Slow sand filtration for small water systems

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Abstract: For over 150 years, slow sand filters have been an effective means of treating water for control of microbiological contaminants. Slow sand filters do not need constant operator attention, making them an appropriate technology for water systems that are small or that employ part-time operators. During the 1970s through the 1990s, research and field evaluations of slow sand filtration have demonstrated its efficacy for control of microbiological contaminants that were unknown in the 1800s. In addition, pretreatment processes such as roughing filters and pre-ozonation have been developed or adapted for use with slow sand filters, increasing the range of source waters that can be treated and the number of contaminants that can be removed in slow sand filters. Inclusion of a layer of granular-activated carbon in a slow sand filter bed has improved capability for control of synthetic organic chemicals. This paper reviews design concepts and process capabilities for slow sand filters and discusses recent innovations in slow sand filter design that now enable this technology to be applied more widely than would have been appropriate two decades ago.

Key words: slow sand filter, design, operation and maintenance, microbiological contaminants, small systems, pretreatment.

Résumé : Depuis plus de 150 ans, les filtres à sables lents représentent un moyen efficace de traiter l’eau pour contrôler les contaminants microbiologiques. Les filtres à sables lents ne requièrent pas la présence constante d’un opérateur ; cette technologie est donc appropriée pour les systèmes de traitement de l’eau qui sont petits ou qui emploient des opérateurs à temps partiel. Entre les années 1970 et 1990, la recherche et des évaluations des filtres à sables lents sur le terrain ont démontré leur efficacité à contrôler les contaminants microbiologiques qui étaient inconnus dans les années 1800. De plus, les procédés de prétraitement tels que les filtres dégrossisseurs et la préozonation ont été développés ou adaptés afin d’être utilisés avec les filtres à sables lents, augmentant ainsi la plage d’eaux sources qui peuvent être traitées et le nombre de contaminants qui peuvent être retirés par les filtres à sables lents. L’incorporation d’une couche de charbon activé granulaire dans le lit d’un filtre à sable lent a amélioré la capacité à contrôler les produits chimiques organiques synthétiques. Cet article présente les bases de conception et les capacités des procédés pour les filtres à sables lents et aborde les innovations récentes dans la conception de filtres à sables lents qui permettent maintenant une plus vaste utilisation de cette technologie qu’il y a à peine deux décennies.

Mots clés : filtre à sable lent, conception, opération et entretien, contaminants microbiologiques, petits systèmes, prétraitement.

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Introduction

Slow sand filtration has been an effective water treatment process for preventing the spread of gastrointestinal disease for over 150 years, having been first used in Great Britain and later in other European countries. The efficacy of this water treatment process was demonstrated during the 1892 cholera epidemic in Hamburg, Germany, when the science of microbiology was in its early years of development. As described by Gainey and Lord (1952), the disease outbreak involved two cites, Hamburg and Altona, which both used the River Elbe as a source of drinking water. Altona, with its water intake located downriver from Hamburg’s sewer outfalls, might have been expected to suffer badly from this outbreak, but Altona used slow sand filtration to purify the Elbe. Hamburg, lacking slow sand filters, bore the brunt of the outbreak, with 8605 deaths. Gainey and Lord (1952) gave the death rates from cholera as 1344 per 100 000 in Hamburg and 230 per 100 000 in Altona. They attributed a large percentage of the 328 Altona cholera deaths to infections that occurred in Hamburg. This event illustrates the efficacy of slow sand filters for controlling microbiological contaminants even when operating staff lacked a modern understanding of microbiology.

Slow sand filters were built to serve communities in North America both before and after 1900, but the advent of effective coagulation, sedimentation, and rapid rate filtration resulted in a declining interest in slow sand filtration in North America in the early part of the twentieth century. This situation changed during the latter part of the twentieth century when slow sand filtration was evaluated for removal of viruses, *Giardia* cysts,

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and *Cryptosporidium* oocysts, which are microorganisms that were either unknown or not considered to be pathogens in the 1800s and early 1900s. A driving force for the reevaluation of slow sand filtration in the United States was the need for simple yet effective water treatment processes for small water systems located in rural areas. A similar reevaluation has occurred in China. According to Li et al. (1996), slow sand filtration was used in China in the 1930s and 1940s, but later, rapid gravity filtration found favor due to the land requirements for slow sand filters in urban areas. Since the 1980s, slow sand filtration has been applied in rural areas in China for small-scale water treatment facilities.

Along with the renewed interest in slow sand filters, some different approaches to design and operation have come about. Modifications to slow sand filters include use of roughing filters for treatment of turbid water before application to slow sand filters, use of ozone to break down complex natural organic matter, and use of a granular-activated carbon (GAC) layer to adsorb organics. Use of precast filters and innovative means of filter access are some recent design concepts. Operators have developed approaches for filter cleaning that depart from the use of manual labor, wheelbarrows, and shovels as commonly practiced a century ago.

This paper reviews design and operating approaches and process capabilities for slow sand filters. Recent improvements in slow sand filter capabilities now enable this technology to be applied more widely than would have been appropriate two or three decades ago. Certain attributes of slow sand filtration are especially beneficial in the context of small water systems, and these are noted in the paper.

Traditional design and performance capability

Engineers designing slow sand filters need to recognize the importance of biological processes in the successful functioning of those filters. Inert particles such as turbidity-causing clays can to some extent be removed by the collision and attachment mechanisms that occur in rapid rate filtration. Instead of chemical coagulants and commercially produced polymers, natural polymers produced by bacteria in the filter seem to aid in turbidity removal. Biological particles also can be removed by biological activity, as larger organisms prey upon smaller ones. The biological action is first encountered at the surface of a slow sand filter in the slimy surface layer referred to as the schmutzdecke. This consists of bacteria and bits of amorphous organic particulate matter, such as fragments of rotting leaves. Because biological action plays an important role in the function of slow sand filters, factors that influence biological action also influence filter performance.

Slow sand filter plants generally do not employ chemical pretreatment, so source water must be of high quality. Cleasby (1991) presented recommendations for source water quality for slow sand filters used without roughing filters:

- Low turbidity, less than 5 nephelometric turbidity units (ntu).
- No heavy seasonal bloom of algae, and chlorophyll *a* less than 0.05 μg/L.
- Iron less than 0.3 mg/L and manganese less than 0.05 mg/L.

Additional recommendations by the authors of this paper are as follows:

- Avoid dissolved heavy metals in source water.
- Avoid pesticides and herbicides unless GAC is used.
- Avoid high true color unless ozone pretreatment is used.
- Either avoid clay-bearing waters or apply roughing filter pretreatment or some other form of pretreatment.
- No residual oxidant, such as chlorine, applied before the filters.

Slow sand filters have traditionally been designed with a bed of sand initially about 1 m in depth with about 1 m of supernatant water. The effective size (d_{10}) of filter sand ranges from about 0.15 to 0.35 mm. Visscher (1990) recommended that the uniformity coefficient (d_{60}/d_{10}) should be less than 5 and preferably less than 3. Filtration rates are typically in the range of 0.1 to 0.3 m/h (Pyper and Logsdon 1991; Galvis et al. 1998), or 1 to 2 % of the rates used in rapid rate coagulation and filtration. Figure 1 is an example of a covered slow sand filter with effluent rate control. Figure 2 shows an open filter with effluent flow control and earth berms used as filter walls.

As with other granular media filtration processes, slow sand filtration performs best when the filtration rate is constant, so frequent rate increases must be avoided. Especially to be avoided is the opening and closing of effluent valves on a frequent basis to maintain a desired water production rate over a day's time. Stopping and starting a slow sand filter may seriously impair filtrate quality. Stop–start operation during a filter run is known to be detrimental to filtered water quality in rapid rate filters, and particle attachment is likely to be weaker in slow sand filters because chemical coagulation is not used for slow sand. Likewise, slow sand filters need to be designed for operation on a 24 h/d basis, without the need for abrupt filtration rate increases. Provision of filtered water storage sufficient for 1 d of use eliminates the need for water production to match system demand and thus allows operators to avoid making frequent rate changes that could deteriorate filtered water quality. Operational flexibility is enhanced when multiple filter beds are provided, so when one bed is removed from service for scraping or sand replacement, others are able to provide a sufficient supply of filtered water without operating at excessively high rates. Figure 3 illustrates the layout of a slow sand filter plant with three beds.

Slow sand filters are usually covered when they are used in cold climates where supernatant water could freeze. In the past, open slow sand filters were used in Denver, Colorado, in spite of freezing conditions, but the operating strategy was to clean

Fig. 1. Covered slow sand filter with effluent rate control (U.S. Environmental Protection Agency 1990).

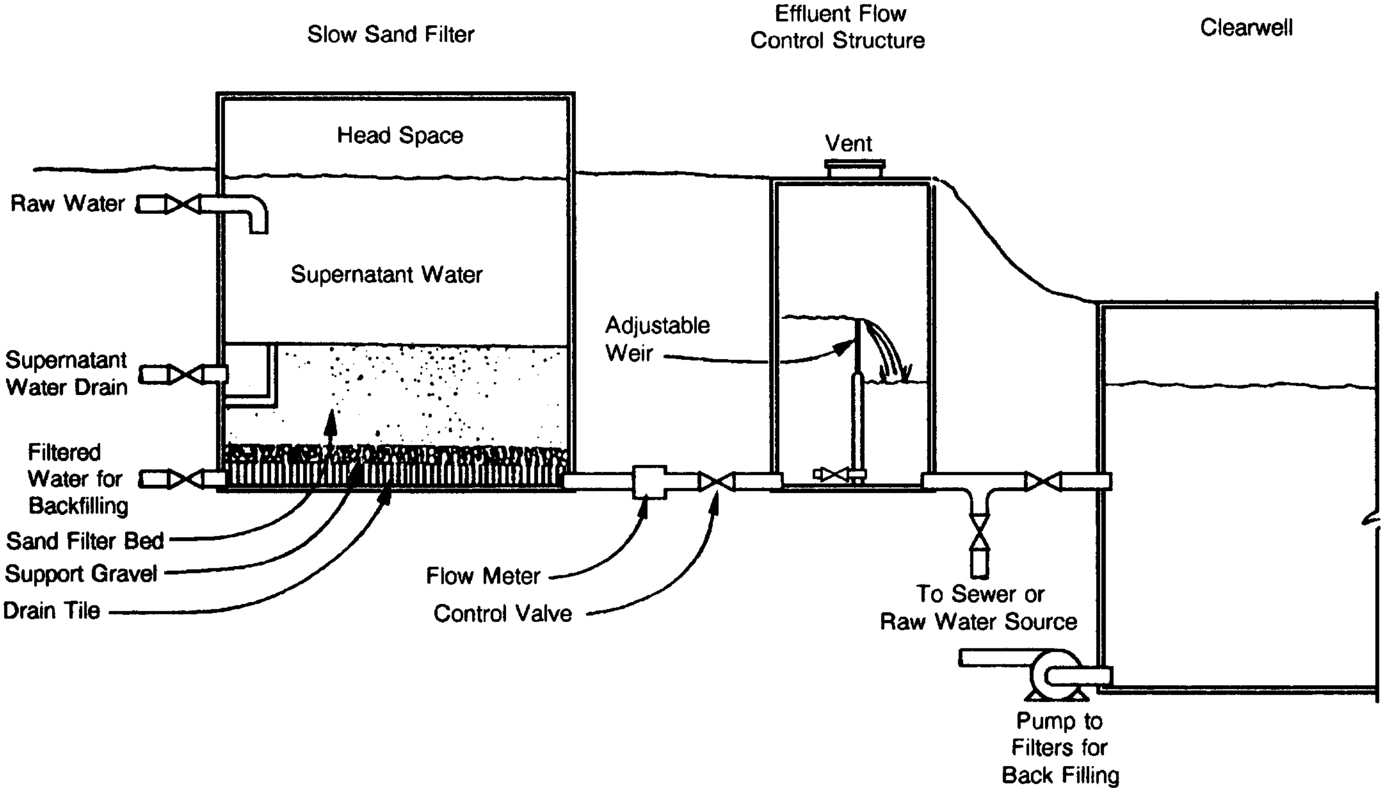
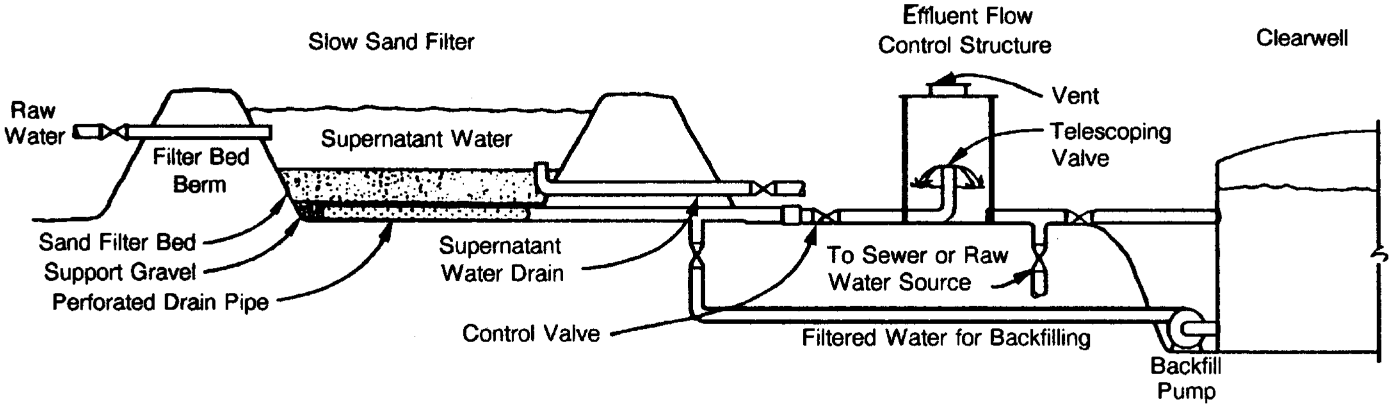


Fig. 2. Open slow sand filter with effluent rate control (U.S. Environmental Protection Agency 1990).



the filters in fall before the freeze and then run through the winter, not cleaning the beds again until ice melted in spring. For small systems the cost of a covered filter generally will be worth the investment, as ice formation can be prevented and covered filters can be cleaned whenever needed. Covered filters *must* provide sufficient headroom for operators to stand erect when performing filter maintenance. Failure to do so will cause very difficult working conditions.

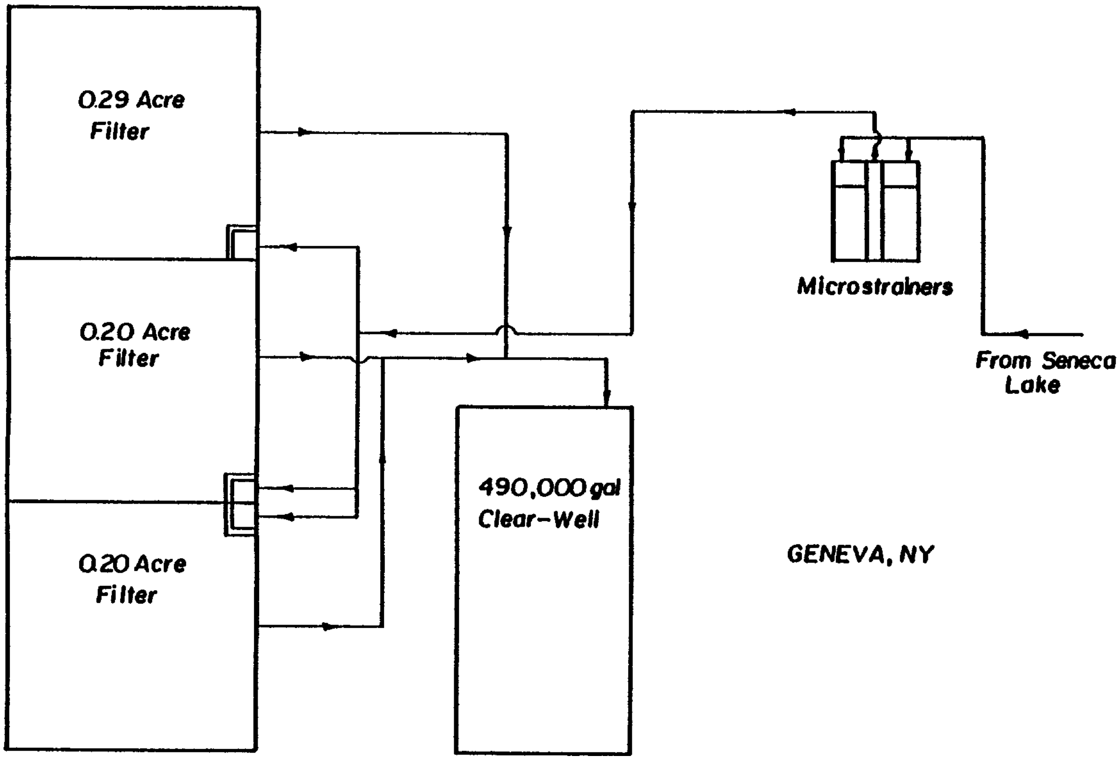
Recent design concepts

With the renewed interest in slow sand filters has come fresh thinking on design concepts related to plant layout, access to filters, filter performance monitoring, and kinds of material to use for filter media.

Modular design can simplify construction of a filter and also can make the design job easier. Precast concrete boxes have been used for a small modular slow sand filter designed for use in a remote area in California (Riesenberg et al. 1995). This is beneficial for quality control, as it is easier to maintain construction quality in a factory than at a field site as well as being more cost effective for smaller systems.

Good slow sand filter designs provide for convenient operator access both for monitoring filter performance and for scraping sand and resanding as necessary. If access to the beds is not provided through the filter walls, providing ramps or ladders will

Fig. 3. Layout of a small slow sand filter plant (Letterman and Cullen 1985).



make it easier for workers to enter the beds and perform maintenance work. For plants large enough to accommodate power equipment, ramps can be used. If workers go into the filter to remove sand manually, ladders may suffice. In one covered slow sand filter plant, access to filter beds is by marine watertight doors constructed in the sidewalls of the filter boxes. This enables operators to use a lawn tractor or some other machine of similar size to haul scraped sand out of the filter in a small trailer. This labor-saving feature eliminates using a wheelbarrow, a tool commonly used for transporting sand removed from the bed.

In Ohio, easy access to a small slow sand filter plant located in a State Park was provided by designing the filter boxes at ground level rather than below ground. Two concrete filter boxes were built, and the superstructure covering the filters was designed to resemble a gable-roofed barn. Sufficient room was provided between the two filter boxes to drive in a dump truck, which was used to carry away scraped sand. Barn doors closed the entry space between the filters. The structure looked like an old wooden barn with concrete walls on the first story level, so it fit in with the rural environment of the park.

When the pipe gallery is located below grade, access to this area by stairs is far more preferable to the use of ladders, even when proper safety equipment is provided with the ladder. An operator trying to climb a ladder while carrying notebooks or water samples could be hurt in an accident.

Monitoring needs for slow sand filters are not complicated. Filtered water flow can be monitored using a totalizing meter, and head loss can be monitored by simple water piezometers if the layout of the plant permits this. Turbidity should be monitored continuously, and sample taps should be provided for raw water and filtered water. If sample taps and instruments are located so they can easily be accessed, sampling and maintenance activities will be easier to carry out. Generally, filtered water is disinfected at the plant, so a sample tap for finished water is needed also. Most data other than turbidity can be recorded once a day by the operator.

Granular-activated carbon has been used in slow sand filters to improve removal of organics. Fox et al. (1984) reported on the use of a slow rate filter with 12 × 40 mesh coal base GAC medium having an initial depth of 0.82 m. After 278 d (979 bed volumes) of operation, removal of trihalomethane precursors was about 90%. Collins et al. (1989) studied the use of a 7.6-cm layer of GAC medium as an amendment to slow sand filters. One filter had the GAC on top of the sand, whereas in the other, it was beneath a 7.6-cm layer of sand. Removal of trihalomethane formation potential in the GAC sublayer was about 80% over 3 months of operation.

Thames Water Utilities followed this research with development of the GAC Sandwich™ filter (Bauer et al. 1996) to remove pesticides in source water, as these chemicals are not readily removed in a conventional slow sand filter. The design consists of 45 cm of sand over a 15-cm layer of Chemviron F400 GAC over a 30-cm layer of sand. As with usual slow sand filter operation, sand is scraped and removed based on head loss development. When new sand needs to be added to the filter, replacement of the GAC would be done also. A full-scale GAC Sandwich™ filter operated at filtration rates ranging from

0.1 to 0.3 m/h produced filtered turbidity averaging 0.l8 ntu for an average removal of 85%, removed 96% of chlorophyll *a* attaining an average effluent concentration of 0.13 μg/L, removed 30 to 40% of influent total organic carbon (TOC), which generally ranged in concentration from 4 to 8 mg/L, reduced trihalomethane formation potential by 28 to 42%, and reduced pesticide concentrations from as high as 0.5 μg/L to less than 0.1 μg/L (Bauer et al. 1996). By the year 2000, Thames Water was using the GAC Sandwich™ concept in slow sand filter plants with a total capacity of over 2400 mL/d, having installed GAC layers ranging in thickness from 100 to 150 mm in the filter beds of five plants (Twort et al. 2000).

Pretreatment

As a result of the limited range of water quality that is suitable for slow sand filtration, studies in process modification have resulted in a number of developments that may foster wider use of slow sand filtration. An important requirement for process modifications or supplemental processes is that they be simple to use and not complicate the operation of a process that is quite simple and straightforward. Otherwise, simplicity, a key advantage of slow sand filtration for small water systems, would be lost.

For turbid, clay-bearing waters, the use of roughing filters has been evaluated. Roughing filters are categorized by their flow patterns. These include upflow roughing filters, upflow roughing filters in series, and horizontal roughing filters. Others, such as dynamic roughing filters, are not discussed in this paper. A typical roughing filter consists of a series of graded gravel beds, with the first bed having the coarsest material and the final bed having the finest material. Typical roughing filters have gravel of different sizes in one, two, or three compartments. If three beds are used the size of gravel in the middle bed would be intermediate between the sizes in the first and last beds. Typical filtration rates for roughing filters are between 0.3 and 1.5 m/h (Hendricks 1991) and typical gravel sizes may be as large as 40 mm and as small as 3 mm.

Collins et al. (1994) operated pilot-scale roughing filters and noted that the most influential design variable for kaolin removal was filter length or depth. For algae removal the most important variable was hydraulic loading rate. For either kind of particles, longer residence time in the roughing filter was related to improved removal. The variables Collins et al. (1994) studied were gravel sizes of 2.68, 5.53, and 7.94 mm, filtration rates of 0.5, 0.75, and 1.0 m/h, and gravel depths of 30, 60, and 90 cm.

Roughing filters also have been studied by Evans (1999), Galvis et al. (1994), Li et al. (1996), and Wegelin (1994). Some of their findings for pilot- or full-scale roughing filters are summarized in Table 1, which gives some design parameters and information on turbidity removal.

Some preliminary design guidelines for roughing filters were presented for horizontal roughing filters (Wegelin and Mbwette 1989) and for upflow roughing filters (Wolters et al. 1989). These are summarized in Table 2. For both types of filters the authors recommend providing at least two roughing filter units to allow for removal of a filter from service for maintenance. Recommended cleaning velocities are much higher for upflow roughing filters than for horizontal roughing filters.

Another approach for coping with turbid source water is to use bank infiltration, extracting water from a well after it has passed through the alluvial materials beneath a stream or river. The permeability of alluvial materials is site specific, as is the filtration capability of the deposits. If the alluvial material consists mostly of coarse gravel, bank filtration for turbidity removal may not succeed. The geology of the proposed intake site should be investigated before funds are expended to construct an infiltration well. Besides inadequate filtration of surface water, a second possible cause for problems with use of an infiltration well is the possibility that the well might provide ground water containing iron or manganese in addition to surface water. Again, this is justification for preliminary investigations. Even with such potential drawbacks, using infiltration wells as water sources for slow sand filters has proven successful in the western United States, and this approach to obtaining appropriate source water quality has considerable merit. A full discussion of bank filtration is beyond the scope of this paper. For additional information, readers are referred to Kuehn and Mueller (2000) and Ray et al. (2002). These papers demonstrate the complexities of riverbank filtration and reveal the need for special expertise if use of riverbank filtration is contemplated in conjunction with a slow sand filter plant.

Slow sand filters typically do not remove natural organic matter that is not readily biodegradable. Because natural color is not readily biodegraded, removal in a slow sand filter typically is not very effective, with 25 % being typical (Cleasby 1991). One approach to removing organics at slow sand filtration plants is to use ozone pretreatment. Ozone can decrease the concentration of color and facilitate biological removal of large organic molecules by breaking them down so they can be assimilated by biota in the filter bed.

Using ozone as a pretreatment before slow sand filtration has been investigated by a number of investigators. Dempsey and Fu (1994) reported that dosages of 0.12 to 0.36 mg ozone/mg dissolved organic carbon (DOC) did not affect the rate of head loss gain, whereas a dosage of 1.08 mg ozone/mg DOC caused head loss to rise about fourfold faster. Greaves et al. (1988) found that pre-ozonation improved true color removal by slow sand filtration from 20% without ozone to 74% with ozone. Average color after ozonation and slow sand filtration was 6.6 color units (expressed as degrees Hazen in the United Kingdom). Using 1.0 mg ozone consumed/mg nonpurgable DOC, Collins et al. (1991) attained slightly more than 20% removal of nonpurgable DOC as compared with less than 10% for slow sand filtration without use of ozone. In a comparison of full-scale slow sand filter performance with and without pre-ozonation treatment, Cable and Jones (1996) reported that 28% removal of trihalomethane formation potential (THMFP) was attained in slow sand filters without pre-ozone as compared with 50%

Table 1. Examples of roughing filter design and performance for turbidity removal.

Reference	Filter type	Flow (m^3/d)	Media size range (mm)	Filtration rate (m/h)	Length or depth of media (m)	Mean filtered water turbidity (ntu)	Mean percent removed
Evans (1999)	URFS	18	40, 20, and 10 in 3 filters	0.6	3 at 0.5 m	2.7	70
Galvis et al. (1994)	URFS	812	25 to 3	0.7	2.0	0.7	70
Galvis et al. (1994)	URFS	588	20 to 6	0.6	1.8	2.7	53
Galvis et al. (1994)	URF	760	25 to 3	0.7	1.0	5.0	66
Li et al. (1996)	HRF	Full scale, nd	5 to 1.2	0.7	nd	Influent turbidity reduced from a few hundred ntu to <100 ntu	
Wegelin (1994)	HRF	260	nd	1.2	nd	About 4	nd

Note: URFS, upflow roughing filters in series; URF, upflow roughing filter; HRF, horizontal roughing filter; nd, no data provided.

Table 2. Preliminary design criteria for roughing filters.

	Upflow filter (Wolters et al. 1989)	Horizontal flow filter for suspended solids >150 mg/L (Wegelin and Mbwette 1989)	Horizontal flow filter for suspended solids to 150 mg/L (Wegelin and Mbwette 1989)
Filtration rate	0.5 to 1.0 m/h	0.5 to 0.75 m/h	0.75 to 1.5 m/h
Number of filters	2 minimum	2 minimum	2 minimum
Number of compartments in filter	3 if separate sizes of gravel used in each compartment	3	3
Depth or length of gravel size fraction	0.3 to 0.8 m	3 to 5 m for coarse gravel, 2 to 4 m for medium gravel, 1 to 3 m for fine gravel	3 to 4 m for coarse gravel, 2 to 3 m for medium gravel, 1 to 2 m for fine gravel
Gravel sizes	Coarse, 24 to 18 mm; medium, 18 to 12 mm; fine, 12 to 6 mm	Coarse, 25 to 15 mm; medium, 15 to 10 mm; fine, 10 to 5 mm	Coarse, 25 to 15 mm; medium, 15 to 10 mm; fine, 10 to 5 mm
Filter bed area	15 to 25 m^2 per compartment	Height 1.0 to 1.5 m, width 1 to 4 m, giving a filter cross-sectional area of 1 to 6 m^2 per compartment	Height 1.0 to 1.5 m, width 1 to 4 m, giving a filter cross-sectional area of 1 to 6 m^2 per compartment
Wash velocity during cleaning	4 to 6 m/h	Initial drainage velocities range from 60 to 90 m/h to as low as 10 to 20 m/h	Initial drainage velocities range from 60 to 90 m/h to as low as 10 to 20 m/h

removal attained by the filters receiving pre-ozonated water. Using pre-ozonation before slow sand filtration improved removal of TOC in water warmer than 8°C, but the improvement in removal of TOC was even greater when water temperature was less than 8°C (Seger and Rothman 1996). This finding is significant in the context of the general decline in performance of slow sand filtration that is noted when cold water is treated. Yordanov et al. (1996) used ozone pretreatment and reported that ozonation and slow sand filtration could decrease color by an average of 58% as compared with an average 49% decrease by ozone alone. Ozone and slow sand filtration reduced TOC concentration by an average of 28%, with effluent TOC typically 3 to 4 mg/L. They noted that conversion of natural organic matter to biodegradable organics increased the amount of biofilm on filter media, causing head loss to increase faster, which would result in more frequent filter cleaning. Metabolism of biodegradable organics within the filter bed is a beneficial treatment result, as this can decrease the tendency for biofilms to develop in the water distribution system.

Algae in source waters can cause treatment problems if they cause tastes and odors that are not removed by the slow sand filter or if they clog the filter surface. Algae in colonies form particles large enough that they may not penetrate into the filter but rather form a surface mat that causes high head loss. Planktonic algae may pass through the filter bed and this also would be problematic. O'Brien et al. (1973) evaluated a submerged rock filter for removal of algae from wastewater lagoon effluent using hydraulic detention times of 5, 24, and 48 h. They concluded that 24 h was sufficiently long. They reported that almost no solid material was observed in the effluent and suggested that a practical approach for such filters would be to use a horizontal filter consisting of rocks in the size range of 4 to 5 cm.

Coagulation, flocculation, and sedimentation generally are not used as pretreatment for slow sand filtration. Pretreatment was implemented in an ad hoc manner using equipment, channels, and natural basins adapted to the purpose during a water treatment emergency at Salem, Oregon, when a major flood occurred in February 1996. The North Santiam River turbidity was about 100 ntu and was not expected to decline to its typical 1 to 5 ntu for a number of weeks. Pretreatment was able to remove about 90 % of the source water turbidity and greatly extended the filter runs. After another flood occurred in 1997, permanent facilities for pretreatment were built during an expansion project at this slow sand filtration plant. Chemical pretreatment is not used except when source water turbidity is excessive and would cause premature run termination.

Removal of microorganisms

Slow sand filters excel at removal of microorganisms. Information on removal of bacteria by slow sand filters has been available for over 100 years and is not discussed in detail here. Data of various researchers are summarized in Table 3.

Several factors influence removal of microorganisms, which can vary from 2 $\log_{10}$ to 4 $\log_{10}$ or greater, depending on treatment conditions and influent microorganism density. The biological condition of the sand bed is very important, as removal is more effective when the biota have become established in a ripened bed. Fresh sand in a newly built filter is not very effective.

Cold water inhibits biological processes that play an important role in microorganism removal. The research by Poynter and Slade (1977) and Pyper (1985) indicated that removal of viruses and *Giardia* cysts was influenced by water temperature. Bellamy et al. (1985*b*) saw this effect for coliform bacteria and for heterotrophic plate count bacteria but not for *Giardia* cysts. In Pyper's (1985) research, the least effective removal of *Giardia* cysts occurred when the water temperature was under 1°C and both *Giardia* cysts and sewage were spiked at the same time to assess removal of cysts and coliform bacteria. Then cyst removal was only 93.7%.

Microorganism removal improves with lower filtration rates and with smaller sand size in the filter bed. Bellamy et al. (1985*b*) observed total coliform removal of greater than 98% for 0.29 mm effective size sand versus 96% removal for 0.62 mm effective size sand for filters having the same bed depth and filtration rate. Poliovirus removal (Poynter and Slade 1977) was quite sensitive to filtration rate, and both Bellamy et al. (1985*a*) and Ghosh et al. (1989) noted a slight effect with lower *Giardia* cyst removals at 0.4 m/h as compared with results for filtration at lower rates.

Three pilot plant investigations of slow sand filtration for *Cryptosporidium* oocyst removal have consistently demonstrated high removal for this organism. What seems to be lacking for this organism is the performance of carefully controlled pilot testing at water temperatures near freezing, which in the research on *Giardia* cyst removal seemed to be a critical condition.

Control of turbidity improves after filter ripening. This may be a result of production of sticky natural polymers by bacteria inhabiting the filter bed (Bellamy et al. 1985*b*), as a slow sand filter treating water with high nutrient levels that could promote greater biological growth performed better than a filter with lower nutrient levels. Turbidity removal can be expected to improve with use of smaller sand sizes in the filter bed and with lower filtration rates. Some source waters in mountainous regions may contain low levels of nutrients and very small particles that are difficult to remove by slow sand filtration. These were encountered by Bellamy et al. (1985*a*, 1985*b*). Turbidity removal by a slow sand filter cannot be predicted in advance for a given source water, so the best way to assess process performance is to install a pilot-scale slow sand filter and operate it for a period of months, preferably through a full cycle of seasons.

Operation and maintenance

Routine slow sand filter maintenance for small water systems is not complicated. In the United States, where systems treating surface water have to comply with regulatory reporting requirements, routine operating tasks may require about 1 h/d. They include measuring raw and filtered water turbidity, measuring disinfectant residual, measuring rate of flow, measuring pH, calculating the product of disinfectant residual and contact time and comparing that value with U.S. Environmental Protection Agency requirements for disinfection, and recording data. In addition, flow rate would be adjusted based on volume of finished water in storage, demand in the distribution system, and rate of water production.

When terminal head loss develops, slow sand filters are scraped to remove the schmutzdecke and 1 to 2 cm of sand and thus restore the filtration capacity. Traditionally, shovels have been used to scrape sand in small filters. Seelaus et al. (1986) reported that at the Empire, Colorado, filtration plant, operators used asphalt rakes to increase sand scraping efficiency. Using these tools, two workers in a filter with a surface area of about 150 m^2 could scrape sand to a depth of 0.5 cm into windrows and remove the sand with shovels and buckets in 0.5 h. Earlier, Letterman (1991) had reported that 1 to 5 h of labor may be required per 100 m^2 of filter area. After sand is removed from a filter, it can be cleaned and saved for reuse or used for other purposes such as sanding roads in winter. If sand is not saved, however, new sand will have to be purchased when the filter bed has to be resanded.

An alternative to scraping sand to remove the schmutzdecke was developed at West Hartford, Connecticut (Collins et al. 1991). When terminal head loss is reached at this filtration plant with covered filters, a rubber-tired tractor equipped with a comb-tooth harrow is placed on the filter bed after supernatant water is drawn down to a level of 30 cm above the sand surface. Then, as the water on the surface of the bed is withdrawn to the side of the bed, the tractor is used to harrow the sand surface. Dirt disturbed by harrowing remains suspended in the water as it drains off to the side of the bed, but the sand settles and remains within the bed. When the supernatant depth reaches 8 cm above the sand, harrowing is discontinued and resumes after the water depth has been increased to 30 cm. Collins et al. (1991) reported that sand was removed from the beds at the West Hartford plant and cleaned at intervals of 8 to 10 years.

After the depth of sand in a slow sand filter reaches about one half of the original depth due to repeated sand scrapings, clean sand is added to the filter to restore the bed depth. Good practice involves removing sand to the bottom of the filter bed, placing new or cleaned sand in the trench created by the sand

Table 3. Microorganism removal by slow sand filtration.

Reference	Organism	Filtration rate (m/h)	Temperature (°C)	Removal percentage
Poynter and Slade (1977)	Poliovirus	0.2	16 to 18	99.997 average
Poynter and Slade (1977)	Poliovirus	0.4	16 to 18	99.865 average
Poynter and Slade (1977)	Poliovirus	0.2	5 to 8	99.68 average
Poynter and Slade (1977)	Poliovirus	0.5	5 to 8	98.25 average
Bellamy et al. (1985*b*)	Total coliform bacteria	0.12	17	97 average
Bellamy et al. (1985*b*)	Total coliform bacteria	0.12	5	87 average
Bellamy et al. (1985*a*)	*Giardia*	0.12	5 to 15	99.994 average
Bellamy et al. (1985*a*)	*Giardia*	0.4	5 to 15	99.981 average
Bellamy et al. (1985*b*)	*Giardia*	0.12	17	>99.93 to >99.99
Bellamy et al. (1985*b*)	*Giardia*	0.12	5	>99.92 to >99.99
Pyper (1985)	*Giardia*	0.08	0.5	93.7
Pyper (1985)	*Giardia*	0.08	0.5 to 0.75	99.36 to 99.91
Pyper (1985)	*Giardia*	0.08	7.5 to 21	99.98 to 99.99
Ghosh et al. (1989)	*Giardia*	0.3	4.5 to 16.5	>99.99
Ghosh et al. (1989)	*Giardia*	0.4	4.5 to 16.5	99.83 to 99.99
Ghosh et al. (1989)	*Cryptosporidium* oocysts	0.15 to 0.40	4.5 to 16.5	>99.99
Hall et al. (1994)	*Cryptosporidium* oocysts	0.2	Not stated	99.8 to 99.99
EES and TWU (1996[a])	*Cryptosporidium* oocysts	0.29	12 to 14	>99.99

[a] Economic and Engineering Services, Inc. and Thames Water Utilities. 1996. Salem slow sand filtration pilot study microbiological challenge test results. Unpublished report.

removal, and placing the sand removed from the trench on the new or cleaned sand. Resanding was described by Letterman (1991) and may require about 50 h of labor per 100 m^2 of filter area.

Application of slow sand filtration for small water systems

Slow sand filtration is a water treatment process that is well suited for use by small water systems (Leland and Damewood 1990). Visscher (1990) observed that the process was being applied in developing countries and that it was appropriate for small water systems in other countries. The simplicity of the process, especially absence of chemical coagulation for pretreatment, enables these filtration plants to be operated by part-time personnel who have little training in chemistry or microbiology. This was demonstrated in England in the 1800s when slow sand filters were operated successfully in an era before the present understanding of water chemistry and microbiology had been developed. The small amount of operator attention, perhaps an hour per day, fits well with the financial capabilities of many small systems that do not sell sufficient water to pay for the salary of a full-time operator. Slow sand filters that are designed for manual operation with a minimum of instruments and electronic controls are less likely than automated package plants employing coagulation and filtration to need service by an electronics technician who may be located hundreds of kilometres away.

Slow sand filter plants sometimes can be constructed by the local population, which may reduce project cost and can be an economic benefit to those in the community who perform the construction. Use of modular, precast concrete boxes as filter beds strengthens the quality control aspect of construction. Providing a structure to house slow sand filter beds is not greatly different from construction of houses or commercial buildings, so this aspect of construction is certainly an appropriate task for the local labor force.

The nature of the slow sand filtration causes some serious limitations on utilization of the process. An important limitation is the need for high-quality source water or appropriate pretreatment or filter modification to cope with water quality that is less than ideal. Developments such as roughing filters, the GAC Sandwich™, and pre-ozonation have extended the range of water quality suitable for slow sand filtration, but these adaptations increase the cost of construction and operation. Perhaps the most important limitation for using slow sand filtration is the lack of a way to predict a priori the treatability of a source water. If a slow sand filter plant is constructed without pretreatment such as ozone or a roughing filter, or without the GAC layer, the range of source water quality that can be treated with success is narrow. If treated water quality is not satisfactory, providing a remedy could be very expensive. This is particularly crucial for small communities, whose financial resources may be strained by constructing a slow sand filter.

Pilot plant testing is the surest way to learn if slow sand filtration will successfully treat a source water (Tanner and Ongerth 1990). This has been the case for over 150 years. M.N. Baker's review of the history of water treatment (Baker 1981) includes a comment by James Simpson (the engineer who was responsible for construction of the slow sand filter at the Chelsea Water Works Company in 1829) that preliminary trials were necessary before funds are spent for construction. Even though engineers and scientists have had over 170 years to learn about slow sand filtration, experimental filtration tests remain the most reliable way to ensure that the process will succeed. Installation of slow sand filters without sufficient pilot testing can result in the failure of a full-scale plant to perform as expected. Engineers working for small water systems should resist the temptation to reduce project costs by omitting pilot testing. Because slow sand filter runs can last for many days or weeks, carrying out pilot studies is not a labor-intensive task. Recommendations for pilot testing programs were provided by Leland and Logsdon (1991).

In a worst-case situation in which money and time are simply not available for pilot testing, the design would have to be very conservative. According to Galvis et al. (1998), the International Reference Centre for Community Water Supply and Sanitation recommends designing for worst-case scenarios, and in some situations, this may be the only option available to the engineer. In such a circumstance, consideration has to be given to the footprint of the plant being designed and also to the possibility that additional facilities might be needed if the plant as designed was not able to provide satisfactory filtered water quality.

An often-mentioned disadvantage of slow sand filters is that they require a much larger land area than rapid rate filters. For large cities, the very large amounts of land needed for slow sand filters generally result in preference for rapid rate filtration. Land requirements of slow sand filters are not substantial for very small water systems. For example, a filter having an area of 20 m^2 and operated at a rate of 0.12 m/h could produce 2.4 m^3/h or 58 m^3 (58 000 L)/d. This daily production could support a village of perhaps 150 persons in a developed country if treated water was not used for irrigating lawns and gardens and other such outdoor uses.

One limiting factor for slow sand filtration in North America may be the lower microbiological removal efficacy at very cold temperatures (near 0°C). Remote locations at northern latitudes where cold weather predominates and mountainous regions having high altitude often have “pristine” source waters, as they may be far from large cities and industries that pollute surface waters. One approach to using slow sand filters for treating cold water is to apply a conservative design so that the filtration rate is low when water is cold. This may be especially appropriate for summer resort areas where the number of persons using water during winter is much smaller, and as a result of reduced demand the filtration rate would be very slow in winter.

Summary

Slow sand filters have a long history of successful water treatment, when applied to appropriate source waters and when designed and operated properly. Failures have happened and will continue to occur, however, if the process is used when source water is not treatable by slow sand or if the design is flawed or basic operating principles are ignored. Design engineers who are aware of the capabilities and limitations of slow sand filtration can in many instances provide for successful use of slow sand filtration by small communities.

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