New Horizons for Slow Sand Filtration

Dr. David H. Manz, P. Eng.

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Introduction

Several novel and significant innovations to the design and operation of slow sand filtration promise to revolutionize its application in municipal, industrial and even household potable water treatment worldwide. These innovations, developed over the past ten years, provide opportunities for demand operation of slow sand filters and filter cleaning without the need to stop, drain and remove the upper surface of the filter media.

Demand operation is made possible by design changes, which first allow the filter to be stopped for extended periods without destroying the biologically active and aerobic schmutzdecke (or biolayer) which forms on the filter surface; and second, to allow filtration to resume without schmutzdecke disturbance or destruction.

The recently developed clean-in-place technology permits slow sand filter cleaning without the removal of the upper few centimeters of the filter bed. This is achieved by recognizing that virtually all of the processes provided by slow sand filtration occur at or near the surface of the filter bed. A certain amount of virus deactivation is thought to occur throughout the entire depth of the filter bed but the accumulation of debris on the filter surface, previously believed to constitute the entire schmutzdecke, really has the primary effect of plugging pores in the media and inhibiting the flow rate through it. The ability of the filter to effectively remove bacteria and viruses is associated with the formation of biofilms on the surfaces of the particles of media at or near the surface of the filter bed. (Parasites are effectively removed by physical-mechanical processes and completely eliminated by subsequent biological processes.) If the upper surface of the slow sand filter can be cleaned by removing the material that is inhibiting flow while leaving the filter media in place, (clean-in-place) the capacity of the filter to remove bacteria, viruses and certainly parasites is not effected by the act of filter cleaning itself.

Used in combination, demand operation and clean-in-place technology have greatly extended the range of applications of slow sand filtration technology. Appropriately configured slow sand filters are being used to effectively treat surface waters (reduction of turbidity and removal of pathogens) that are many times more turbid than previously thought practical with or without the aid of minor amounts of coagulant. Slow sand filters are being used to treat ground water not only for removal of pathogens but also for the removal of iron and manganese, previously thought impractical because of cleaning requirements. Slow sand filters, when used in combination with other treatment technologies, have proven effective in completely eliminating all pathogens, removing colloidal particles, reducing dissolved organic compounds including those which contribute to colour, taste and smell, hydrogen sulfide, algae, organic toxins, arsenic, uranium and other heavy metals.

Demand operated slow sand filters, which incorporate 'clean-in-place technology', are physically much simpler and smaller than their comparable traditionally designed counter parts, are much more simple and reliable than virtually any other filtration technology considered practical in a similar application, minimize the use of chemicals in the treatment process, and generate a minimum amount of waste water during the cleaning process.

Traditional Slow Sand Filtration

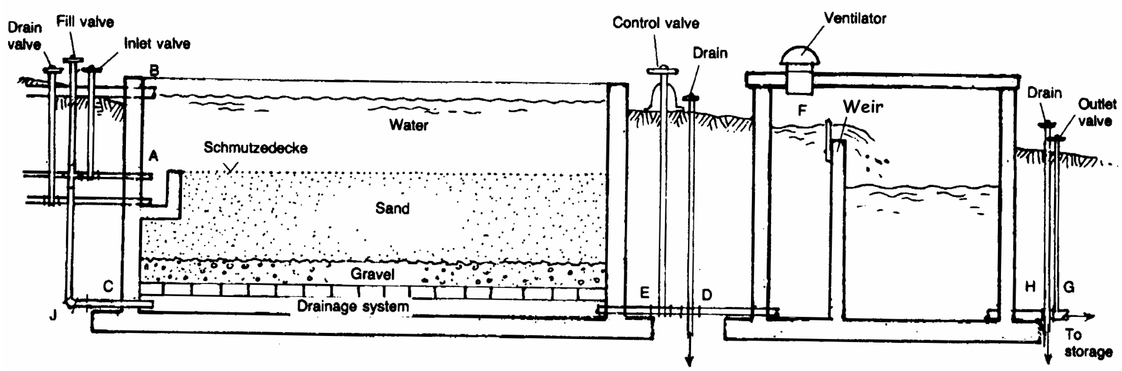

Figure 1. Cross-section of a typical small capacity traditionally designed slow sand filter.

Slow sand filters have been in use for more than 150 years. Their effectiveness to reduce risk of water borne disease was recognized even before relationships between the organisms causing the disease and the disease itself were fully understood. The designs used today (traditional) have been established more than 100 years ago and are illustrated in Figure 1. Recently established guidelines for the construction, operation and maintenance of traditionally designed slow sand filters may be found in Barrett, et al 1991. The principles are simple and well understood. They are as follows:

1. The media layer consists of a layer of filtering 'sand' overlying an under drain system that consists of a layer of coarse material on the bottom with one or two less coarse layers above. The filtering sand must not be allowed to plug the under drain gravel.
2. The depth of the filtering sand is often much more than a meter. This is greater than that considered a minimum for deactivation of viruses (approximately 0.8 meter or so) and sufficient to allow the filter to be scraped (removal of 5 cm of top surface) several times before more filter sand would need to be added.
3. The maximum flow through the filter is considered to be 0.3 m^3/m^2/hour, (equivalent to 0.3 m/h or 300 litres per square meter per hour). The flow through the filter is controlled by the size and size range of the particles used for the filter

sand (effective size equal to 0.35 mm and uniformity coefficient of 3 or less), the depth of the filter media, and the difference between the maximum depth of water in the filter and the height of the weir controlling the flow from the filter. When the filter sand has recently been replenished the flow through the filter may be as low as 100 litres per square meter per hour. There is no lower limit except that the filter size may become too large to be practical.

4. Water enters the filter in such a way that it does not disturb the top surface of the filter sand. The water may be one meter or more in depth. Water flow down through the filter bed, into the under drain and out of the filter itself. The water may be disinfected and stored for subsequent distribution.
5. Suspended solids and suspended microorganisms, including parasites, bacteria and viruses are captured on the filter surface. Initial bacteria capture is in the range of 60%. Parasite removal is near 100%. Virus removal is believed to parallel that of bacteria removal. The rate of increase in the ability of the filter to remove bacteria increases with time (frequently several weeks) often approaching 100%; and. is believed to be related to the rate of accumulation of organic material on the surface of the filter sand – the schmutzedecke, a German word, which may be approximately translated as 'dirty blanket'.
6. With time the accumulation of material on the top of the filter sand begins to impede the flow of water through the filter. When this is no longer acceptable the filter will need to be cleaned. This consists of removing approximately 5 cm of the top surface of the filter sand using a process known as scraping. Scraping requires that the filter be stopped and dewatered. The upper surface is mechanically removed and the filter is recharged with treated water that is forced upward from the under drain through the filter bed until water pools above the bed surface. This eliminates the danger of the media air binding. The entire process of draining the filter, scraping and restarting make take several days – even for a relatively small slow sand filter. Normal filter operation is resumed but the capacity for bacteria removal is reduced to pre- schmutzedecke formation levels. Bacteria removal capacity recovers in a fraction of the time originally required to achieve its previous, pre- cleaning levels (only a few days)
7. The flow through the filter must be continuous. The schmutzedecke is an aerobic ecosystem and its primary source of oxygen is that dissolved in the water as it moves through the top surface of the filter bed. If the flow is stopped or is too low the schmutzdecke receives too little oxygen and the organisms that need the oxygen to survive either die or go dormant. The ability of the filter to remove bacteria immediately drops to pre- schmutzedecke levels. Once the flow through the filter is resumed, the aerobic microorganisms in the schmutzedecke recover and the ability of the filter to remove bacteria recovers to maximum capacity. (The recovery may require two or more days.)

The advantages of traditional slow sand filtration for potable water treatment are:

1. Effectiveness in removing parasites, bacteria and viruses.
2. Effectiveness in removing non-colloidal suspended particles.
3. Simplicity of construction.

4. Simplicity of operation and maintenance – minimum operator skills and training required to operate filters.
5. Reliability – minimum liability to engineers, regulatory authorities, owners and operators.

The most serious limitations of the traditional designed slow sand filter are:

1. Requirement for low flow rate.
2. Requirement for continuous flow to preserve bacteria removal characteristics..
3. Limited ability to remove colloid-sized particles.
4. Limited ability to remove dissolved organic compounds (colour, taste and those causing excessive THM concentrations when chlorinated).
5. Significant effort required to clean the filter and the impact cleaning has on filter performance.
6. Need to construct large civil works, which often inhibits provision of needed environmental protection (roof and heating in cold climates). Traditional slow sand filters require large areas of land.

Cleaning requires such effort its frequency must be minimized. This is achieved by only treating water with relatively low concentrations of suspended solids – a factor that has limited their use to low turbidity water (less than 20 NTU). Traditional slow sand filters are not used for removal of oxidized iron and manganese and coagulants are never used for pretreatment.

Demand Operated Slow Sand Filtration

Demand operated slow sand filtration was developed in response to the apparent need to develop effective, inexpensive, small-scale water treatment for disadvantaged communities in developing countries. The design and operation of demand operated slow sand filters is distinctly different from traditional slow sand filtration. The significance of the differences has motivated the need to give demand operated slow sand filtration several other names including 'intermittently operated slow sand filtration', 'Manz filter' and 'biosand water filter', depending on the author and the circumstances.

The design of demand operated slow sand filters overcome most of the limitations of their traditionally designed counterparts while maintaining their efficacy. The design modifications are as follows:

1. The single layer of filter 'sand' used in traditional slow sand filters is replaced with two layers of filter media each of which exceed the criteria for filter media as outlined by the Barrett, et al 1991. The #1 sand has an effective size of approximately 0.15 mm and a uniformity coefficient of one. The #2 sand has an effective size of approximately o.35 mm with a uniformity coefficient of one. The combined depth of both the #1 and #2 sand is approximately equal to the minimum depth for filter sand as outlined by the Barrett, et al 1991.

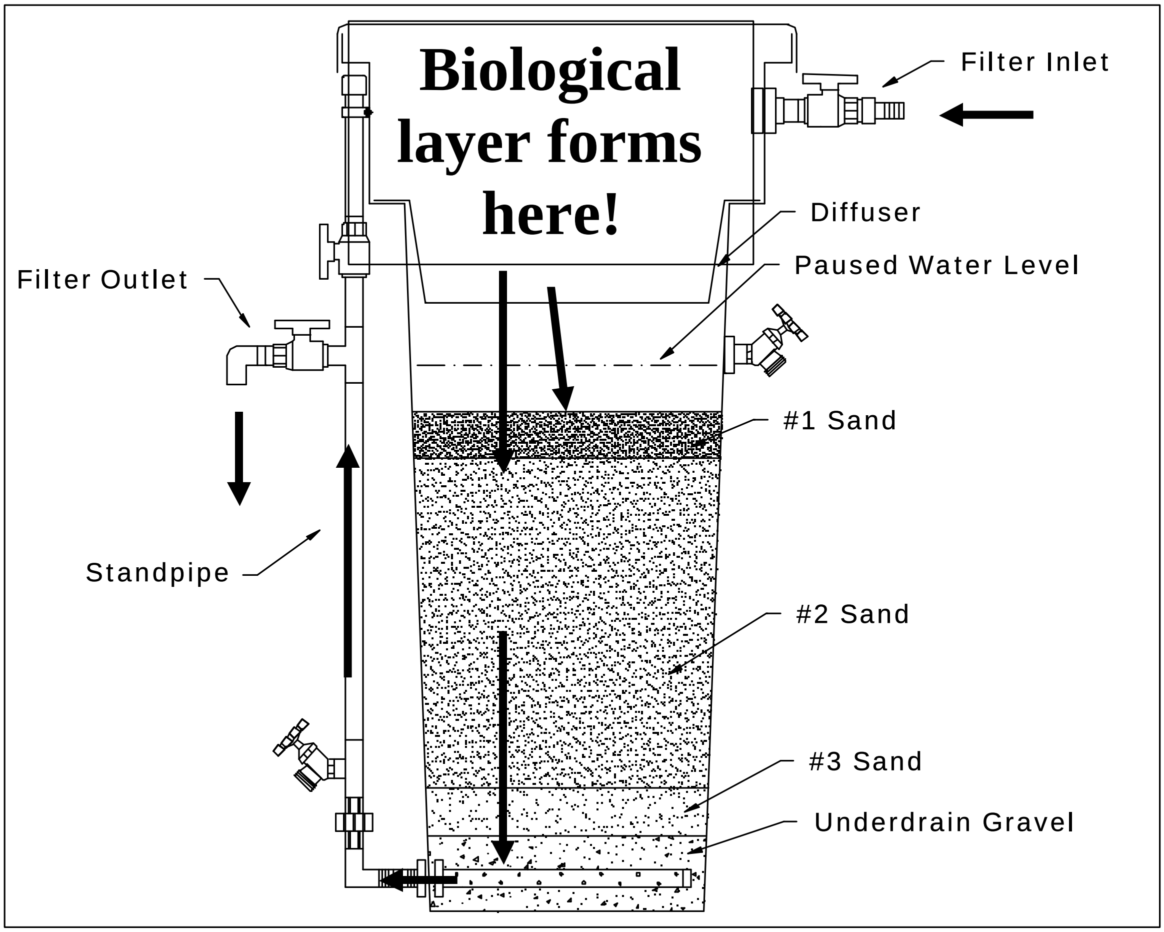

Figure 2. Cross-section of a typical low capacity demand operated slow sand filter.

2. Filters are operated in exactly the same fashion as their traditionally designed counterparts; however, when the filters are stopped, the water above the filter is allowed to drain to a depth of approximately 5 cm above the filter surface. The shallow layer of water allows sufficient oxygen to diffuse through to the oxygen demanding schmutzedecke or 'biolayer'. The effectiveness of this filter design has been proven by research performed by Buzunis 1995, Palmateer, et al 1999 and in several research programs conducted in the Davnor Water Treatment Technologies Ltd. laboratories. The research performed by Buzunis and Palmateer was performed using natural raw water supplies. The research performed by the author in Davnor laboratories was performed using both natural supplies and laboratory produced and controlled supplies. The laboratory supplies had the advantage of having of a much higher colliform bacteria count (1000 bacteria or more) and consistent concentration over extended periods of time. The laboratory scale, demand operated filters had a capacity of only sixty litres per hour and were given only twenty litres of water each day. Filter performance was tested on a daily basis. Diffuser basins, shallow containers with

perforations of pre-established size and distribution ensure that the addition of water to the filter does not disturb the surface of the filter media irrespective of the violence with which the water is added to the filter.

3. Maximum filter surface loading rates were increased to double that recommended for use with traditional slow sand filters without loss of performance. The filters can be operated at any flow rate less than maximum without perceptible decrease or gain in performance.
4. Removal of Giardia cysts and Cryptosporidia oocysts were in excess of 99.99 % as determined by studies performed by Palmateer, et al 1999.
5. Turbidity reductions were consistent with those reported for traditionally designed slow sand filters – that is, the demand operated filters were not successful at removing colloidal sized particles or significant amounts of DOC causing colour.
6. Filters were cleaned without scraping. The procedure consists of adding more water to top of filter to achieve approximately 15 cm of water above top of filter sand; agitating surface of sand and re-suspending material blocking flow of water; allowing sand to settle and decanting the suspension from filter. This process took less than 5 minutes for laboratory filters and less than 30 minutes for filters with a capacity of 10,000 litres per hour (compared to several days for traditional designs). Laboratory testing revealed that the ability of the filter to remove bacteria was not negatively impacted by the cleaning process – even though the flow rate through the filter was completely recovered. This is attributed to the belief that the biolayer contributing to bacteria removal is not in fact the collection of organic debris collectively called a schmutzedecke but is in fact the coating of micro-organisms or biofilm on each of the particles at or near the surface of the filter bed. If these particles are not removed the ability of the filter to remove bacteria is not impaired. Studies performed in Davnor laboratories used a filter media that was almost pure white silica. The media exhibited only a slight discoloration as the bacteria removal rates exceeded 99%.
7. Field installations of demand operated slow sand filters occasionally demonstrated air binding. The cleaning procedure was modified to include a 'reverse flow', an upward flow through the filter drain to allow trapped gases to escape through the top of the filter surface. Treated filter water was used for this purpose, provided at a flow rate approximately equal to the filtration rate, to ensure that the filter bed was not fluidized. The filter bed was completely degassed (as evidenced by lack of bubbles at filter surface) before treated water reached the filter surface. Even if chlorinated water is used for degassing the biolayer is never in danger of being destroyed.
8. Filter cleaning does not consume any filtered water – only untreated water. Filter cleaning results in production of 150 to 300 litres of wastewater per square meter of filter surface. The wastewater contains the same organisms and substances that are in the raw water supply and is easily disposed of.

The advantages of demand operated slow sand filters include all those reported for traditionally designed slow sand filters plus the following:

1. Demand operation – used as required. This facilitates the construction of very small slow sand filters for household use, convenient use in smaller communities where continuous operation is impractical or results in excessive waste of treated water, minimum use of energy and use of alternative energy sources, which may be intermittent in nature (solar). Demand operation facilitates use with other treatment processes, which normally operate on a demand basis such as pressurized water treatment processes including water softeners and membrane technologies.
2. Small scale allows a much wider range of applications – many of which would have been impractical for traditional designed filters. Filters may be constructed off-site, transported and located as needed. Demand operated filters can be used in portable applications.
3. Convenient filter cleaning. There is no loss of media with each filter cleaning or excessive production of wastewater. This facilitates treatment of raw water with much greater suspended solid load.
4. No need for replacement of filter media. Filter media can be prepared with maximum quality control unlike that prepared for traditional slow sand filters, where filter media may vary widely (within AWWA guidelines) with each installation.
5. Minimal structural requirements. Filters are shorter and weigh significantly less than traditional designs. Several demand operated filters can be stacked, in parkade-like fashion, and still be shorter and weigh less per unit area than that of a single traditionally operated slow sand filters.
6. Much smaller surface area – environmental protection feasible even in cold climates.

The disadvantages of demand operated slow sand filters operating alone include:

1. Limited ability to remove colloidal sized particles.
2. Limited ability to remove organic compounds (colour, taste and those causing excessive THM concentrations when chlorinated).
3. Large scale compared with many other treatment technologies.

The first two of these disadvantages are easily overcome with the use of pre-treatment using coagulants or post-treatment using granular activated carbon. Because coagulant dosage does not require the development of large flocs that will quickly settle in a clarifier, the coagulant dosage is approximately 10% of that typically used – pin flocs are sufficient. Either organic or inorganic coagulants may be used. The use of a coagulant will often reduce DOC to acceptable levels (including colour reduction). In those instances where coagulant addition is not adequate post-treatment using GAC will normally solve the problem. Because most of the suspended organic material has been removed, GAC life is greatly extended. Demand operated slow sand filters, which use coagulant addition upstream of filtration have proved to offer a low tech, simple to operate, highly forgivable, very reliable alternative to conventional treatment systems using coagulation, flocculation, sedimentation and rapid sand filtration.

Other inorganic polymers such as oxidized iron and manganese salts are readily removed as well. Iron is readily removed at a pH commonly found in potable water but manganese normally requires use of oxidants prior to filtration. Concentrations of both iron and manganese can be reduced to concentrations well below those specified in drinking water guidelines.

Arsenic has long been known to be removed from water by adding ferric or alumina salts to water containing arsenic (III) and (V), the former being more difficult to remove USEPA 2000 and MacPhee 2001. When either of these salts are added to the water, the resulting metallic polymers complex the arsenic (cause the arsenic to be attached to the polymer). The arsenic is removed when the polymers are removed. Historically, the dosage of coagulants was quite large in order to facilitate settling. Significant testing in Davnor laboratories has indicated that arsenic concentrations in excess of 3 mg/l can be removed with minimal ferric salt dosages. These concentrations of iron are very easily removed using slow sand filtration. Arsenic concentrations are reduced below 0.01 mg/l and frequently below 0.005 mg/l.

Combined treatment of ground water for removal or pathogens or iron and manganese is possible and has been implemented using demand operated slow sand filtration. Similarly, combined surface and ground water supplies may be treated by the same demand operated slow sand filtration system.

Hydrogen sulfide gas is eliminated by first oxidizing the gas to produce elemental sulfur in a colloidal form that may be sufficiently removed by the slow sand filter. Coagulants, usually in a polymer form, may be also be used to expedite the removal process. Low concentrations of hydrogen sulfide gas may be eliminated by simple aeration followed by filtration.

Conclusions

Slow sand filtration has long been known as a valuable technology for treating water to potable quality. Demand operated slow sand filtration had simply expanded the role. Practical designs for individual filters are available to treat as little as 20 litres per hour to very large units that can treat 1,000,000 litres per hour. Filters may be operated in parallel to achieve whatever treatment plant capacities are desired. A complete comparison of traditional and demand operated slow sand filtration may be found in Table 1.

The range of applications is only just being explored. As well as treating the wide variety of raw water quality commonly considered potential sources for potable water, demand operated slow sand filtration can be used to treat storm water runoff, waste water from greenhouses to recyclable condition, municipal waste water from secondary treatment facilities to recyclable condition, pre-treatment for membrane water treatment plants, waste water from coal bed methane production, waste water from food production facilities to recover valuable products that would otherwise be wasted and produce water that can be reused, grey water treatment, refitting of existing treatment plants, etc.

Demand operated slow sand filtration has dramatically expanded the role of slow sand filtration – by two very important improvements, the ability to use a slow sand filter as required and by cleaning the filter without removal and replacement of the filter sand. The body of knowledge gathered over more than one hundred years on slow sand filtration design and operation has not been ignored but is included in this important new form of the technology.

Table 1. Comparison of Traditional and Demand Operated Slow Sand Filtration

	Traditional (continuous-flow)	Demand Operated
Operation	**Continuous** • Performance impaired if stopped and started • Normally requires significant treated water storage • Difficult to operate effectively using alternative energy sources	**Intermittent (stop/start)** • Performance unaffected by intermittent operation. • Demand-based operation results in minimized water storage and reduced water waste. • Opportunity to use alternative energy sources such as solar and wind. • Readily used with other treatment processes.
Performance	**Removal Rates:** • Parasites – up to 100% • Bacteria – up to 99% • Turbidity < 1 NTU • Toxins – unknown • Arsenic – not used • Iron/manganese – not used • H_2S/CO_2/methane – not used	**Removal Rates:** • Parasites – up to 100% • Bacteria – up to 99% • Turbidity < 1 NTU • Toxins – 0% to 100% (depending on the toxin) • Arsenic – up to 100% • Iron/manganese (up to 38 mg/L) – up to 100% once oxidized. • H_2S/CO_2/methane – effective with low concentrations
Design	• Very large civil works – typically several meters in depth. • Significant foundation requirements. • Substantial construction works requiring large, skilled work force. • Not portable. • Not normally constructed off-site. • Not usually considered modular – must construct with up to 25 years future needs in mind • Filter media normally prepared on site – frequently replaced several times over life of filter – limited quality control.	• Compact – 1 to 2 meters in height. Constructed of medium-density polyethylene plastic or stainless steel. • Minimal foundation requirements. • Minimum construction works requiring small skilled work force. • Constructed off-site or portable, depending on size. • Convenient modular design is easily expanded for future needs. • Filter media supplied and never replaced – very good quality control.
Production (Loading Rate)	150–300 litres/m²/hour	Up to 600 litres/m²/hour
Raw Water Quality (turbidity in the absence of color)	Max. Turbidity: up to 20 NTU Suspended solids including Iron & manganese concentrations: < 1 mg/L	Max. Turbidity: 50 NTU or more Suspended solids including Iron and manganese concentrations: < 40 mg/L
Method of Maintenance	• Removal of upper sand surface by scraping, disposal or cleaning. • Periodic media replacement required. • Manual – scraping only • Expensive, labor & time intensive • Filter capacity affected • Filter efficacy affected • Substantial amounts of waste water produced when systems are cleaned	• Davnor Clean-in-place (CIP) technology. • No surface scraping. • No media disposal. • No media replacement. • Manual or automated CIP • Degassing function included. • Negligible waste water generated. • Cleaning does not impact filter performance – even temporarily. • Cleaning may be performed as frequently as required since media is never removed or replaced.

Applications	Polishing	Primary and/or Polishing (may be operated in series)
Use of Coagulants	Never	As required.
Community Size	25 to several 100,000 persons	1 to several million persons
Skid Mounting	Never done	Routinely done for units 2000 lph or less
Shipping	Never done	Routinely shipped by truck, train, container, ship or air
Backwash	Never done	Uses reverse flow as part of a "Clean-in-Place" process and/or to eliminate bed compaction.

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