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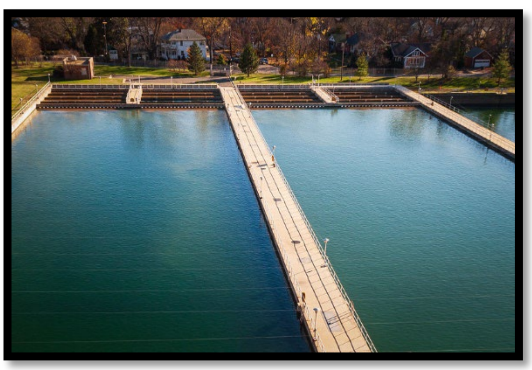
U.S. EPA Area-Wide Optimization Program (AWOP) Water Quality Goals and Operational Criteria for Optimization of Slow Sand Filtration



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Introduction

This document presents water quality performance goals, as well as operations and maintenance (O&M) criteria to assist water system managers, operators, and primacy agency staff with ensuring optimal performance of slow sand filtration/filters (SSF) systems. These water quality goals and O&M criteria were developed through the U.S. Environmental Protection Agency's (EPA's) Area-Wide Optimization Program (AWOP) during a pilot project conducted in partnership with the Idaho Department of Environmental Quality, the Oregon Health Authority, the Washington Department of Health, and Hayden Haven Gem Shores (an Idaho surface water SSF drinking water treatment plant owned and operated by the North Kootenai Water and Sewer District).

The AWOP program was developed in the late 1990s by the EPA, initially to optimize surface water treatment plant performance against microbial contaminants. The program is led by the EPA's Technical Support Branch of the Standards and Risk Management Division in Cincinnati, Ohio. Participation in the program and adoption of the program goals are voluntary but encouraged. The goals and recommendations described in this document apply to those who have chosen to pursue SSF optimization.

Microbial pathogens can be physically, chemically, or biologically removed or inactivated during the water treatment process. Therefore, public health protection can be maximized by optimizing these processes (EPA, 2004). In SSF, treatment occurs primarily via both physical and biological mechanisms, typically near the sand surface or within the top 24 inches of media. SSF consists of granular media with an active biological layer that develops at the media surface, called a *schmutzdecke*. This process relies on filtering water at a low flow rate through a sand medium. A well-designed, properly operated and maintained SSF system can remove microbial pathogens such as *Giardia, Cryptosporidium,* bacteria, and viruses. SSF are advantageous for their relative simplicity and effectiveness of operation. Although there are many advantages to SSF in drinking water treatment, these systems also have limitations. Primarily, SSF can be prone to limited filter run times due to biological clogging and contaminant breakthrough (AWWA PSW Self-Assessment, 2015). Some of these limitations can be addressed through the addition of treatment processes such as those presented on page 22, however consistent SSF monitoring and optimized process control can also help maintain effective hydraulic and water quality treatment performance.

Slow Sand Filtration Terminology and Definitions

A schematic of a generalized SSF plant layout is provided below to help introduce and define terminology used throughout this document.

Water typically enters from the raw water intake through a flow-metered inlet. This water becomes supernatant (headwater) above the filter media and a thin biological layer forms atop the filter media (i.e., schmutzdecke). Pathogen removal occurs through biological and physical removal mechanisms and does not depend on coagulants as with conventional or direct filtration plants. Filter media also has a much smaller effective size (0.15 – 0.35 mm) compared to conventional and direct filtration media – this facilitates these removal mechanisms without coagulation.

After water passes through the schmutzdecke and filter sand, it is collected by a filter underdrain system and passed to an effluent weir. The effluent weir helps modulate the water level in the filter, with the intent of maintaining the weir level above the top of the sand bed to prevent air binding in the filter media. The filtered water is then conveyed to the rest of the treatment process, depending on the design and arrangement of the treatment plant (e.g., disinfection, activated carbon, etc.). Flow metering is an important process control tool to maintain a consistent flow of nutrients and oxygen to keep the schmutzdecke biota viable and to ensure that filter rates are not excessive (maintain less than 0.1 gpm/ft^2). Piezometers are also useful in monitoring head loss development, which is an indicator of when the filters need to be cleaned, as described below.

Depending on the source water quality, filters are generally cleaned every one to six months. Cleaning consists of scraping and removing the schmutzdecke and a small layer of filter sand (e.g., < 0.5 inches) off the top of the filter. Some filters are designed such that cleaning is performed by raking the top few inches of the filter media with about 6-inches of water remaining above the filter sand and flushing the floating debris out of the filter through a waste valve located just above the filter bed or a waste collection channel located at the end of the filter box. This is a process called wet harrowing.

Figure 1 shows common design elements of SSFs (although not all elements may be present in all designs). Table 1 contains acronyms and definitions commonly used for SSFs and referred to within this document.

Figure 1. Common design elements of slow sand filters.

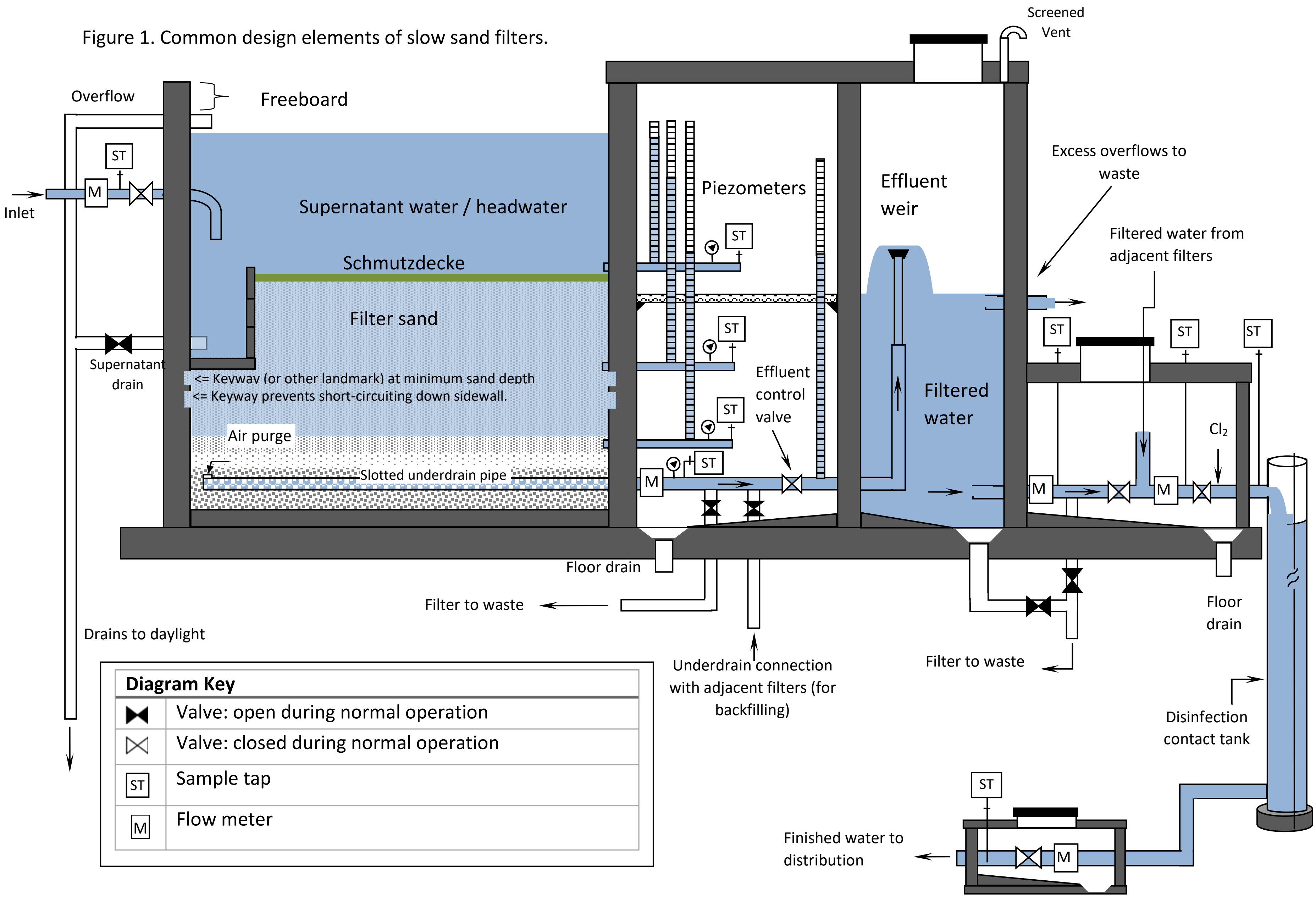


Table 1. Acronyms and Definitions	
IFE	Individual filter effluent
CFE	Combined filter effluent
NTU	Nephelometric turbidity units
TC	Total coliform bacteria
MPN	Most probable number
CFU	Colony-forming units per standard methods
DS	Distribution system
EPTDS	Entry point to distribution system (post-treatment, prior to first customer)
T&O	Taste & odor
O&M	Operations & maintenance
Gpm	Gallons per minute
DO	Dissolved oxygen
HLR	Hydraulic loading rate of the filter. Synonymous with "filter loading rate" and typically calculated by dividing the filtration rate in gpm by the surface area of the filter in square feet, expressed as gpm/ft^2
SSF	Slow sand filtration, slow sand filter(s)
Effective size	The effective size (d_{10}) of a given sample of sand is the particle size where 10% of the particles in that sample (by weight) are smaller (i.e., passing through a sieve) than the remaining 90% retained on the sieve (10th percentile particle diameter of the sand sample). This parameter is determined by sieve analysis.
Uniformity coefficient (UC)	A measure of how well-graded or uniform the sand particles are. UC = d_{60} / d_{10} (60th percentile particle diameter divided by 10th percentile particle diameter). This parameter is determined by sieve analysis.
Sieve Analysis	A procedure to determine the particle size distribution, or gradation, of a granular material (i.e., sand) by passing material through a series of sieves of progressively smaller mesh size, and then weighing the amount of material retained on each sieve as a fraction of the total mass.
Headwater	This is the water in the filter above the filter media. Headwater may be supplied by the raw source (e.g., intake) or may be water that has been pre-treated (e.g., roughing filters).
Scraping	The most common method of cleaning slow sand filters by removal of the schmutzdecke and a thin layer of sand to reduce filter head loss and restore operational filtration rates. The surface of the slow sand filter media and schmutzdecke is cleaned by draining the supernatant water below the level of the media surface. Scraping is conducted when the filter sand remains damp and the water level is drained below the sand surface just enough to allow walking or operating cleaning equipment safely. See O&M section.
Harrowing / Wet Harrowing	A method of cleaning some types of SSFs specifically designed for this cleaning method. This cleaning technique requires the water level to be maintained about 6-inches above the sand and the ability to introduce sufficient cross-flow above the filter media surface to carry the suspended solids out through either a harrowing waste pipe or channel. Oftentimes during this type of cleaning, a low flow of filtered water (typically from an adjacent filter in service) is needed to prevent migration of debris down into the filter bed during cleaning. This flow occurs upward at a slow rate so as

	not to fluidize the sand media. Once water levels and flows are established, cleaning occurs by raking the top few inches of schmutzdecke and sand to sufficiently break up the plugged top portion of the filter and float the debris out the waste valve or channel. See O&M section.
Filter ripening	The period of time following filter cleaning that is needed to recover performance as a result of the cleaning. Ripening time includes the filter-to-waste period following cleaning up until the filter is returned to service. This term is not synonymous with “filter maturation”.
Filter maturation	The period of time following re-sanding of an existing filter or following the construction of a new filter needed to demonstrate effective filtration as indicated by filter-to-waste time, turbidity, and coliform counts. This period includes the filter-to-waste period until the filter is ready to be placed into service and may extend for several weeks or months, depending on the quality of the filter media and the method of placement. This term in not synonymous with “filter ripening”.

AWOP Water Quality Goals Defining Optimal Slow Sand Filtration Performance

Performance Goals for Regular Operation	Monitoring Goals for Regular Operation
IFE & CFE turbidity ≤ 1.0 NTU	In 95% of maximum daily readings, measured at intervals of 1-minute or less for continuous monitoring
IFE & CFE turbidity ≤ 5.0 NTU	100% of maximum daily readings, measured at intervals of 1-minute or less for continuous monitoring.
When raw water TC MPN or CFU ≥ 100 / 100 mL, then IFE TC ≤ 10 / 100 mL When raw water TC MPN or CFU < 100 / 100 mL, then IFE TC ≤ 5 / 100 mL	At least once per month during normal operation. Increase frequency to weekly with significant changes in raw water quality (e.g., after storms, wildfires, changes to watershed, seasonal changes, etc.). (Analyze by CFU or MPN methods)
Plant effluent TC absent	Weekly presence/absence monitoring whenever IFE or CFE turbidity > 1.0 NTU

Performance Goals Following Slow Sand Filter Cleaning (scraping or harrowing)
The following goals are used to indicate when a filter has ripened and may be returned to service following cleaning. These goals do not apply to newly sanded or re-sanded filters as the maturation period following re-sanding may take several weeks or months. Filter to waste at least 24 hours and until sampling demonstrates that the optimal operations goals below have been met, i.e., 1. IFE TC MPN or CFU ≤ 5 / 100 mL (sample no earlier than 24 hours after the start of filtering to waste). 2. IFE *E. coli* MPN or CFU = absent (0 / 100 mL) 3. IFE turbidity ≤ 1.0 NTU Consistent Performance Guideline: performance of the newly cleaned filter should be compared with the performance of other filters that remained in service, or to the performance of the same filter prior to its cleaning. If the performance of the newly cleaned filter does not meet the goals, consider extending the ripening period.

AWOP Operational & Maintenance Criteria for Optimal Performance

Criteria for Regular Operation

Flow Rate

- SSFs perform best when operated continuously with minimal filter effluent flow rate changes. If filter effluent flow changes are needed, they should be made gradually to minimize disruption to the schmutzdecke. Generally, this can be accomplished by limiting flow variation to no more than 50% over a 24-hour period. Intermittent on/off operation of SSFs should not be used to control flow rate, as this can reduce dissolved oxygen (DO) and nutrient concentrations needed for the active microbial community in the schmutzdecke.
- Use filter effluent flow controls to accommodate changes in system demands. For example, set the filtration rate high enough to meet anticipated daily peak demands and divert excess filtered water to waste, back to the source, or filter headwater influent during low demand times.
- Ensure that hydraulic loading rates (HLR) are between 0.03 to 0.10 gpm/ft^2 (0.07 to 0.24 m/hr). Regardless of the HLR however, influent flow should be monitored to minimize scouring of the sand bed and filter walls.
- Filtration rates may need to be reduced if raw water quality deteriorates (e.g., higher turbidity than normal) or if water temperatures are low. Especially when water temperatures are less than 5°C, microbial activity within the schmutzdecke decreases. In such cases, a flow rate of 0.05 gpm/ft^2 (0.12 m/hr) may be necessary to continue to achieve optimal performance. Filter cleanings should generally be scheduled to avoid months where water temperatures are expected to regularly drop below 5°C.

Water Levels

- In order to prevent air binding within the filter, the filtered water elevation should be maintained at or above the level of the sand bed.
- SSF performs best with minimal changes to water levels. Effluent weir levels should be routinely checked, and adjustments should be well-planned and intentional.

Dissolved Oxygen

- Dissolved oxygen is critical for maintaining a healthy schmutzdecke for optimal performance. Low DO may harm the beneficial organisms needed for effective filtration. Some SSF plants use pretreatment aeration to increase DO (Ellis, 1985).
- Potential problems resulting from low DO include taste and odors, dissolution of oxidized metals such as iron and manganese, and increased chlorine demand (Ellis, 1985).
- Operators of optimized SSFs will periodically monitor filter effluents for DO, especially during periods of elevated water temperature (lower DO solubility). Weekly raw and finished water DO monitoring is recommended (AWWA, 2012).
- A minimum filter effluent DO concentration of 3 mg/L will help ensure a healthy schmutzdecke.

Operational Guidelines for Filter Cleaning (Scraping or Harrowing)

When?

For optimal performance, cleaning of the SSF schmutzdecke should be conducted before any of the following conditions are met:

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 demand forecasts exceed anticipated production capability.

Headloss:

- Daily head loss measurements should be plotted for each filter to help schedule filter cleanings during times when demand is low and water temperature is above 5°C.

Demands:

- Cleanings should be scheduled during low distribution system demand to help ensure that the system can meet the demand without overloading adjacent filters and also minimize the amount of time a dewatered filter is offline. Filter downtimes for cleaning should be minimized (less than 1 to 3 days, depending on the filter size) to minimize impacts to the microbial community in the filter media (Collins, 2012).
- Staggering cleanings among multiple filters can help ensure the system can continue to meet demand.

Water temperature

- Cleanings should be scheduled during times of warmer water temperature (i.e., above 5°C) to help minimize the adverse effects of cold temperatures on the filter biota and facilitate filter ripening and recovery (e.g., time cleanings for the spring and fall to avoid cleaning in the winter).

Dewatering

Minimize dewatering to only the level needed to properly and safely clean the filter. Cleaning equipment should be equipped with wide tires to spread the load over a broader area, to minimize ruts in the filter.

- For filters that are designed to be cleaned by scraping, minimize the amount of headwater drawdown such that the sand stays wet, yet the water level is low enough to properly and safely walk or drive on as needed to clean the filter. For most filters, this is about 2 – 12 inches below the sand surface, depending on the type of equipment used for cleaning. Keeping the sand wet ensures that the biota needed for effective schmutzdecke formation and filtration does not dry out and die off.
- For filters that are designed to be cleaned by harrowing, lower the water level to the level of the harrowing waste valve or channel (e.g., about 6” (15 cm) above the sand bed). Maintain an influent flow of water into the top of the filter to help wash out debris raked out during harrowing. Introduce water from the bottom of the filter at a rate of about 2 inches of water level rise per hour (0.02 gpm/ft^2 or 0.05 m/hr) with filtered, unchlorinated water. This rate is low enough to prevent the sand from being fluidized or washed out, while simultaneously suspending debris and keeping it from settling back into the filter bed during harrowing.

Scraping

Scraping is the most common method of cleaning SSFs and involves scraping the schmutzdecke and just a small amount of sand (typically < 0.5 inches) to remove the plugged portion of the filter. Scraping can be performed manually using flat-bladed shovels or using specially designed machinery. Because a small amount of sand is removed with each cleaning, it is important to measure how much sand is retained in the filter after each cleaning. This can help with anticipating when the filter needs to be re-sanded.

- Minimize the amount of sand removed such that no more than 0.5 inches of sand is lost with each cleaning. Measuring and recording head loss before and after each scraping can help determine how much sand needs to be removed to maximize filter recovery while avoiding excessive sand removal. This can depend on seasonal water quality changes and the filter run time (time between cleanings).
- Use a staff gage or tape measure measured down from a fixed reference point to monitor how much sand is remaining after each cleaning. There may also be permanent markings in the filter walls that can assist with this regular measurement. These measurements can then be used to calculate how much sand is removed with each cleaning and that number, multiplied by the number of cleanings per year, can be used to estimate how many years the filter media will last before it needs to be replaced.
- The minimum sand bed depth should be no less than 24 inches.
- Avoid walking or driving directly on the schmutzdecke during cleaning. Always try to stay on cleaned areas of the filter to prevent compacting the schmutzdecke into the sand.

Harrowing

Harrowing (or wet harrowing) is a cleaning technique only recommended for slow sand plants specifically designed for this type of cleaning. See "Definitions" table. Harrowing can be performed manually using stiff tined rakes or using tractors that pull a harrowing rake across the filter. Harrowing is conducted with about 6-inches of water above the sand bed. This water is needed to suspend the raked-up solids so that they can be washed out of the filter. Typically, sand is more likely to be retained in the filter with the harrowing method than the scraping method, however, the depth of remaining sand should still be measured with each cleaning.

- Open the harrowing waste valve once the water level is appropriate (see dewatering section above).
- Then influent flow should be adjusted to maintain a steady water level above the sand during raking. 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.
- Gently agitate the top 2 – 3 inches (5 – 8 cm) of sand with a tined rake or harrowing equipment until the headwater begins to clarify, as indicated by the ability to see the sand bed when the raking is stopped.
- Avoid walking or driving directly on the schmutzdecke during cleaning (always try and stay on cleaned areas of the filter to prevent compacting the schmutzdecke into the sand). Note, this may not always be possible where harrowing rakes are pulled behind a tractor. Wide tires can help spread the load of the tractor over a broader area to minimize formation of deep ruts in the sand bed.

Refilling

- To ensure that any entrained air is purged from the media, refill the filter from the bottom with filtered, non-chlorinated water from one of the other filters at a rate of 4-7 inches of water level rise per hour (0.04 – 0.07 gpm/ft^2 or 0.10 – 0.18 m/hr) until the water level is 1-foot above the sand surface, then refill from the top. This minimizes disturbance of the sand bed that may occur from water pouring in from the top.

Filter-to-waste / Ripening

- Minimize flow variation to 50% or less in any 24-hour period.
- Keep the filtration rate ≤ 0.10 gpm/ft^2 (0.24 m/hr), typically at the same loading rate as was used prior to the cleaning, or at the anticipated rate needed when the filter is brought back on-line.
- 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 water quality optimization goals following filter cleaning have been met.

Consistent Performance: performance of the newly cleaned filter should be compared with the performance of other filters that remained in service, or to the performance of the same filter prior to its cleaning. If the performance of the newly cleaned filter does not meet the performance goals, consider extending the ripening period.

Guidelines for Filter Re-sanding

When?

For optimal performance, SSF should be re-sanded when the sand bed depth reaches 24 inches or less. The regulatory agency (typically the state) should be contacted well in advance of re-sanding to ensure their requirements are met. Use a staff gage or tape measure measured down from a fixed reference point to monitor how much sand is remaining after each cleaning. There may also be permanent markings in the filter walls that can assist with this regular measurement. These measurements can then be used to calculate how much sand is removed with each cleaning and that number, multiplied by the number of cleanings per year, can be used to estimate how many years the filter media will last before it needs to be replaced. Re-sanding also presents an opportunity to inspect the filter box/basin underdrains and support gravels for damage or plugging and affords a chance to survey the filter elevations and install permanent markers indicating the top of the support gravel, the depth at which re-sanding should occur (i.e., 24-inches above the gravel), and the design depth of the filter media along with marks every few inches in between to help assess media loss over time.

What Method?

- Filter re-sanding should be planned for times when demands are low and shortly after all the remaining filters have all been cleaned and are back in service.
- The filter to be re-sanded should be drained down and cleaned, and the schmutzdecke should be removed prior to re-sanding.
- The remaining sand may either be fully removed and replaced, or a method called the throw-over method may be employed to place the new sand (see below for more information on the throw-over method).
- New sand should never be placed on top of old sand that may be left in the filter. This can result in taste and odor issues as the biota, now buried beneath the new sand, begins to decay.

Throw-over method: The throw-over method (also called the trenching method) is where the sand is replaced in rows. The filter is cleaned and flushed prior to removing any sand. In the first row, the sand is excavated down to within about 3-6 inches of the support gravel (to protect the gravel and underdrains) and temporarily placed out of the way on top of the old sand. New sand is then placed in the first row. Previously excavated old sand is then placed on top of the new sand to the desired design depth. The second row is excavated down to within 3-6-inches of the support gravel and process is repeated until all the old sand is placed on top of the new sand. The process is repeated through the number of rows required to re-sand the filter. This process is shown schematically below for a filter with 20 inches of sand remaining and re-sanded in 3 rows, to a design sand bed depth of 36 inches.

Row 1		Row 2		Row 3	
Prior to re-sanding at 20”	Re-sanded at 36”	Prior to re-sanding at 20”	Re-sanded at 36”	Prior to re-sanding at 20”	Re-sanded at 36”
	6 inches of sand from row 2		6 inches of sand from row 3		10) Throw 6 inches of sand saved from row 1 on top of new sand in row 3
1) Remove upper 14-inches of old sand (discarded)	3) Fill with 30-inches of new sand	4) Remove upper 14-inches of old sand (discarded)	6) Fill with 30-inches of new sand	7) Remove upper 14-inches of old sand (discarded)	9) Fill with 30-inches of new sand
2) Remove lower 6-inches of old sand and save for placement on top of new sand in row 3		5) Remove lower 6-inches of old sand and throw on top of new sand in row 1		8) Remove lower 6-inches of old sand and throw on top of new sand in row 2	
Support Gravel					

Sand specifications

- Ideally sand specifications should match those of the original filter design, provided those original specifications are consistent with the criteria below.
  - Media should be silica and free of organic matter, clay, and contaminants.
  - Ideally, the sand should be certified to ANSI/NSF Standard 61.
  - Effective size (d_{10}) between 0.20 and 0.35 mm (No. 70 Sieve = 0.212 mm; No. 45 Sieve = 0.355 mm).
  - Uniformity Coefficient (d_{60}/d_{10}) of 1.5 to 3.0.
  - Percent of fines passing the #200 sieve < 0.3% by weight (important to ensure fines do not keep turbidity high for long periods of time as they get washed out during filter maturation)
  - Acid solubility < 5% (important to ensure the media is fee of acid soluble minerals like limestone and organic matter and other impurities – refer to AWWA B100 for more information)
  - Apparent specific gravity > 2.5
- Ensure the supplier provides a sieve analysis and other documentation as needed to demonstrate conformance with the desired specifications.

Sand delivery and placement

- Sand should be washed prior to placement, either by the supplier or on site.

- If not immediately placed, sand should be stored on a clean dry hard surface and covered until installed.
- If possible, sand should be placed in layers or "lifts" (e.g., 12-inch – 24-inch layers) and graded level between each layer. Water introduced through the underdrains to the desired sand layer depth may help with leveling. Repeated filling, draining, and rinsing may help with not only leveling the sand, but washing fines out with the placement of each layer.
- Care must be taken in placing the first lift so as not to damage the underdrains.
- ANSI/AWWA standard B100 may be referenced for the delivery, placement, and storage of granular filter media.

Refilling

- To ensure that any entrained air is purged from the media, refill the filter from the bottom with filtered, non-chlorinated water from one of the other filters at a rate of 4-7 inches of water level rise per hour (0.04 – 0.07 gpm/ft^2 or 0.10 – 0.18 m/hr) until the water level is 1-foot above the sand surface, then refill from the top. This minimizes disturbance of the sand bed that may occur from water pouring in from the top.
- Once the re-sanding is completed, disinfection according to ANSI/AWWA C653 is recommended prior to filter maturation and may be required by the regulatory agency. Unless directed otherwise, this can be accomplished by dosing with sodium hypochlorite while filling the filter to attain a free chlorine residual of 25 mg/l, which is then held and sustained at 25 mg/l for a minimum of 12-hours after which time the filter is flushed by filtering to waste as part of the maturation process (see filter-to-waste and maturation below). Note that chlorinated water may need to be neutralized before disposal to waterways or through other means. Disinfecting the filter will help ensure that coliforms detected during maturation are not because of re-sanding and reflect raw water as it is being filtered.

Filter-to-waste & maturation

Filter maturation is similar to the ripening process following cleaning, however, the length of time needed to fully ripen a filter to maturation following re-sanding is greatly extended because of the time it takes to wash fines out of the new sand and grow and mature the filter biota.

- Begin filtering to waste at a rate of around 0.10 gpm/ft^2 (0.24 m/hr) or less. Flow can be tapered gradually to match the loading rate of existing filters in service towards the end of the maturation period.
- Seeding the filters with schmutzdecke from an adjacent filter may help with the development of the filter biota following re-sanding.
- Filter-to-waste for one week and begin monitoring turbidity daily and coliform counts weekly.
- Continue filtering-to-waste and monitoring until the same water quality goals following cleaning are met and the performance matches that of existing filters.
- Consistent Performance: performance of the newly sanded filter should be compared with the performance of other filters that remained in service, or to the performance of the same filter prior to its re-sanding. If the performance of the newly sanded filter does not meet performance goals, consider extending the maturation period.

Recommended Source or Post-Pretreatment Water Quality Criteria Avoid adding groundwater to an SSF: Blending groundwater with a surface water source can harm the beneficial microorganisms in the filter by decreasing the nutrients and oxygen they need to thrive.		
Parameter	**Recommended Value**	**Notes**
Turbidity	< 10 NTU and absent colloidal clays	Operation is more efficient with lower, consistent turbidity in the 5-10 NTU range. Most SSFs successfully treat water (after any pre-treatment such as roughing filters) 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 (Ingallienella 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 general threshold 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. The Secondary Maximum Contaminant Level (SMCL) for color is 15 color units (40 CFR 143.3), which is also identified as a maximum level for SSF under the Recommended Standards for Water Works (aka "Ten States Standards), 2012 Edition. Pre-ozonation and granular activated carbon are effective at reducing color.
Coliform Bacteria	< 800 CFU or MPN / 100 ml	Coliform removals range from 1 to 3-log (90 – 99.9%) (Collins, M.R. 1998).
Dissolved Oxygen (DO)	> 6 mg/l	Dissolved oxygen is critical for maintaining a healthy schmutzdecke for proper filtration. Potential problems resulting from low DO include taste and odor, dissolution of precipitated metals such as iron and manganese, and increased chlorine demand (Ellis, 1985). It is recommended that filtered water DO be ≥ 3 mg/L.
Total Organic Carbon (TOC)	<2.5 mg/l	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 SSFs is < 15-25% (Collins, M.R. 1989). About 90% of TOC is DOC (USEPA, Microbial and Disinfection Byproduct Rules Simultaneous Compliance Guidance Manual, 1999). TOC removal is variable and may range from 10 – 25% (Collins et. Al, 1989; Fox et al, 1994). Determining DBP formation potential using the EPA's Free Chlorine Distribution System Influent Hold Study Protocol 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	Fe < 1 mg/L Mn < 1 mg/L (Collins, 2012)	SSFs remove iron and manganese by biological precipitation at the sand surface. This can enhance organics removal, but too much iron and manganese precipitate can clog the filters. Iron and manganese removal has been reported as > 67% (Collins, M.R. 1998) up to 99% (Fadel, 2010) in SSF systems. The Secondary Maximum Contaminant Level (SMCL) for iron is

		0.3 mg/L and the SMCL for manganese is 0.05 mg/L. The current AWOP goals for iron and manganese in finished water are 0.10 mg/L and 0.02 mg/L, respectively.
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 are recommended to determine algae species and concentration.

Classification of Common Algal and Cyanobacteria Species[1]

Filter Clogging[2]	Filamentous	Floating
Tabellaria Asterionella Stephanodiscus Synedra	Hydrodictyon Oscillatoria[3] Cladophora Aphanizomenon[3] Melosira	Protoccous Scenedesmus Symara Anabaena[3] Euglena

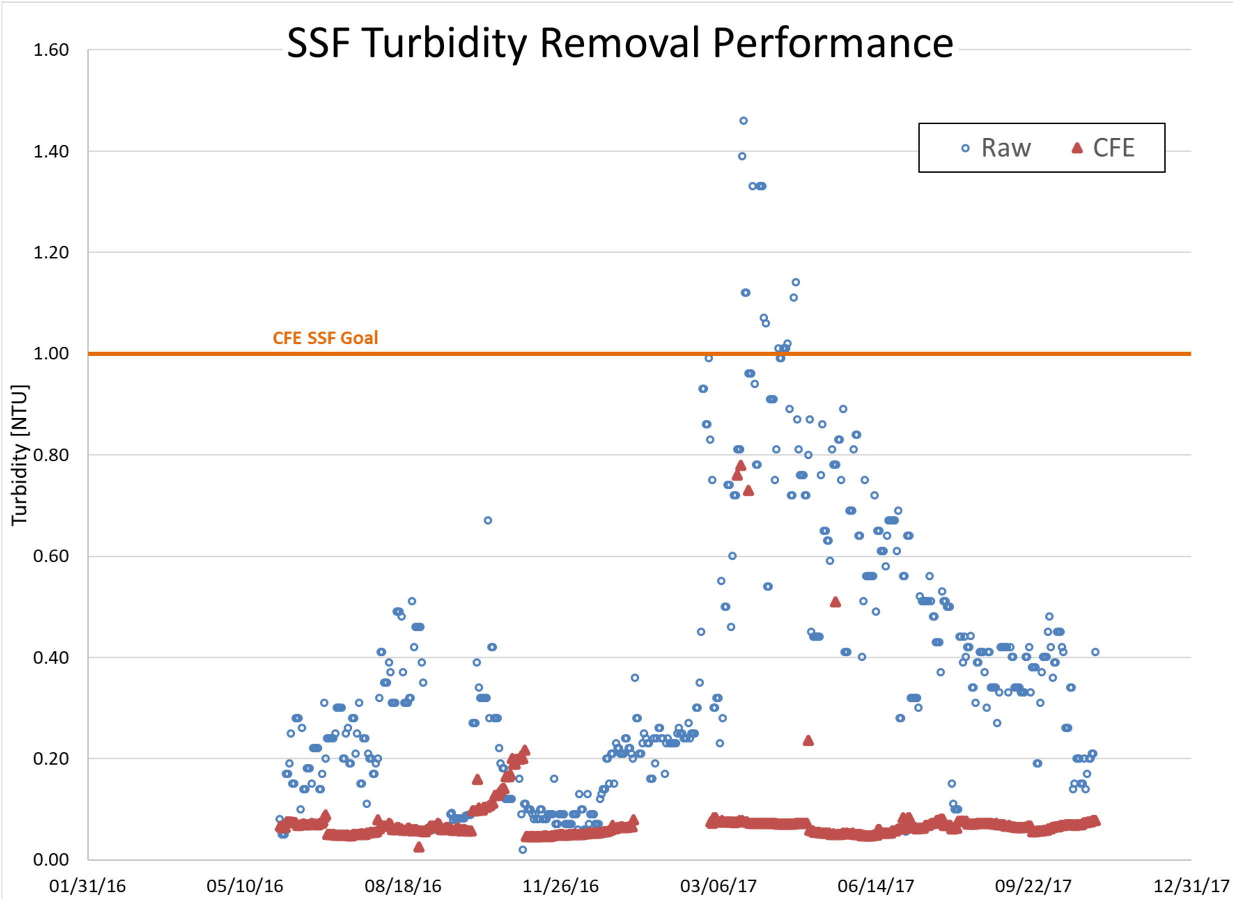
[1]Table adapted from Table 10.2 Water Treatment Plant Design, AWWA/ASCE/EWRI, 2012
[2]Diatoms of all species can generally cause clogging due to their rigid inorganic shells
[3]Can also release algal toxins (microcystins, anatoxin, cylindrospermopsin, and saxitoxin, among others)

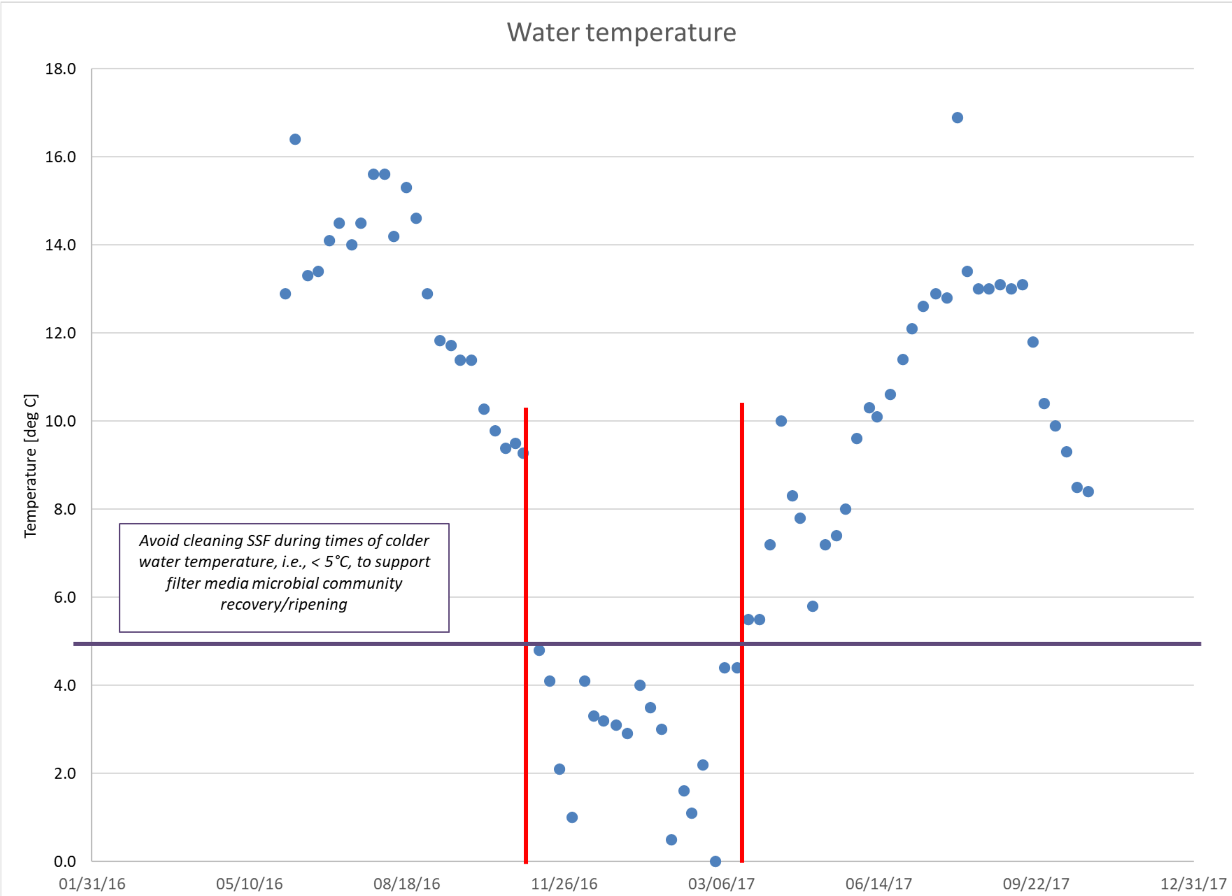
Data Recording and Trending

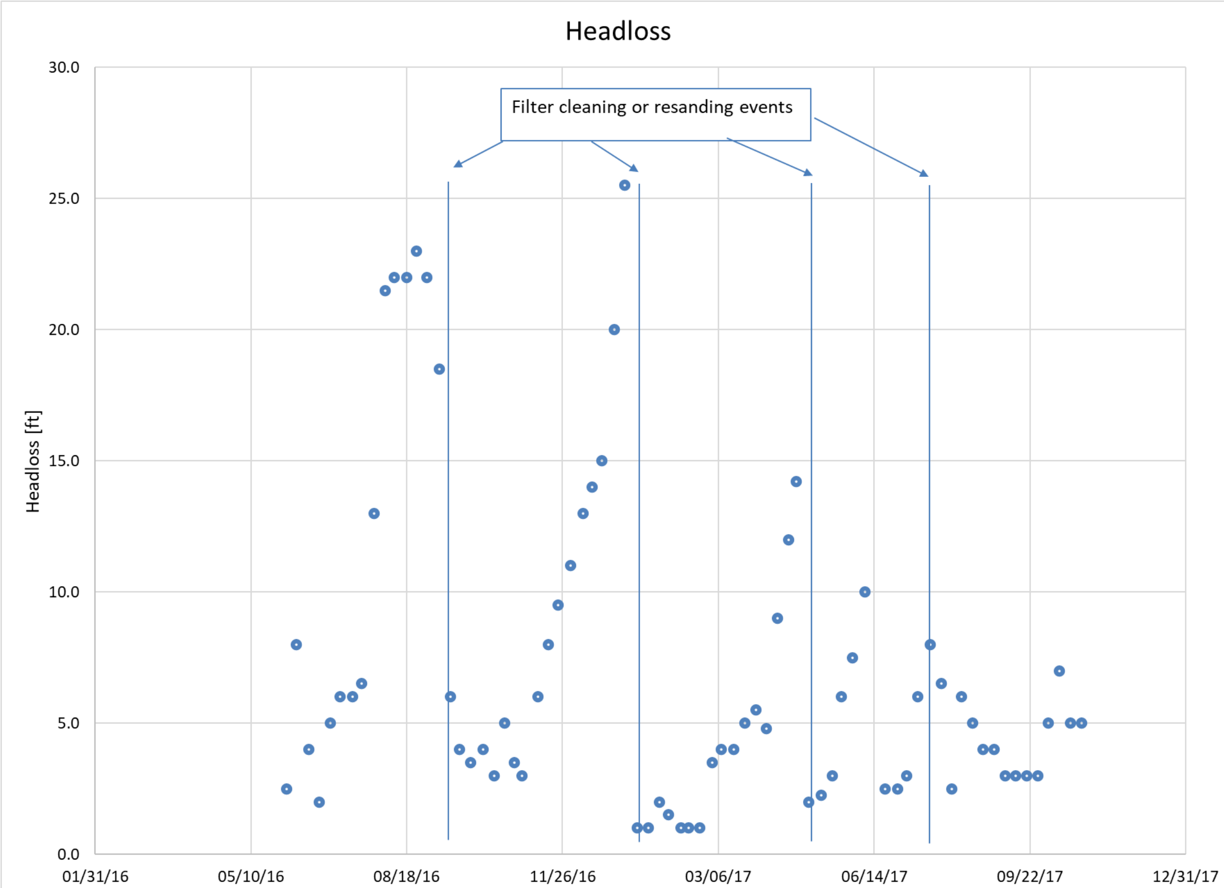
Based on the water quality and monitoring goals and guidelines presented in this document, it is important to regularly record and trend the following process control parameters at an appropriate frequency (see below) to ensure optimized SSF performance. Trending these data can provide operators an understanding of how the SSF is performing in real-time and what types of proactive operation and maintenance may be necessary to continue optimized performance.

- Daily filter headloss measurement to help determine when to perform cleaning.
- IFE and CFE turbidity measured at 1-minute intervals
- Monthly raw water total coliforms, then weekly when watershed or source water quality changes
- Weekly IFE/CFE total coliforms presence/absence when IFE/CFE NTU > 1.0.
- At least daily measurement of filter loading and production rates due to the importance of flow measurement in SSF.
- At least daily measurement of water levels / headwater depth.
- Media depth after each cleaning. This is to help schedule cleanings and re-sanding events.
- At least daily water temperature measurement. Temperature affects filter microbial community viability.
- Weekly raw and finished water dissolved oxygen to ensure filter microbial community viability.
- Daily demand trend understanding relative to production rate.

Example water quality trend graphs are presented below for turbidity, temperature and headloss. Notes are added to help visualize the benefit of trending these data for process control.


SSF Turbidity Removal Performance
Raw
CFE
CFE SSF Goal
Turbidity [NTU]
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
01/31/16
05/10/16
08/18/16
11/26/16
03/06/17
06/14/17
09/22/17
12/31/17


Water temperature
Temperature [deg C]
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
01/31/16
05/10/16
08/18/16
11/26/16
03/06/17
06/14/17
09/22/17
12/31/17
Avoid cleaning SSF during times of colder water temperature, i.e., < 5°C, to support filter media microbial community recovery/ripening



Troubleshooting Potential Slow Sand Filter Issues:

Issue	Response
Applied water quality outside recommended ranges	Roughing filters, microstrainers, riverbank filtration gallery, sedimentation
Long filter downtimes for cleaning and ripening	Filter modification to allow for wet harrowing
High TOC, DBP precursors	Preozonation, activated carbon media amendments (GAC sandwich layer) or post-SSF GAC filter

Adapted from Collins, 2012.

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