Draft Slow Sand Filtration Optimization Goals and Guidelines
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Note: This document is in draft form
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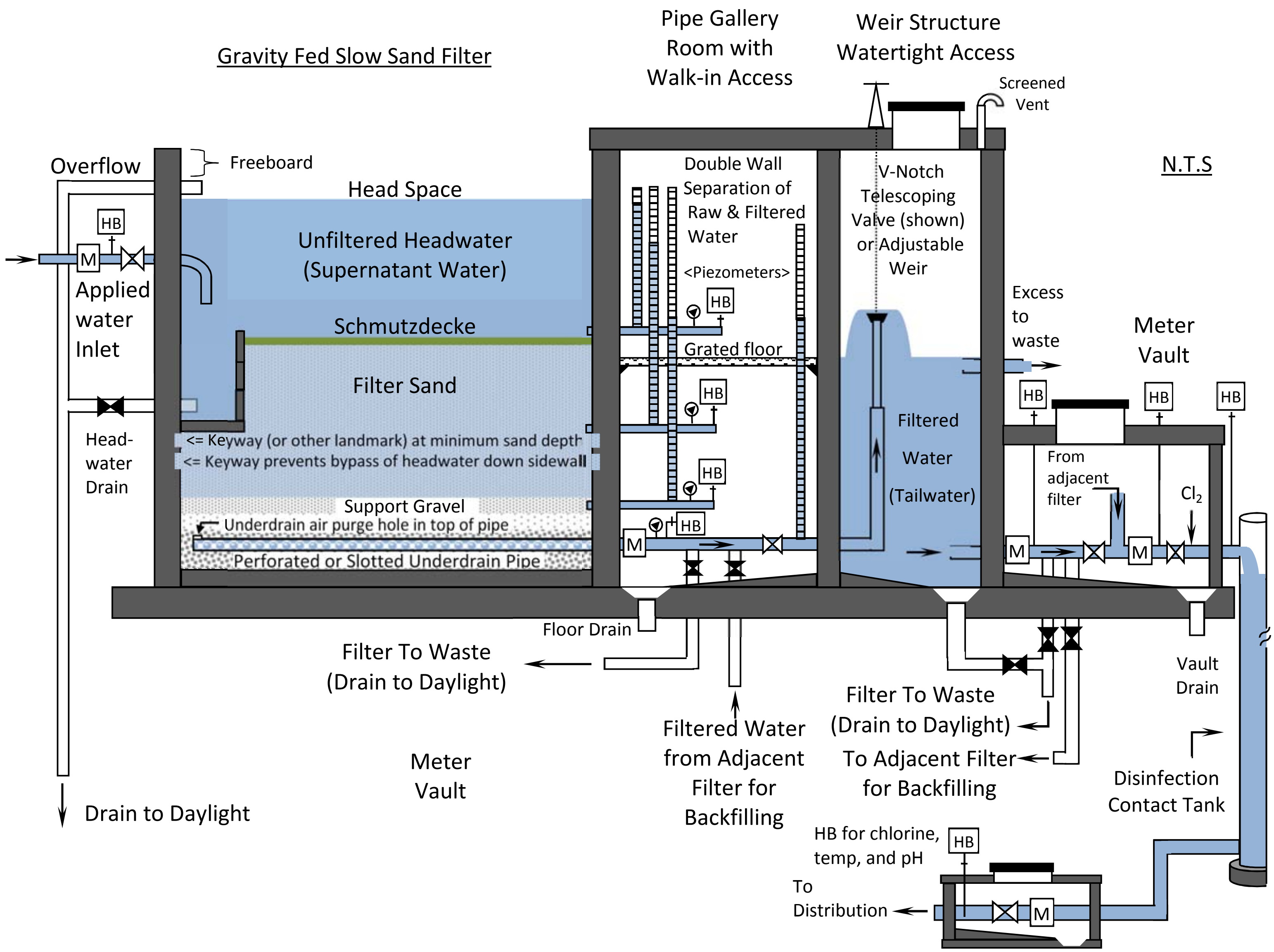

Recommended Applied Water Quality (following pre-treatment)		
Parameter	Limit	Notes
Turbidity	< 10 NTU (colloidal clays are absent)	Operation is more efficient with lower, consistent turbidity in the 5-10 NTU range. Most slow sand plants successfully treat water (after any pre-treatment such as roughing filters if applicable) with a turbidity of less than 10 NTU (Slezak and Sims, 1984), which is recommended for an upper limit in designing new facilities. Colloidal clays may penetrate deeper into the filter bed causing higher effluent turbidity and may cause long-term filter clogging. Roughing filters can provide up to 50-90% of turbidity removal (Wegelin et al., 1998).
True Color	< 5 platinum color units	The source of color should be determined. Color from iron or manganese may be more effectively removed than color from organics. True color removals of 25% or less were reported by Cleasby et al. (1984). The point of consumer complaints about water aesthetics is variable over a range from 5 to 30 color units, though most people find color objectionable over 15 color units (USEPA). The Secondary Maximum Contaminant Levels (SMCL) for color is 15 color units, which is also identified as a maximum level for slow sand filtration under the Recommended Standards for Water Works, 2012 Edition. Pre-ozonation or granular activated carbon may be used to reduce color.
Coliform Bacteria	< 800/100 ml (Colony Forming Units or Most Probable Number)	Coliform removals range from 1 to 3-log (90 - 99.9%) (Collins, M.R. 1998).
Dissolved Oxygen (DO)	> 6 mg/l (filtered water DO should be $\geq$ 3 mg/l)	Dissolved oxygen is critical for maintaining a healthy schmutzdecke for proper filtration. Potential problems resulting from low DO include tastes and odors, dissolution of precipitated metals such as iron and manganese, and increased chlorine demand (Ellis, 1985).
Total Organic Carbon (TOC)	<3.0 mg/l (low TOC to prevent DBP issues)	Recommendations for raw water dissolved organic carbon (DOC) concentrations range from < 2.5 – 3.0 mg/l in order to minimize the formation of disinfection byproducts (DBP) in the finished water. DOC removal in slow sand filters is < 15-25% (Collins, M.R. 1989). About 90% of TOC is DOC (USEPA, Microbial and Disinfection Byproduct Rules Simultaneous Compliance Guidance Manual. 1999). Total Organic Carbon (TOC) removal is variable and may range from 10 – 25% (Collins et. al, 1989; Fox e al, 1994). Determining DBP formation potential may provide additional information by simulating DBP formation in the distribution system due to the addition of disinfectants in the presence of organics.
Iron & Manganese	Each < 1 mg/l	Slow sand filters remove iron and manganese by precipitation at the sand surface. This can enhance organics removal, but too much iron and manganese precipitate can clog the filters. The Secondary Maximum Contaminant Level (SMCL) for iron is 0.3 mg/l and the SMCL for manganese is 0.05 mg/l. Iron and manganese removal can be > 67% (Collins, M.R. 1998).
Algae	< 200,000 cells/L (depends upon type)	By providing greater surface area for particle removal, certain types of filamentous algae may enhance biological activity and be beneficial for filtration, but in general, the presence of algae reduces filter run length. Filter clogging species are detrimental to filtration and the presence of floating species may shorten filter run length due to the associated poorer-quality raw water (see the table below for common algal species). Microscopic identification and enumeration is recommended to determine algae species and concentration.

Classification of Common Algal Species[1]		
Filter Clogging[2]	Filamentous	Floating
Tabellaria Asterionella Stephanodiscus Synedra	Hydrodictyon Oscillaria[3] Cladophora Aphanizomenon Melosira	Protoccous Scenedesmus Symara Anaboena[3] Euglena

[1]Table adapted from Table 10.2 Water Treatment Plant Design, AWWA/ASCE/EWRI, 2012
[2]Diatoms of all species can generally can cause clogging due to their rigid inorganic shells
[3]Can also release algal toxins (Microcystin and Anatoxin-a, among others)

General Design Guidelines
Minimum of 2 filter beds, each filter capable of meeting peak day demands. If more than 2 filters are used, peak day demands should be able to be met with the largest filter out of service. Finished water storage should be capable of meeting peak hour demand with adequate disinfection contact time, fire flow, and emergency storage requirements.
Ensure design provides for continuous operation without filter effluent flow rate variability. Any filter effluent flow variations included in the design should be gradual to minimize detachment of particles from the sand with no more than 50% change in any 24-hour period. Provisions should be made to filter-to-waste or return the filter effluent to the headwater when demands are low. Intermittent operation of slow sand filters should not be used as a means of rate control.
Influent water should be introduced to the filter with enough clearance above the sand to prevent scouring (at least 1-ft). Energy dissipating structures may also be used to prevent sand scour.
Maintain continuous filter effluent rates (Hydraulic Loading Rates, or HLR) between 0.03 - 0.10 gpm/ft^2 (0.07 – 0.24 m/hr). Intermittent operation is not recommended. Designing for lower filtration rates may be needed as raw water quality can deteriorate with lower temperatures. A flow rate of 0.05 gpm/ft^2 may be used with water temperatures less than 5°C.
In order to prevent air binding within the filter, the tail water elevation must always be at or above the level of the sand bed. An effluent weir is the simplest way to accomplish this.
If scraping is the intended filter cleaning method, consideration should be given to allow scraped sand to be washed and stored on-site, covered, or otherwise protected from contamination.
Design should consider safety and ease of operations, avoiding confined space entry, trip hazards, and situations that make maintenance activities difficult. Table-top exercises for start-up, normal operations, and cleaning procedures should be conducted with operations staff and designers in order to identify design-related operational problems in time to be corrected prior to construction. Operations and maintenance manuals and monitoring data collection, recording and reporting procedures should be drafted as part of the design phase in order to facilitate a clear understanding of how the plant will be operated and filter performance monitored. Operations staff should be consulted early in the design phase whenever possible.
Design should be based on the results of pilot studies, which are used to evaluate the: 1. Suitability of slow sand filtration for the specific raw water supply and potential pre-treatment needs; 2. Impact of seasonal water quality changes; 3. Impact of cold water temperatures and the need for covering or otherwise mitigating cold temperature effects; 4. Suitability of the selected filter sand and support gravels intended to be used; 5. Hydraulic loading rate; 6. Filtration area and number of filters needed to meet system demands; 7. Optimal flow control strategy; 8. Amount of time needed to ripen and commission a new filter; 9. Headloss development (or filter run time); 10. Cleaning frequency and most appropriate method; 11. Ripening time and most appropriate ripening indicators (e.g. turbidity, coliform counts, time, etc.); 12. Filter-to-waste and filter backfilling capacity; 13. Amount of sand that can be expected to be removed on an annual basis due to cleanings, which will yield information on how long the sand bed will last before resanding is needed; 14. Removal, handling, and stockpiling requirements for scraped sand; 15. Most appropriate level of automation and supervisory control and data acquisition (SCADA) systems; and 16. Operational staff time needed for operations and maintenance tasks and to monitor performance.

Underdrain Design Parameters	Recommended Specification
Maximum Velocity in Laterals[1]	0.75 fps (0.23 m/sec)
Maximum Velocity in Main Drain[1]	0.75 fps (0.23 m/sec)
Spacing of lateral drain pipes[2]	36 inches (91.4 cm)
Spacing of bottom lateral drain holes[3]	4 – 12 inches (0.1 – 0.3 m) Placed as close to the filter floor as possible and secured in place to prevent movement.
Diameter of drain holes[3,4]	1/4-inch (6.35 mm) Include air release holes or slits at the top near the midpoint of the main drain and each lateral.
Material[5]	PVC (noncorrosive, ANSI/NSF Standard 61)

[1] According to the 2012 Edition of the Recommended Standards for Water Works (Great Lakes – Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers), each filter should be equiped with a main drain and an adequate number of lateral underdrains to collect the filtered water. The underdrains should be placed as close to the floor as possible and spaced so that the maximum velocity of the water flow in the underdrain will not exceed 0.75 feet per second (0.23 m/sec).

[2] Although spacing lateral drains up to 79" (2 m) may be satisfactory due to the low hydraulic resistance in the support gravel, a smaller spacing increases the uniformity of flow through the drains (Hendricks, et al., 1991. pg 112). The Recommended Standards for Water Works recommends a maximum lateral spacing of 36 inches (Great Lakes – Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers. 2012 Edition).

[3] The underdrain system should ensure uniform flow through the overlying sand bed. This is achieved by having a uniform distribution and sufficient number of collection orifices and designing the ratio of the orifice area/conduit (pipe) area such that the headloss within the underdrain pipe is negligible relative to the orifice (Hendricks, et al., 1991, pg 108). This yields a headloss through the drain holes much greater than the headloss in the laterals and main drains to ensure the even flow distribution. The diameter and spacing of the underdrain pipes and the diameter of the orifices should be determined theoretically by hydraulic calculations.

[4] Alternatively, slotted drain pipe may be used where the width of the slots is in the 5/64" – 5/32" (2-4 mm) range, provided the headloss through the slots is determined to be much greater than the laterals and main drains.

[5] Other materials may be used provided they are noncorrosive and are verified safe for contact with potable water (i.e., meet ANSI/NSF Standard 61 or equivalent certification).

Refer to the following references for more detailed design criteria:

1. Hendricks, David et al. 1991. *Manual of Design for Slow Sand Filtration*. American Water Works Association Research Foundation.
2. Huisman, L. & Wood, W.E. 1974. *Slow Sand Filtration*. Geneva: World Health Organization
3. Recommended Standards for Water Works. 2012 Edition. Great Lakes – Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers.

Support Gravel				
Support gravel should conform to published design guidelines (see references provided at the end of this table). An example of a 5-layer support gravel system is provided for filter sand with an effective size of 0.2 mm – 0.35 mm using design guidelines from Appendix D of ANSI/AWWA Standard B100-09 and commercially available gravel sizes according to standard sieve sizes under ASTM E11-13. The gravel support using 5 layers as shown below will work if the orifices in the under drain pipe are less than or equal to 1/4" in diameter. 4 layers are adequate with 1/8" (3.175 mm) diameter drain orifices and a bottom gravel layer of 1/2" x 1/4" (12.7 x 6.35 mm).				
Filter Sand	Effective Size = 0.2 mm – 0.35 mm (medium sand is 0.25-0.5 mm)			
Support Media[1]	*Passing Screen Size (largest particle)*[2]	*Retaining Screen Size (smallest particle)*[2]	*Depth of Layer*[3]	*Criteria* *(The actual ratio demonstrating how well the criteria has been met is provided in parentheses)*
Layer 1 - Top Layer ("very course" sand)	No. 10 Sieve (2 mm)	No. 20 Sieve (0.85 mm)	3 inches (76.2 mm)	Within Layer 1: The largest particle size in layer 1 is less than or equal to 2 times the size of the smallest particle size in layer 1. (2.5) Between Layer 1 and the Filter Sand: The smallest particle size in layer 1 is between 4 and 4.5 times the smallest effective size of the filter sand. (4.00)
Layer 2 (No. 6 Sieve x No. 12 Sieve)	No. 6 Sieve (3.35 mm)	No. 12 Sieve (1.7 mm)	3 inches (76.2 mm)	Within Layer 2: The largest particle size in layer 2 is less than or equal to 2 times the size of the smallest particle size in layer 2. (1.97) Between Layers 1 and 2: The largest particle size in layer 2 is less than or equal to 4 times the smallest particle size in layer 1. (4.19)
Layer 3 (1/4" x No. 6 Sieve)	1/4" (6.3 mm)	No. 6 Sieve (3.35 mm)	3 inches (76.2 mm)	Within Layer 3: The largest particle size in layer 3 is less than or equal to 2 times the smallest particle size in layer 3. (1.90) Between Layers 2 and 3: The largest particle size in layer 3 is less than or equal to 4 times the smallest particle size in layer 2. (3.74)
Layer 4 (1/2" x 1/4")	1/2" (12.5 mm)	1/4" (6.3 mm)	3 inches (76.2 mm)	Within Layer 4: The largest particle size in layer 4 is less than or equal to 2 times the smallest particle size in layer 4. (2.00) Between Layers 3 and 4: The largest particle size in layer 4 is less than or equal to 4 times the smallest particle size in layer 3. (3.79)
Layer 5 - Bottom Layer (3/4" x 1/2")	3/4" (19.0 mm)	1/2" (12.5 mm)	3 inches minimum and such that the gravel completely surrounds and provides for at least 1" (25.4 mm) of cover over the laterals and main drain to provide for a level surface for upper gravel layers	Within Layer 5: The largest particle size in layer 5 is less than or equal to 2 times the size of the smallest particle size in layer 5. (1.50) Between Layers 4 and 5: The largest particle size in layer 5 is less than or equal to 4 times the smallest particle size in layer 4. (3.00) Between Layer 5 and the Underdrain: The smallest particle size in layer 5 is at least twice the size of the underdrain orifice size. (2.00)
Underdrain	Underdrain orifice size = 1/4" diameter			

Support Gravel, Continued

Footnotes:

[1]Refer to ANSI/AWWA Standard B100-09 or latest revision for more detailed specifications.
[2]No more than 8% by dry weight of particles should be greater than the passing screen size and no more than 8% by dry weight of particles should be smaller than the retaining screen size.
[3]The thickness of each layer of support gravel should be at least 3 times the diameter of the largest particles. For practical reasons, the thickness of each layer should be 2-3 inches for course sand and gravel up to 1/2" (12.7 mm) in size. Keep gravel clean and only store on a clean, hard, dry, covered surface until placement. Gravel should be washed thoroughly to remove deleterious materials like clay fines and organics prior to placement. Layers should be placed to a uniform thickness, leveled, and washed in succession according to ANSI/AWWA Standard B100.

References:

Refer to the following references for more detailed support gravel design criteria:

4. ANSI/AWWA Standard B100-09 or latest revision.
5. Hendricks, David et al. 1991. *Manual of Design for Slow Sand Filtration*. American Water Works Association Research Foundation.
6. Huisman, L. & Wood, W.E. 1974. *Slow Sand Filtration*. Geneva: World Health Organization
   According to Huisman and Wood (1974, pg 57):
   1. "The uppermost layer of gravel must be selected with a D_{10} value more than 4 times greater than the D_{15} value of the coarsest filtration sand and less than 4 times greater than the D_{85} value of the finest filtration sand taken from natural deposits, which will vary in grain size from one spot to another."
   2. When the D_{90} of a layer is between 1.4 and 2 times the D_{10} within the same layer, it is recommended that each successive layer be graded so that its smaller particle diameters (D_{10}) are not more than 3 times smaller than those of the layer immediately below. If the D_{90} of a layer is less than or equal to 1.4 times the D_{10} within the same layer, each successive layer can be graded so that its smaller particle diameters (D_{10}) are not more than 4 times smaller than those of the layer immediately below.
   3. The thickness of each gravel layer should be greater than three times the diameter of the largest stones. As a practical matter the minimum thickness of gravel layers should be 2 to 2.75 inches (5 – 7 cm) for finer material and 3 to 4.75 inches (8 – 12 cm) for coarser gravel.
   4. "The grains of the bottom layer of gravel should have an effective diameter of at least twice the size of the openings into the drainage system."
7. Recommended Standards for Water Works – 2012 or latest edition. Great Lakes – Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers.

Filter Sand Specification Recommended Range	
Effective Diameter (d10)	0.2 – 0.35 mm (No. 70 Sieve = 0.212 mm; No. 45 Sieve = 0.355 mm)
Uniformity Coefficient (UC)	1.5 – 3.0
% fines passing #200 sieve (75 µm)	< 0.3% by Wt.
Acid Solubility	< 5%
Apparent Specific Gravity	$\geq$ 2.55
Minimum Sand Bed Depth Prior to Resanding (This minimum sand bed depth is in addition to the amount of sand anticipated to be removed due to cleanings throughout the life of the filter)	20 - 24 inches (A horizontal keyway incorporated into the walls along the entire perimeter of the filter with the bottom of the keyway at the 20-inch level serves the dual purpose of indicating the absolute minimum sand bed depth while preventing raw water from seeping down the side walls of the filter to the under drains. A second keyway or scribe mark situated at the 22 to 24-inch level can indicate when the bed is approaching the minimum level.
Delivery/Installation	Sand should be washed thoroughly to remove deleterious materials like clay fines and organics prior to placement. Keep sand clean and only store on a clean, hard, dry, covered surface until placement. Refer to ANSI/AWWA Standard B100-09 or latest revision for additional storage and handling information.

Operational Guidelines for Normal Operation
Operate slow sand filters continuously without filter effluent flow rate changes. If filter effluent flow changes are needed, ensure that the flow changes are made gradually to minimize detachment of particles from the sand with no more than a 50% variation in flow in a 24-hr period. Use filter effluent flow controls to accommodate changes in system demands (e.g., set the filtration rate high enough to meet anticipated peak day demands and divert excess water to waste or filter headwater influent during low demand periods). Intermittent operation of slow sand filters should not be used as a means of rate control.
Influent flows should be monitored to prevent scouring of the sand bed and filter walls.
Ensure filter effluent rates (Hydraulic Loading Rates, or HLR) of between 0.03 - 0.10 gpm/ft^2 (0.07 – 0.24 m/hr). Filtration rates may need to be lowered should raw water quality deteriorate with lower temperatures. A flow rate of 0.05 gpm/ft^2 may be used with water temperatures less than 5°C.
In order to prevent air binding within the filter, the tail water elevation must always be maintained at or above the level of the sand bed. Filtration rates and effluent weir levels should be routinely checked and adjusted only if needed.

Optimization Goals IFE = Individual Filter Effluent CFE = Combined Filter Effluent NTU = Nephelometric Turbidity Units TC = Total Coliform, Most Probable Number (MPN) or Colony Forming Units (CFU) per Standard Methods
IFE & CFE Turbidity ≤ 1.0 NTU in 95% of the highest daily readings, measured at least once daily.
IFE & CFE Turbidity ≤ 5.0 NTU measured at least once daily.
IFE Total Coliform ≤ 10/100 ml measured at least weekly.
Water entering the distribution system is absent of total coliform bacteria (measure weekly when IFE or CFE turbidity > 1 NTU)

Operational Guidelines for Cleaning by Scraping
Scraping should be done when: 1. Headwater depth reaches the headwater overflow level; 2. The achievable filter production rate decreases to 0.03 gpm/ft^2 (0.073 m/hr); or 3. Daily demands are anticipated to not be met.
When removing a filter from service for cleaning, schedule the event to avoid overloading the remaining filters.
Minimize the time a de-watered filter is off-line.
Do not de-water the filter more than necessary in order to safely clean the filter (e.g., 2-12 inches below the sand surface).
Remove the schmutzdecke and no more than 1/4" - 1/2" (0.635-1.27 cm) of sand with each cleaning. Depending upon the effective size (d10) and applied water quality, more sand may need to be scraped (1/2" – 1") in order to remove the plugged portion of the filter, allowing clean bed headloss to recover. Operators should monitor headloss before and after each scraping in order to determine how much sand is needed to be removed to maximize filter recovery while avoiding excessive sand removal. Monitoring headloss development by plotting daily headloss readings for each filter should be used to schedule filter cleanings during times of low demands and higher applied water temperatures (above 5^{o}C). Scheduling cleanings during low systems demands will help ensure that demands are able to be met without overloading adjacent filters. Scheduling cleanings during times of warmer water temperature will help minimize the adverse effects of cold temperatures on the filter biota. The minimum permissible sand bed depth should be no less than 20-24 inches.
Avoid walking or driving directly on the schmutzdecke during cleaning.
After the filter has been cleaned, slowly refill the filter from the bottom at a rate of 0.3-0.6 ft of bed depth per hour (0.1 – 0.18 m/hr or 0.0374 – 0.0748 gpm/ft^2) in order to purge entrained air. Refill with non-chlorinated filtered water from one of the other filters until the headwater is 1-ft above the sand to minimize scouring of the sand bed when filling from the top begins. Then fill from the top at a rate that minimizes disturbing the sand bed. *Note: To convert ft/hr to gpm/ft^2, multiply (ft/hr)by (1 hr/60 min) and then multiply by (7.48 gal/ft^3). Example: 0.3 ft/hr x (1 hr/60 min) x (7.48 gallons/ft^3) = 0.0374 gpm/ft^2.*
Begin filtering to waste at the same rate as was used prior to cleaning, or at the anticipated rate needed when the filter is brought back on-line. Do not exceed the design flow rate and keep the rate $\leq$ 0.1 gpm/ft^2.
Filter to waste one hour for each hour that the filter is off-line, but for no less than 24 hours. Filter to waste until the optimization goals following filter cleaning have been met.

Operational Guidelines for Cleaning by Harrowing
Lower water level to the level of the harrowing waste valve (e.g., about 6" (15 cm) above the sand bed). This is done to keep the head pressure low in order to minimize migration of debris down into the filter during the raking process.
Open the harrowing waste valve and begin introducing filtered unchlorinated water from the bottom of the filter at a rate of 0.16 ft/hr (0.02 gpm/ft^2) and low enough to prevent the sand from being fluidized. This serves to suspend debris, and keeps it from settling back into the filter bed during raking.
Introduce water into the top of the filter at a rate low enough to prevent sand migration, but high enough to flush the debris to waste during raking. For rectangular filters, a typical flow rate of about 20 gpm times the depth of water above the sand during harrowing times the length of the filter that is perpendicular to the incoming flow will work. For example, 1,000 gpm will work with 6 inches of water depth in a 100-ft wide filter provided the flow path is directed across the width of the filter. For other filters, influent flow should be adjusted to maintain a steady water level above the sand during raking. In either case, it is important to maintain a constant water level above the sand throughout the harrowing process by balancing flows into and out of the filter.
Using a stiff tined rake or harrowing equipment, gently agitate the top 2 – 3" (5 – 8 cm) of sand until the headwater begins to clarify, as indicated by the ability to see the sand bed when the raking is stopped.
After it has been cleaned, slowly refill the filter from the bottom at a rate of 0.3-0.6 ft of rise per hour (0.1 – 0.18 m/hr or 0.0374 – 0.0748 gpm/ft^2) in order to purge entrained air. Refill with non-chlorinated filtered water from one of the other filters until the headwater is 1-ft above the sand to minimize scouring of the sand bed when filling from the top begins. Then fill from the top at a rate that minimizes disturbing the sand bed. *Note: To convert ft/hr to gpm/ft^2, multiply (ft/hr)by (1 hr/60 min) and then multiply by (7.48 gal/ft^3). Example: 0.3 ft/hr x (1 hr/60 min) x (7.48 gallons/ft^3) = 0.0374 gpm/ft^2.*
Begin filtering to waste at the same rate as was used prior to cleaning, or at the anticipated rate needed when the filter is brought back on-line. Do not exceed the design flow rate and keep the rate $\leq$ 0.1 gpm/ft^2.
Filter to waste one hour for each hour that the filter is off-line, but for no less than 24 hours. Filter to waste until the optimization goals following filter cleaning have been met.

Optimization Goals Following Filter Cleaning (scraping or harrowing) IFE = Individual Filter Effluent CFE = Combined Filter Effluent NTU = Nephelometric Turbidity Units TC = Total Coliform, Most Probable Number (MPN) or Colony Forming Units (CFU) per Standard Methods
Filter to waste for each hour that the filter is off-line, but no less than 24 hours, until sampling demonstrates that the goals below have been met.
Filter not to be brought on-line until: 1. IFE Total Coliform $\leq$ 10/100 ml (sample no earlier than 24 hours after the start of filtering to waste) 2. IFE Turbidity $\leq$ 1.0 NTU
Performance of the newly cleaned filter (e.g., turbidity effluent and/or filter effluent coliform counts if available) should be compared to the other filters that have remained in service or to the performance of the cleaned filter prior to cleaning. If there is considerable difference in the performance of the newly cleaned filter, the operator should consider extending the filter to waste period. Filtration rates may need to be lowered should raw water quality deteriorate with lower temperatures. A flow rate of 0.05 gpm/ft^2 may be used with water temperatures less than 5°C. Filter cleanings should generally be scheduled to avoid months where water temperatures are expected to regularly drop below 5°C.