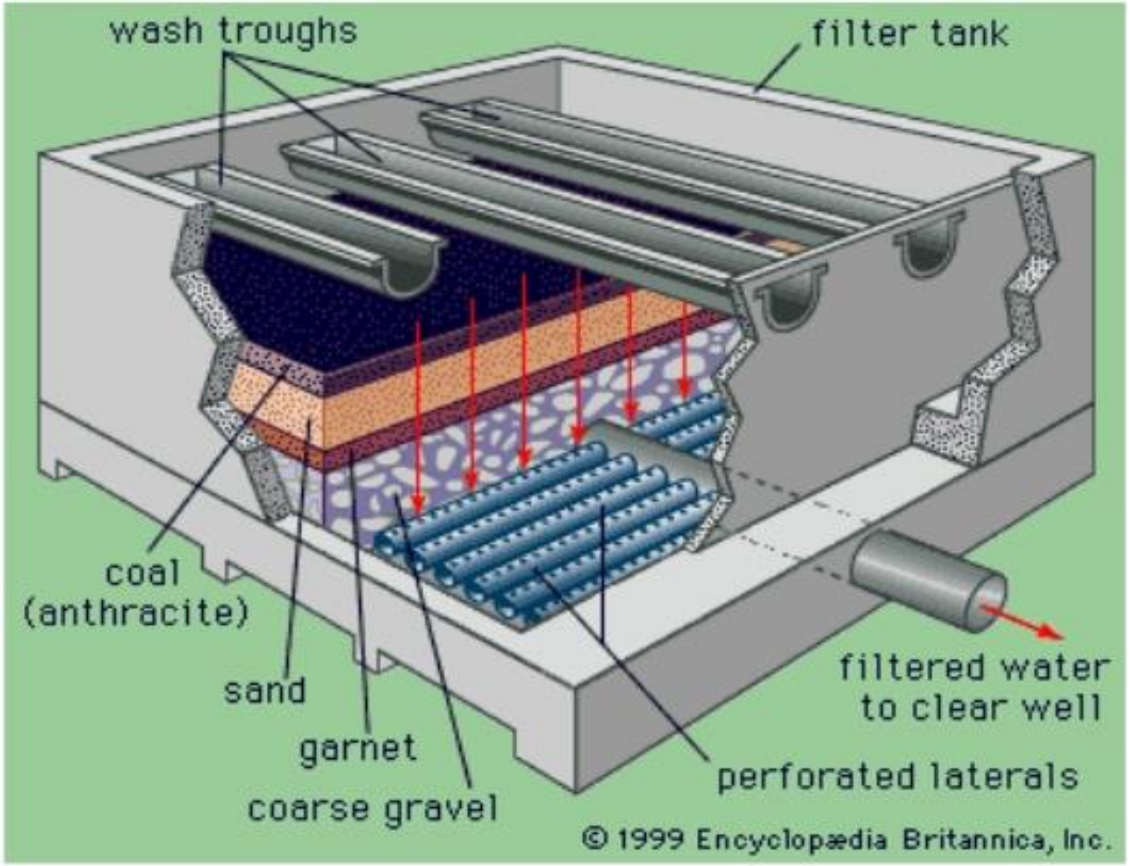
Key Terminologies in Media Filtration (cont.)

- **Filtration Rate** (Filter Loading Rate): Key process variable; the superficial water velocity through the filter bed, calculated as the flow rate divided by the cross-sectional area of the bed. (gpm/ft2)
- **Ripening**: Process of granular media conditioning at the beginning of a filter run during which clean media captures particles and becomes more efficient at capturing additional particles. During ripening filter effluent water may not meet quality requirements (off-spec water) and must be wasted; typically it is recycled to the head of the plant.

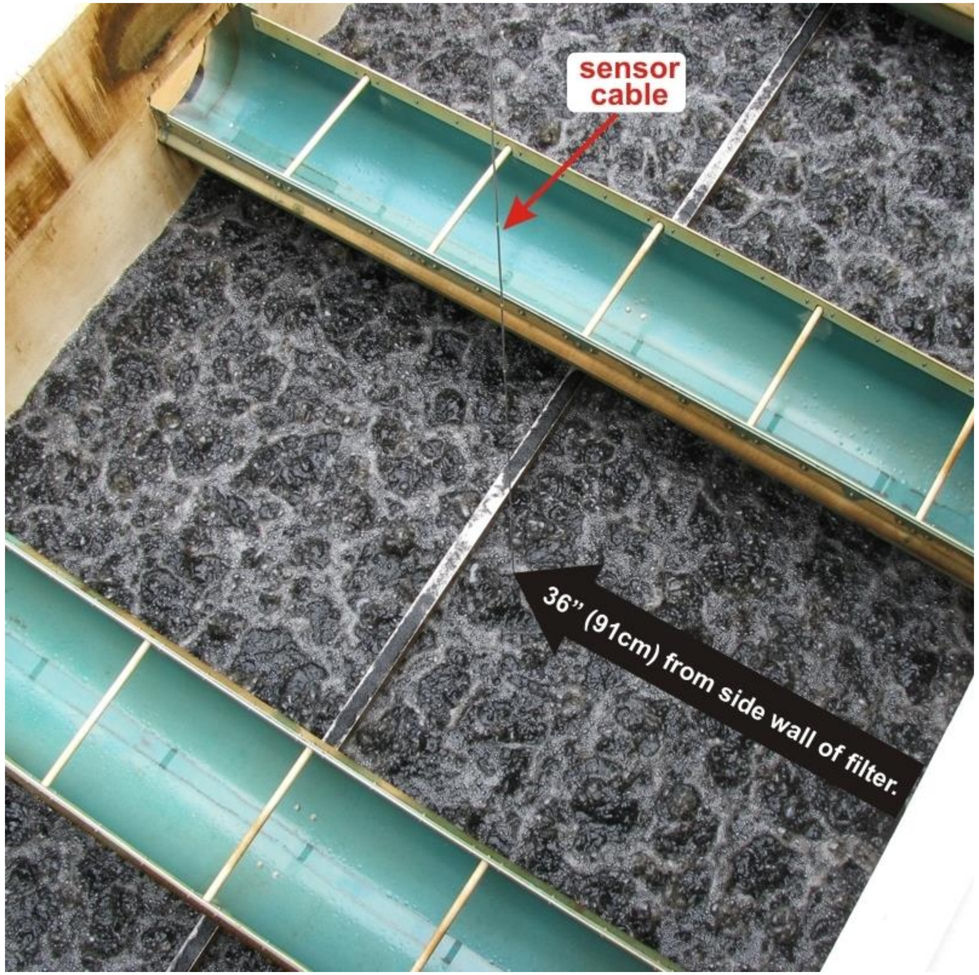


Key Terminologies in Media Filtration

– **Backwash:** Process for removing accumulated solids from a filter bed by reversing the water flow.



Multi-media filter



Key Terminologies in Media Filtration

- **Backwash:** Process for removing accumulated solids from a filter bed by reversing the water flow.
- **Air Scouring:** Optional feature during backwash in which air is introduced into filter underdrains along with backwash water; the vigorous scouring action helps clean deep-bed filters.
- **Contact Filtration:** Process train consisting of coagulation and filtration (opposed to size exclusion filtration).
- **Depth Filtration:** Filtration mechanism in which particles accumulate throughout the depth of a granular filter bed by colliding with and adhering to the media. Captured particles can be many times smaller than the pore spaces in the bed.
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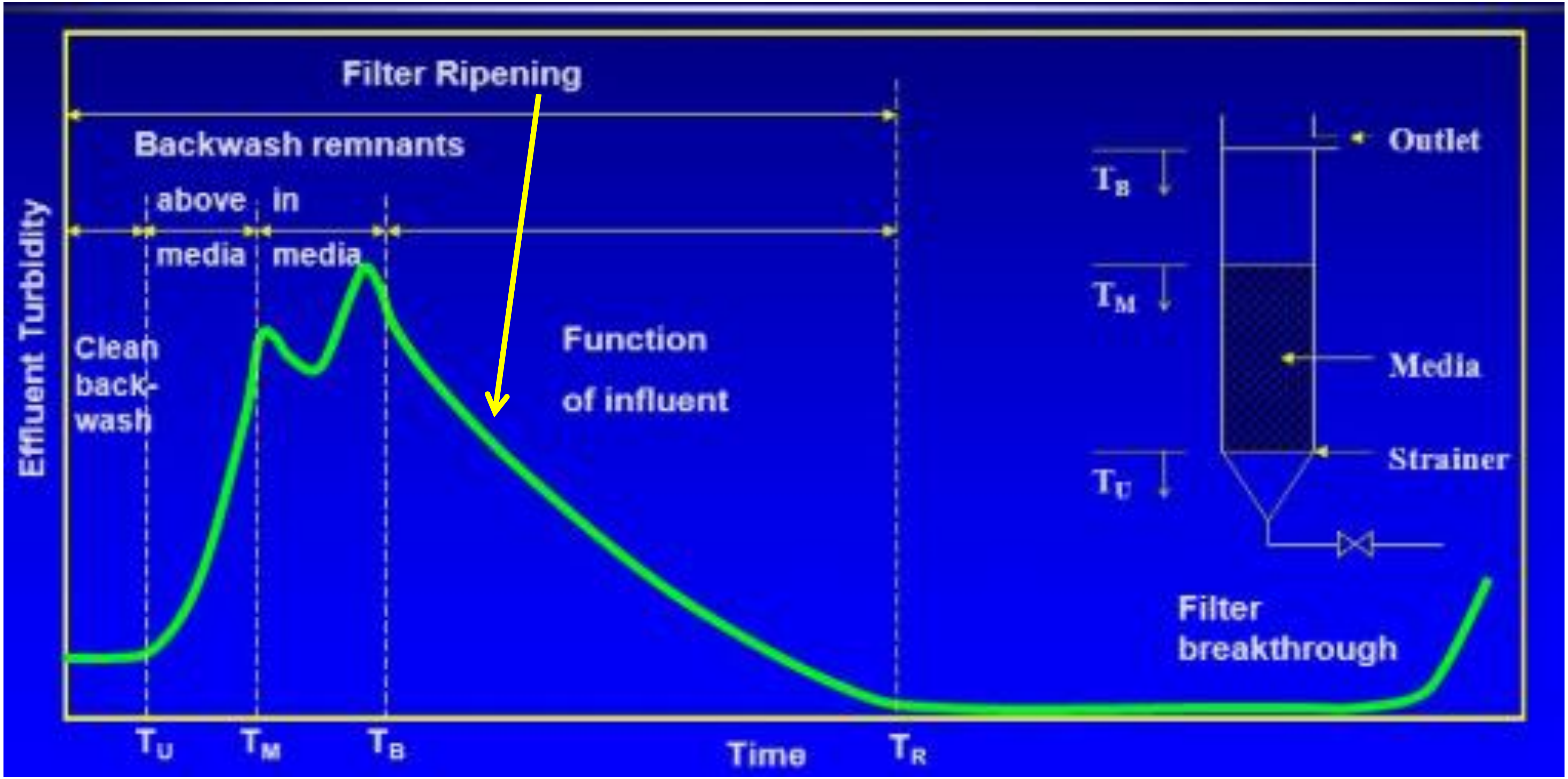
Turbidity within a Filtration Cycle



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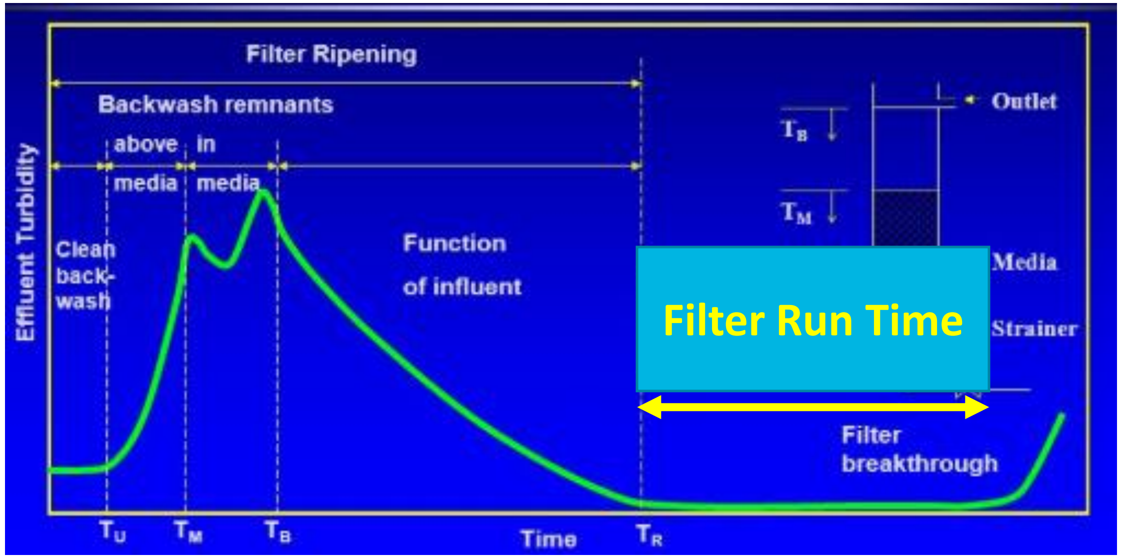
– Filter Breakthrough: Turbidity in the filtrate start increasing above the baseline

– Filter Run Time: Duration of filter operation between the end of filter ripening and turbidity start increasing (filter breakthrough)

– Under Drain: Components installed at the base of a filter bed. Underdrains must support the media and evenly collect filter effluent and distribute backwash water (and air) to avoid channeling in the filter bed. Some underdrain can also provide air for scouring



Underdrain at Grants Pass

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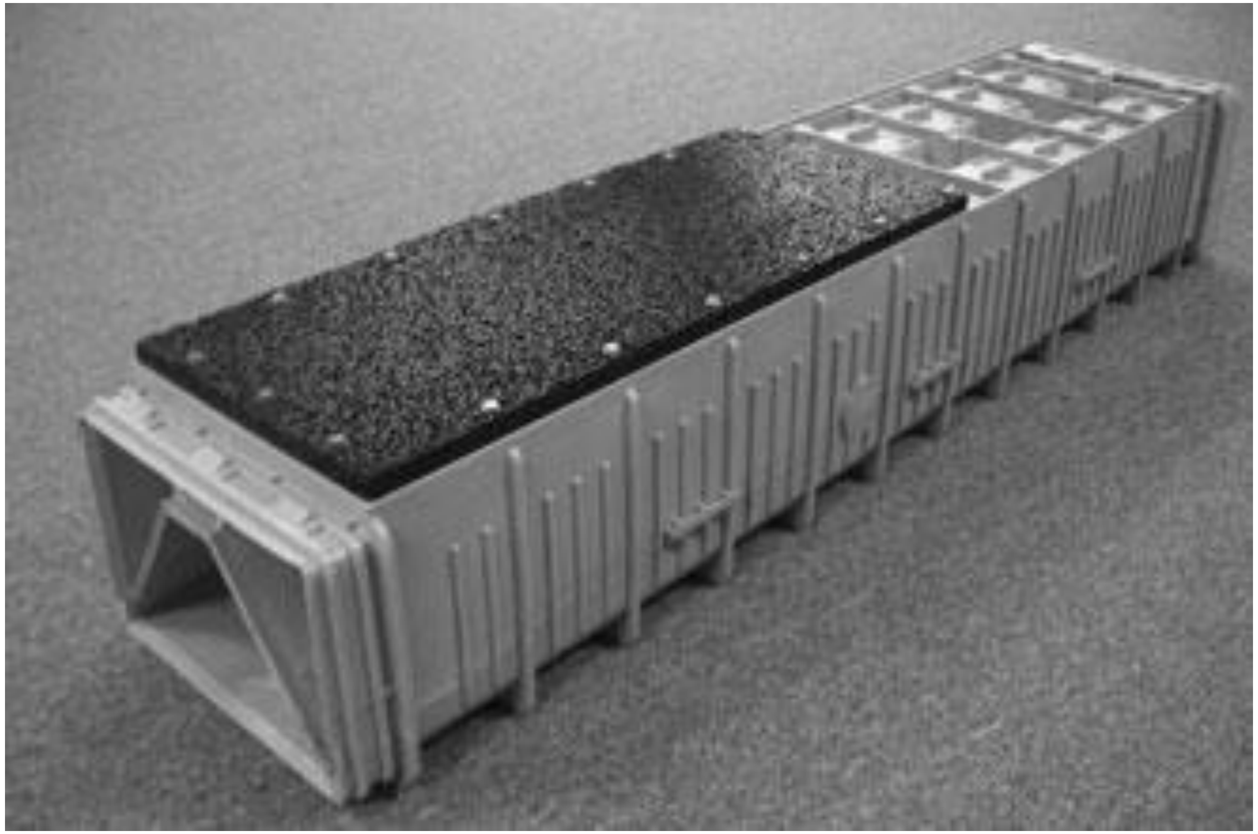

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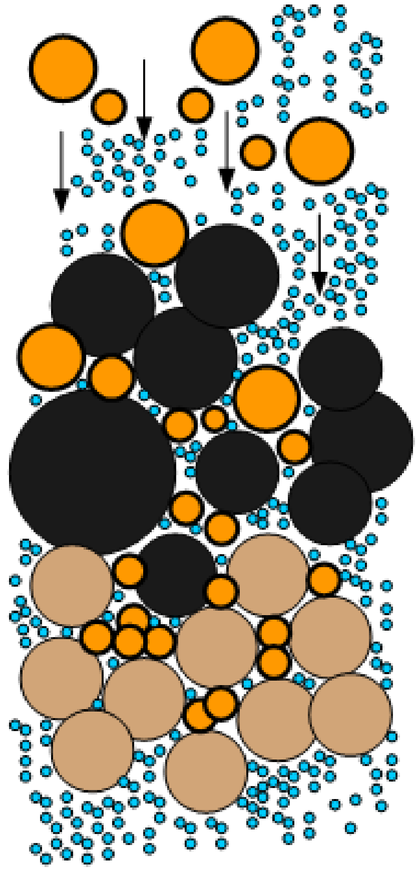
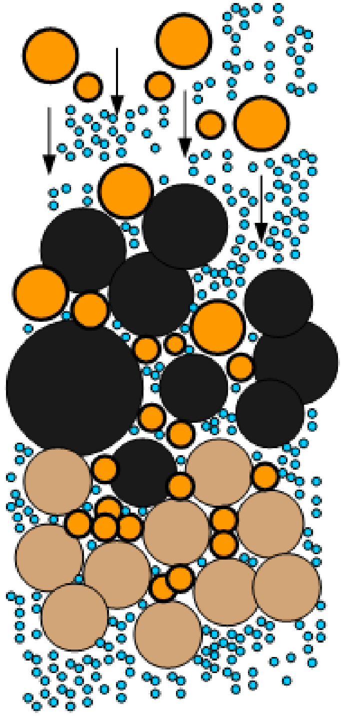


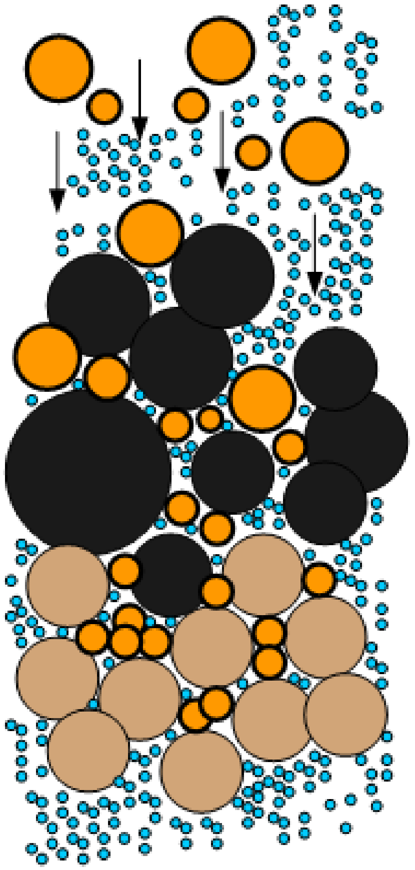
Key Terminologies in Media Filtration (cont.)



- Channeling: a significant portion of water flows through certain pathways (with least resistance) and thereby reducing effectiveness of filtration efficiency
  - Much higher flowrate will create shearing/scouring force on media surface and thereby reduce solid retention (early breakthrough)
  - Usually caused by air binding and “mud balls”
- Mud Balls: Large aggregates of particles and filter media bound by (excessive) flocculation polymers. Presence of mud balls will cause significant uneven water distribution within the filter and reduce the effectiveness of filter performance (e.g., faster breakthrough and shorter filter run time)

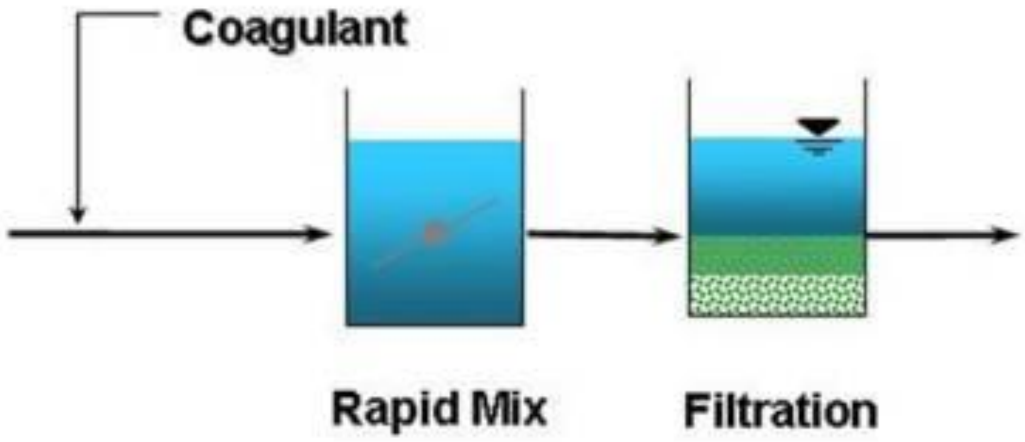
Key Terminologies in Media Filtration (cont.)

- Air binding: Caused by release of dissolved gasses (CO_2, or O_2) and air from water to form bubbles.
- These bubbles occupy void space of the filter media and drainage system.
- Usually it is caused by negative pressure within the filters; warm water temperature, and increased dissolved oxygen (DO) in water.
- It can be minimized by avoiding excess head loss, warming of water, control of algal growth and avoiding super saturation of air in water.



Key Terminologies in Media Filtration

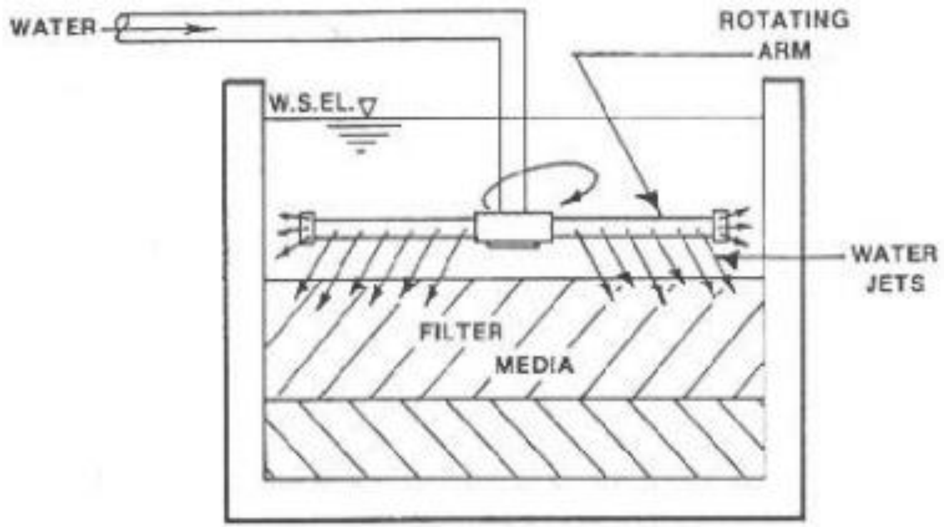
- **Contact Filtration:** Process train consisting of coagulation and filtration.
- **Depth Filtration:** Filtration mechanism in which particles accumulate throughout the depth of a granular filter bed by colliding with and adhering to the media. Captured particles can be many times smaller than the pore spaces in the bed.
- **Direct Filtration:** Process train consisting of coagulation, flocculation, and filtration. (No sedimentation)
  - Usually is suitable for raw water with low turbidity, low organics (TOC) and consistent water quality



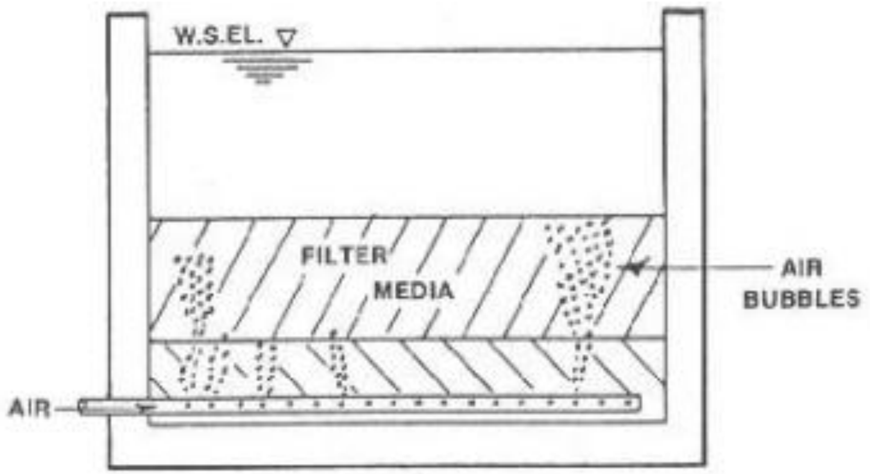
Filter Surface Wash

- The upper 6 -10 inches of filter media remove most of the particulates
- Typical backwash cannot clean this top layer of media thoroughly
- Additional media agitation is needed to assist the cleaning
- Compressed air is usually used to assist cleaning

Rotary Surface Wash

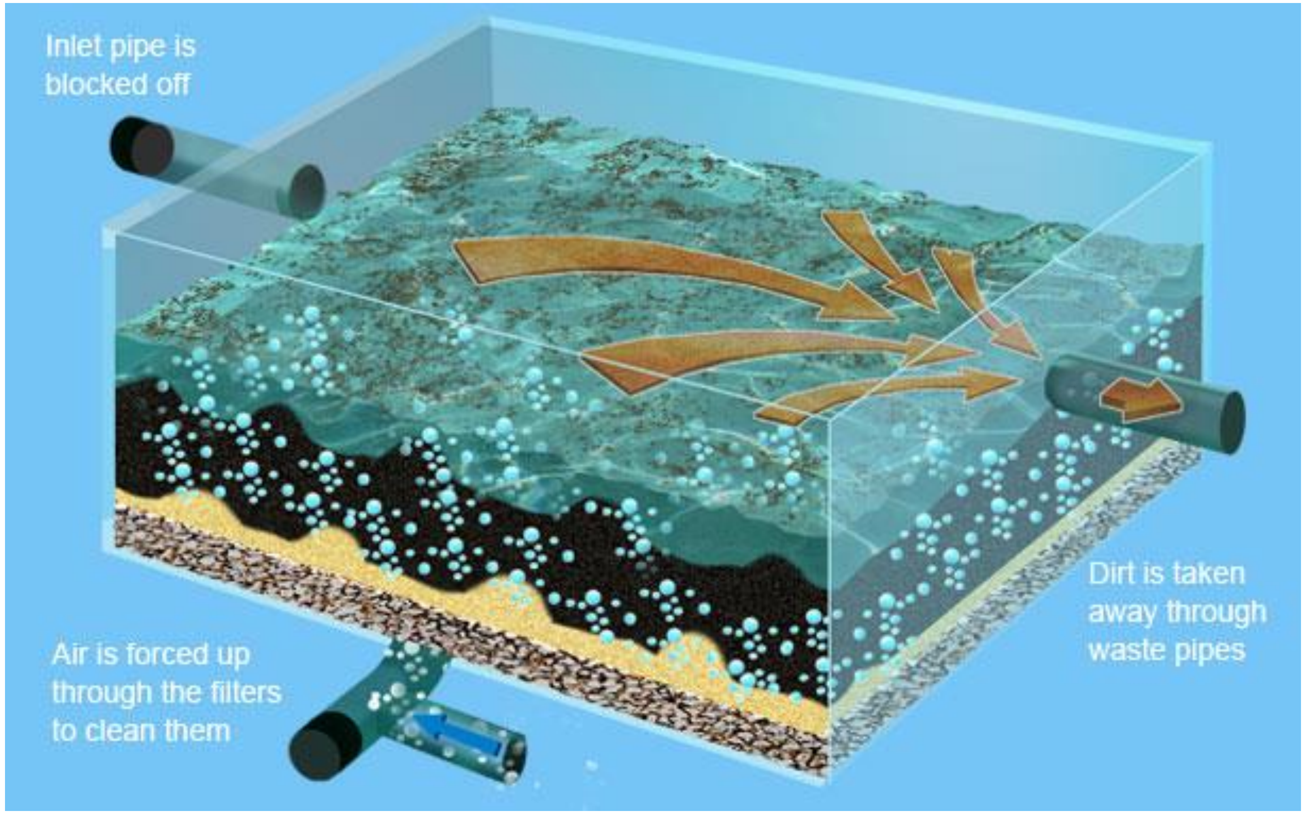


Air Wash:
Add air to backwash water



Key Terminologies in Media Filtration

– **Air Scouring (air wash)** Optional feature during backwash in which air is introduced into filter underdrains with high pressure along with backwash water; the air expands the sand bed and vigorous scouring action helps clean deep-bed filters.



Filter Surface Wash & Air Scouring

- Surface wash usually starts 1 – 2 min before backwash start (to break apart the “matt” on the surface) and continue for 5 – 10 min into a backwash cycle after the filter bed is fluidized.
- Surface wash is usually more effective for filter bed < 3 ft and not as effective for a deep bed filter
- Air scouring is necessary for cleaning deep-bed filters
- Newer filter under drain system will have the function of distributing air through underdrains together with water
- Air scouring is most effective when the backwash flow velocity is 25 ~ 50% of what’s needed to fluidize media bed

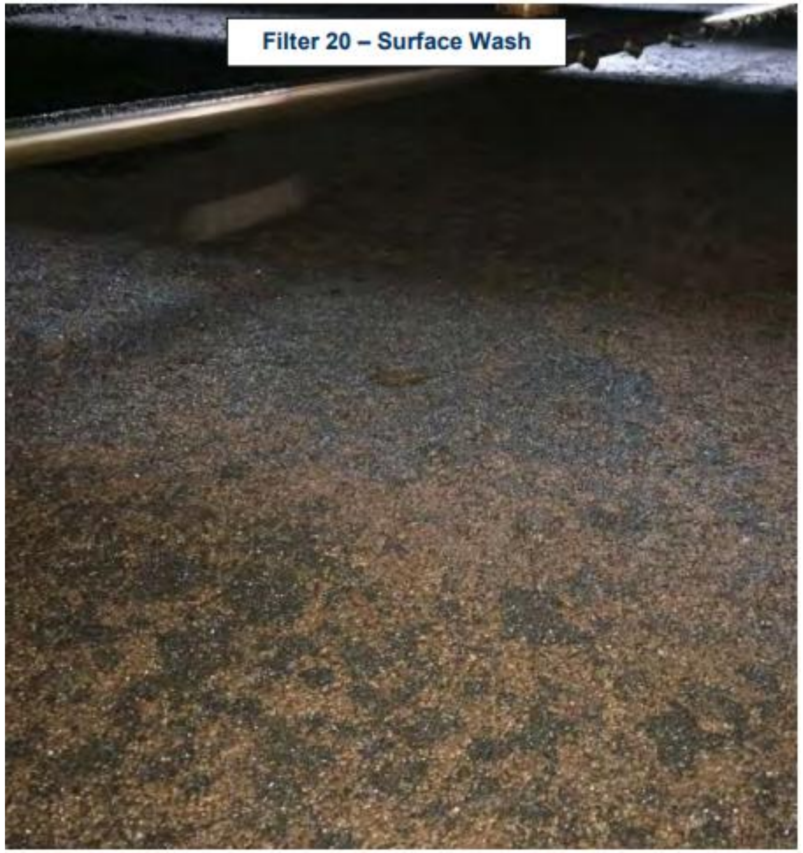
Typical Air Scouring Procedure

1. Drain the water to a level about 150mm (6 in.) above the top of the media
2. Start the water & air at appropriate rates for collapse pulsing
3. Continue the air scour while the water level gradually rises in the filter box
4. Terminate the air flow rate just before the water level reaches the lip of the wash water troughs
5. Increase the backwash water rate to the fluidization velocity and continue to wash the filter for several more minutes to flush solids from the bed, and
6. Terminate backwash water slowly to allow dual-media filters to re-stratify.

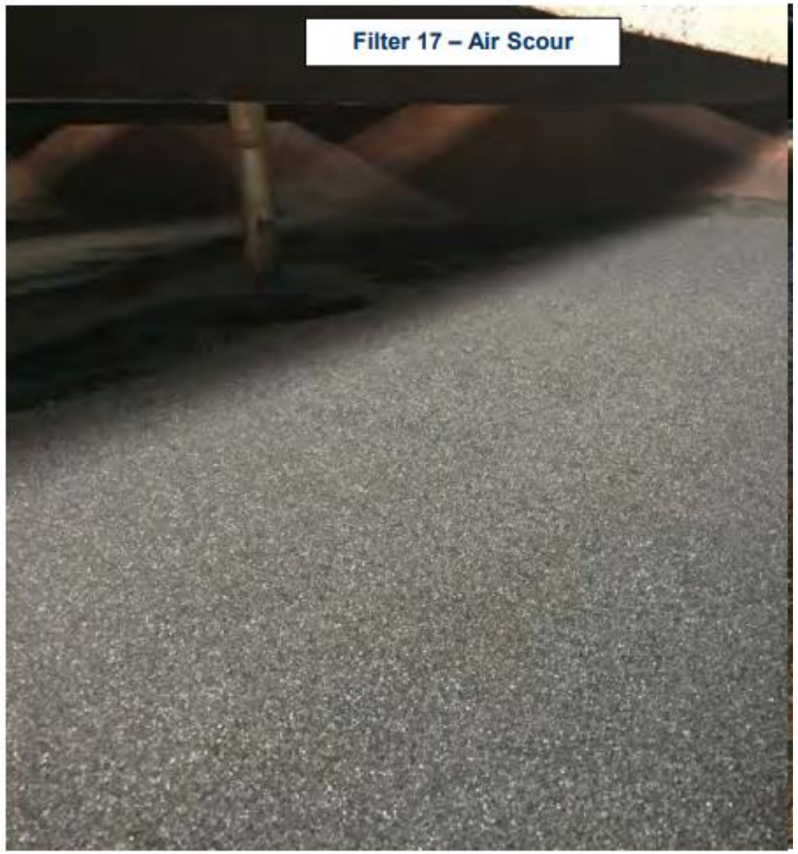
Air Scouring

Air Scouring System

Filter after Surface Wash



Filter after Air Scour



Key Design Parameters for Various Supplemental Backwash

Table 11-8
Typical design criteria for supplemental backwash systems

Criteria	Units	Fixed-Nozzle Surface Wash	Rotating-Arm Surface Wash	Air Scour
Surface wash water flow rate	m/h gpm/ft^2	7–10 2.8–4	1.2–1.8 0.5–0.7	— —
Air flow rate	$m^3/m^2 \cdot h$ scfm/ft^2	— —	— —	36–72 2–4
Pressure at discharge point	bar psi	0.5–0.8 7.2–11.6	5–7 73–100	0.3–0.5 4.3–7.3
Duration of washing	min	4–8	4–8	8–15
Backwash water flow rate	m/h gpm/ft^2	30–60 12–24	30–60 12–24	15–45 6–18

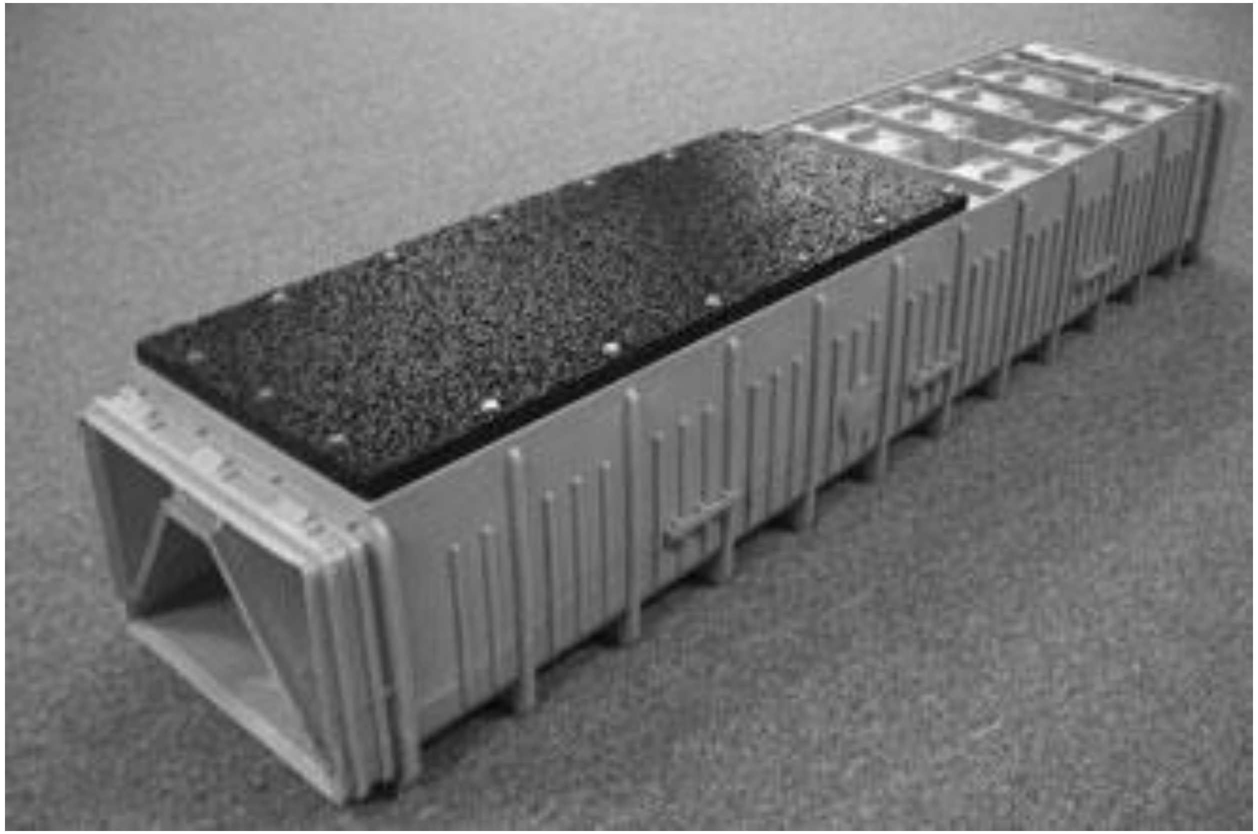
SCFM: Standard Cubit Feet per Minute

Underdrain at Grants Pass

– Leopold U-Block Underdrain

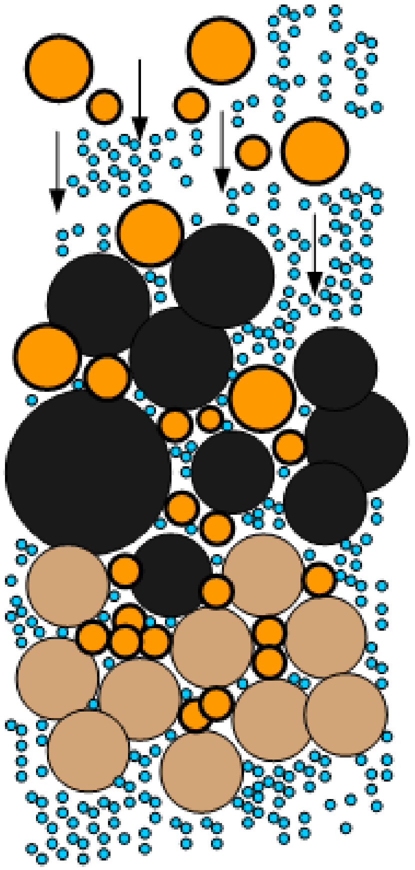
Underdrain at Grants Pass

- Leopold Underdrain with Cap
- Garnet and Gravels are not required with the Cap



Key Terminologies in Media Filtration (cont.)

- Channeling: a significant portion of water flows through certain pathways (with least resistance) and thereby reducing effectiveness of filtration efficiency
  - Much higher flowrate will create shearing/scouring force on media surface and thereby reduce solid retention (early breakthrough)
  - Usually caused by air binding and “mud balls”
- Air binding: Caused by release of dissolved gasses and air from water to form bubbles. These bubbles occupy void space of the filter media and drainage system. Usually it is caused by negative pressure within the filters; warm water temperature, and increased dissolved oxygen (DO) in water. It can be minimized by avoiding excess head loss, warming of water, control of algal growth and avoiding super saturation of air in water.

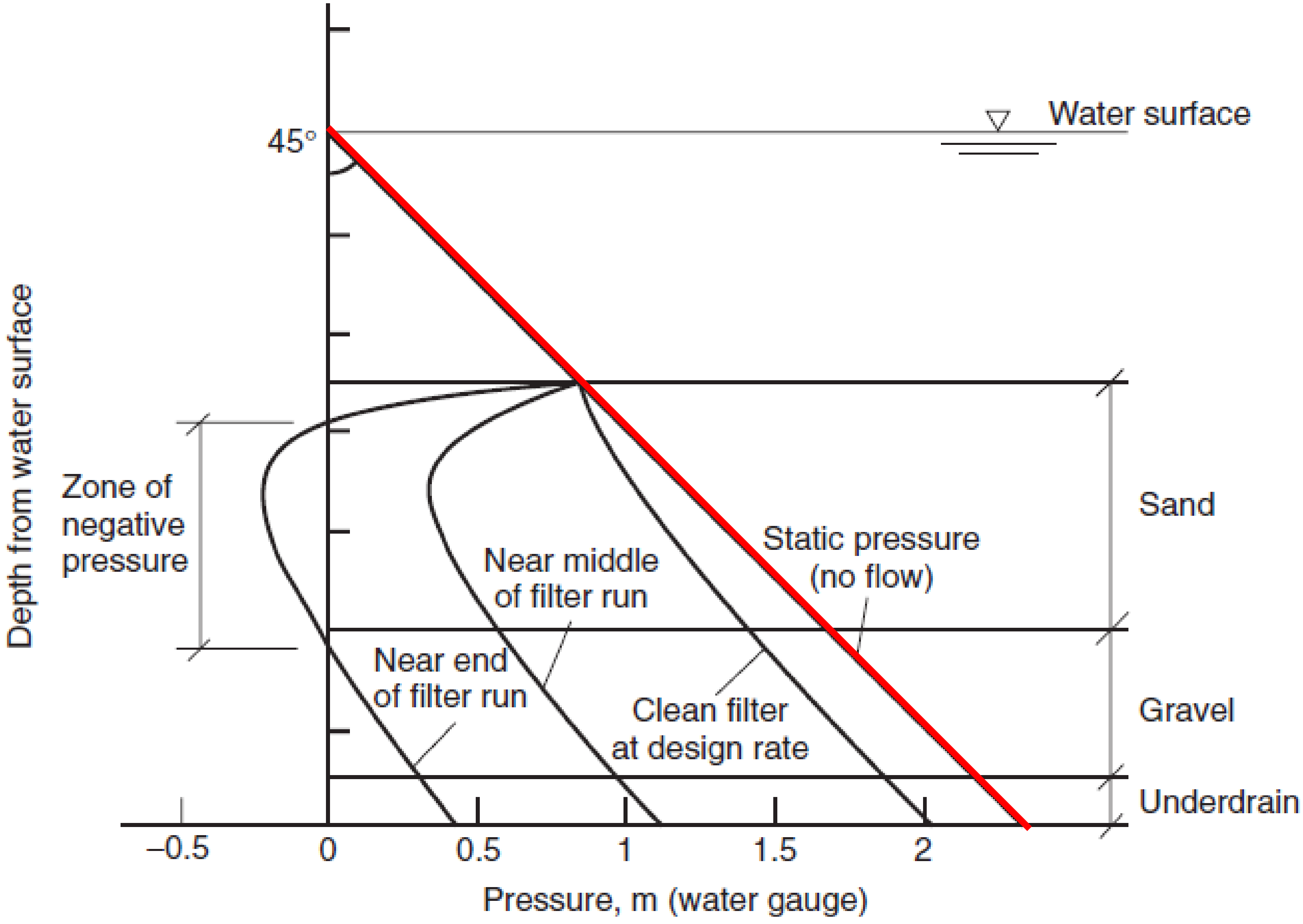


How Does Negative Pressure Happen in a Filter?

– During filtration, the hydraulic gradient (head loss per unit depth) can be greater near the top of the bed because of the greater collection of solids near the top of the bed. If the hydraulic gradient is greater than the static head gradient, low or even negative pressure

Development of Negative Pressure in a Filter

- Without water flowing downward, static pressure at any given point in the filter should be static water head (depth of water above that point)
- When filter started getting clogged, the resistance increases, thereby reducing the pressure at lower zone
- Eventual pressure could be < 0 and becomes negative



Typical Filter Design Parameters

Parameter	Units	Value
Filter type	—	Conventional, deep-bed monomedia
Flow control	—	Influent weir split, constant level
Number	—	8
Inside dimensions	m · m	10 × 4.55 × 2 cells
Media surface area (each filter)	m^2	91
Media surface area (total)	m^2	728
Maximum available head	m	2.5
Filtration rate (at plant design flow rate)		
One filter off-line	m/h	15
All filters in service	m/h	13.2
Filter media		
Type	—	Anthracite
Depth	m	1.8
Effective size	mm	1.0
Uniformity coefficient	—	<1.4
Density	—	1700
Backwash criteria		
Maximum rate	m/h	48.2
Normal rate	m/h	38.6
Duration	min	15

Homework & Reading Assignments

- Reading: Chapter 11
- Homework: Problem #11-1

Calculation of Clean-Bed Hydraulic Head Loss

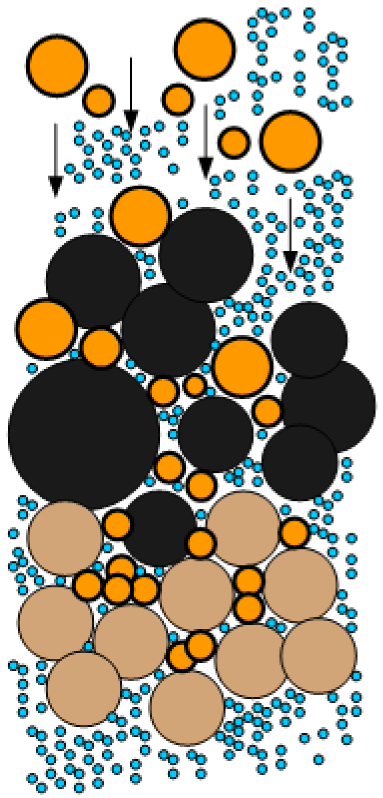
- **Filtration Rate**
  - Higher loading rate results in higher head loss
- **Effective Filter Media Diameter**
  - Head loss doubled as the effective particle size of anthracite decreases from 1.2 mm to 0.8 mm
- **Filter bed porosity**
  - Head loss increased by 65% as porosity decreases from 0.52 to 0.47
- **Water temperature**
  - Head loss increased by 60 - 70% as water temperature decreased from 25 ^{0}C to 5 ^{0}C

Filter Bed Porosity

– Usually 40% - 60%

$$\varepsilon = \frac{V_V}{V_T} = \frac{V_T - V_M}{V_T} \qquad (11\text{-}4)$$

where ε = porosity, dimensionless
V_V = void volume in media bed, m^3
V_T = total volume of media bed, m^3
V_M = volume of media, m^3



Specific Surface Area

- Total surface area of all filter media divided by the bed volume of the filter bed

$$S = \frac{(\text{number of grains})(\text{surface area of each grain})}{\text{bulk volume of filter bed}} \tag{11-5}$$

Development of Clean Bed Head Loss Calculations

- Darcy Equation describes relationship between head loss, water flow velocity, and bed depth in granular media under creeping-flow conditions

$$v = k_p \frac{h_L}{L} \tag{11-9}$$

where v = superficial velocity (filtration rate), m/s
k_p = coefficient, known as hydraulic permeability, m/s
h_L = head loss across media bed, m
L = depth of granular media, m

But….

- Darcy's Law/equation does not consider porosity of a filter bed so it is not useful for predicting head loss within a granular media filter
- Kozeny modify the equation with the following assumptions
  - Flow paths within granular media is similar to "a system of parallel cylindrical channels"
  - Assume Laminar Flow described by Poiseuille's Law

$$\frac{h_L}{L} = \frac{32\mu v}{\rho_W g d^2} \qquad (11\text{-}10)$$

where g = acceleration due to gravity, 9.81 m/s^2

μ = dynamic viscosity of fluid, $kg/m \cdot s$

ρ_W = fluid density, kg/m^3

Kozeny Equation

– Kozeny coefficient is an empirical coefficient that fits the model results from experimental data; which was determined to be about 5 for spherical media.

$$\frac{h_L}{L} = \frac{\kappa_k \mu S^2 v}{\rho_w g \varepsilon^3} \qquad (11\text{-}11)$$

where κ_k = Kozeny coefficient, unitless

S = specific surface area from Eq. 11-5, m^{-1}

ε = porosity from Eq. 11-4, dimensionless

Clean-Bed Hydraulic Head Loss: The Ergun Equation

– Based on Navier-Stokes Equation with 2 assumptions
  - Filter medium & fluid are homogeneous in isotropic
  - Thermodynamic & chemical effects are small and negligible

Ergun Equation

$$h_L = \kappa_V \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu L v}{\rho_w g d^2} + \kappa_I \frac{1-\varepsilon}{\varepsilon^3} \frac{L v^2}{g d} \quad (11\text{-}13)$$

where κ_V = head loss coefficient due to viscous forces, unitless
κ_I = head loss coefficient due to inertial forces, unitless

Data compiled from 640 experiments covering Reynolds numbers between 1 and 2,000; proposed $\kappa_V = 150$ and $\kappa_I = 1.75$

Recommended Values for Parameters

– Ergun equation and proposed coefficients are reasonable for spherical glass beads

Table 11-3

Recommended parameters for use with Eq. 11-13[a]

Medium	κ_V	κ_I	ε_I,
Sand	110–115	2.0–2.5	40–43
Anthracite	210–245	3.5–5.3	47–52

[a]When effective size as determined by sieve analysis is used for the diameter.

Impact of Media Size, Porosity, & Temperature on Head Loss

- Head loss doubles when effective size of anthracite decreases from 1.2 to 0.8 mm
- Head loss increases by 65% as porosity declines from 0.52 to 0.47
- Head loss increases by 60 – 70% when temperature drops from 25 ^oC to 5 ^oC

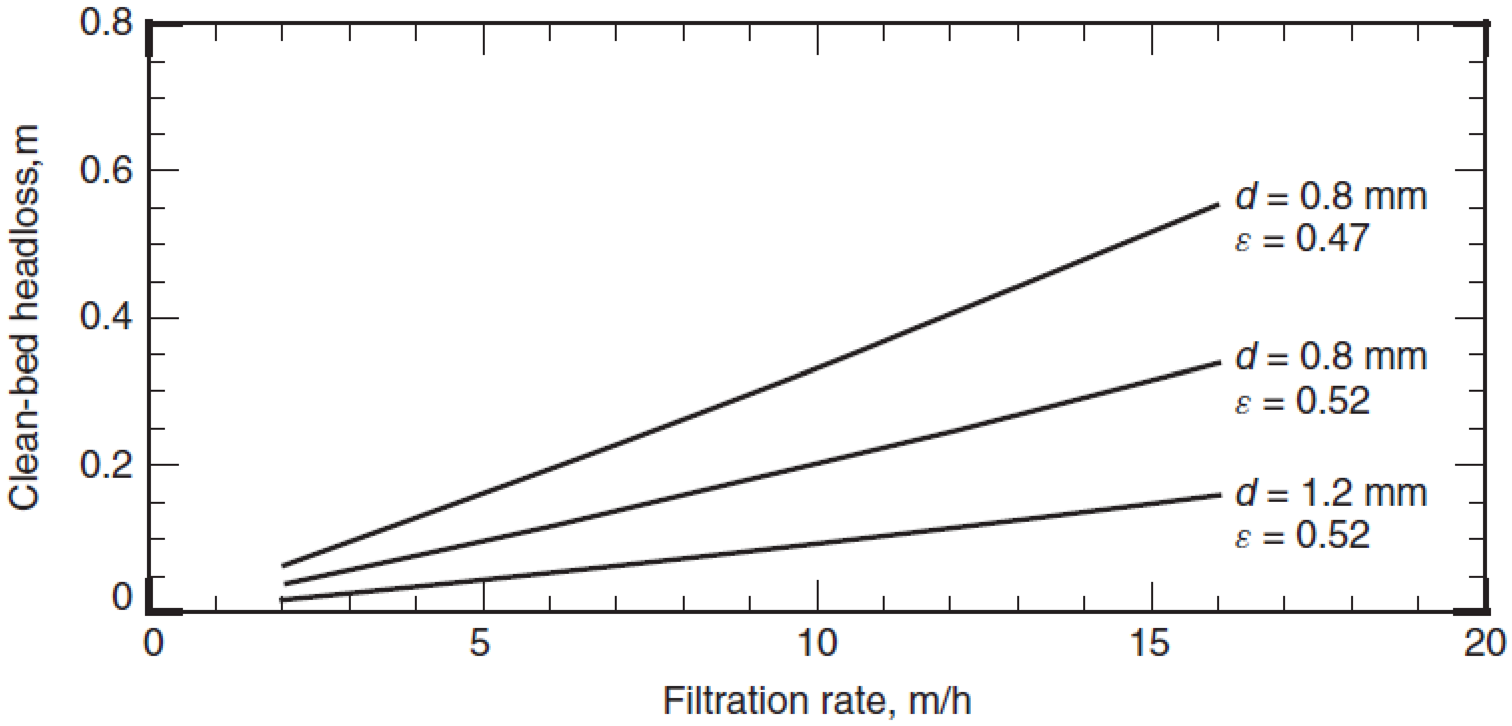


Figure 11-6
Effect of media size, bed porosity, and filtration rate on head loss through a clean granular filter bed. Calculated using Eq. 11–13 for anthracite ($L = 1$ m, $T = 15°C$, $\kappa_V = 228$, $\kappa_I = 4.4$).

Clean Bed Head Loss Calculation

Example 11-2 Clean-bed head loss through rapid filter

Calculate the clean-bed head loss through a deep-bed anthracite filter with 1.8 m of ES = 0.95 mm media at a filtration rate of 15 m/h and a temperature of 15°C.

Solution

The head loss through anthracite is calculated first using Eq. 11-13.

1. No pilot or site-specific information is given, so midpoint values are selected from Table 11-3; $\kappa_V = 228$, $\kappa_I = 4.4$, and $\varepsilon = 0.50$. Values of ρ_W and μ are available in Table C-1 in App. C ($\rho_W = 999\ \text{kg/m}^3$ and $\mu = 1.14 \times 10^{-3}\ \text{kg/m} \cdot \text{s}$).

Clean Bed HL Calculation cont.

2. Calculate the first term in Eq. 11-13:

$$\frac{(228)(1-0.50)^2(1.14\times10^{-3}\ \text{kg/m}\cdot\text{s})(1.8\ \text{m})(15\ \text{m/h})}{(0.50)^3(999\ \text{kg/m}^3)(9.81\ \text{m/s}^2)(0.95\ \text{mm})^2(10^{-3}\ \text{m/mm})^2(3600\ \text{s/h})}$$

$$= 0.44\ \text{m}$$

3. Calculate the second term in Eq. 11-13:

$$\frac{(4.4)(1-0.50)(1.8\ \text{m})(15\ \text{m/h})^2}{(0.50)^3(9.81\ \text{m/s}^2)(0.95\ \text{mm})(10^{-3}\ \text{m/mm})(3600\ \text{s/h})^2} = 0.06\ \text{m}$$

$$h_L = \kappa_V \frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu L v}{\rho_w g d^2} + \kappa_I \frac{1-\varepsilon}{\varepsilon^3}\frac{L v^2}{g d} \qquad (11\text{-}13)$$

where κ_V = head loss coefficient due to viscous forces, unitless
κ_I = head loss coefficient due to inertial forces, unitless

Clean Bed HL Calculation cont.

- When filter loading rate is lower head loss from inertial term is not significant
- When filter loading rate is high, inertial term becomes critical
- Deeper bed will have much more significant clean bed HL (20% for a 8.2 ft bed)

4. Add the two terms together:

$$h_L = 0.44 \text{ m} + 0.06 \text{ m} = 0.50 \text{ m} \quad (1.6 \text{ ft})$$

$$h_L = \kappa_V \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu L v}{\rho_W g d^2} + \kappa_I \frac{1-\varepsilon}{\varepsilon^3} \frac{L v^2}{g d} \qquad (11\text{-}13)$$

where κ_V = head loss coefficient due to viscous forces, unitless
κ_I = head loss coefficient due to inertial forces, unitless

Rapid Filter Design Procedure

- Preliminary Design
  - Set performance criteria (Effluent turbidity; filter run time; filter recovery; Unit filter run volume)
  - Select Process Design parameters (level of pretreatment, filter media type, size, filter depth, filtration rate, number of filters, and available head)
  - Select a method for flow distribution and control
  - Select major process components (e.g., backwash/cleaning systems, underdrains, wash troughs, process piping, electrical/control system, etc.

Basic Filter Production Calculation

Example 11-8 Calculation of parameters for net water production

A filter is operated at a rate of 12.5 m/h for 72 h, of which 30 min was discharged as filter-to-waste volume. After filtration, it is backwashed at a rate of 40 m/h for 15 min. Calculate the UFRV, UBWV, UFWV, and recovery.

Solution

1. Calculate UFRV using Eq. 11-66: **Volume of water treated by each filter**

$$\text{UFRV} = (12.5\ \text{m/h})(72\ \text{h}) = 900\ \text{m} = 900\ \text{m}^3/\ \text{m}^2$$

2. Calculate UBWV using Eq. 11-67: **Volume of water used for BW by each filter**

$$\text{UBWV} = (40\ \text{m/h})(0.25\ \text{h}) = 10\ \text{m} = 10\ \text{m}^3/\ \text{m}^2$$

3. Calculate UFWV using Eq. 11-68: **Volume of Filter-to-wast by each filter**

$$\text{UFWV} = (12.5\ \text{m/h})(0.5\ \text{h}) = 6.25\ \text{m} = 6.25\ \text{m}^3/\ \text{m}^2$$

4. Calculate recovery using Eq. 11-69:

$$r = \frac{(900 - 10 - 6.25)\ \text{m}^3/\ \text{m}^2}{900\ \text{m}^3/\ \text{m}^2} = 0.982 = 98.2\%$$

Homework & Reading Assignment

- Chapter 11
- Problem 11-4; use **Sample C** for the calculation of clean bed media head loss
- Problem 11-6

Homework due on October 3rd (Wed)