Stacked Filters: Novel Approach to Rapid Sand Filtration

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Abstract: Rapid sand filters are a familiar and mature technology, but the mechanical sophistication they incorporate in industrialized nations limits their sustainable application in developing countries. Conventional rapid sand filters require pumps, elevated tanks, or multiple filter units to generate high flow rates for backwashing. Stacked rapid sand filtration is introduced here as a more robust and sustainable alternative. A stacked rapid sand filter can backwash itself with no additional flow, which eliminates the need for pumps or other expensive equipment. This study presents laboratory and field proof-of-concept demonstrations of this novel technology. The multilayer configuration of stacked rapid sand filters allowed a laboratory unit to be loaded at 1.4–1.83 mm/s (120–160 m/day) per layer and backwashed at 10–11 mm/s (860–950 m/day) with the same or similar total flow rate. The filtered effluent met U.S. Environmental Protection Agency drinking water standards. The backwash cycle was also demonstrated, and flushing of contaminants from the sand bed was effective even with 5–10 NTU backwash water. A test stacked filter unit also demonstrated satisfactory filtration performance and effective backwashing at several water treatment plants in Honduras. **DOI:** 10.1061/(ASCE)EE.1943-7870.0000562. © *2012 American Society of Civil Engineers.*

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Background

Untreated or insufficiently treated surface water is responsible for a large portion of the health problems caused by poor water quality around the world (Mihelcic et al. 2009). The unit process sequence of flocculation, sedimentation, filtration, and disinfection effectively removes turbidity and pathogens from surface water in many municipalities in the industrialized world. However, municipal-scale drinking water treatment, even the familiar and reliable processes in a rapid sand filtration plant, have shown limited economic viability and technical effectiveness in many less developed areas of the globe (Whittington and Hanemann 2006; Mintz et al. 2001). Large-scale water treatment processes have generally been developed for application in a "First World" milieu where electric grids are reliable, technical expertise is available to support operation and maintenance, supply chains exist for replacement of machined parts, and communities have sufficient economic resources to afford sophisticated treatment systems. Water treatment projects outside of this context often face more difficult technical, material, or economic constraints (Hokanson et al. 2007; Ahrens and Mihelcic 2006).

The development of more efficient water treatment processes also can benefit the industrialized world. Substantial investments will be needed to maintain and improve American water treatment infrastructure in the coming decades (ASCE 2009) and the same is true in other developed countries. While many alternatives exist for water treatment, such as membrane processes, it is likely that rapid sand filtration plants will remain an important part of the technology portfolio for municipal-scale infrastructure. More sustainable and efficient processes for plants of this type will be desirable, especially with an increasing emphasis being placed on the energy costs and carbon footprint associated with water infrastructure (Stillwell et al. 2010).

Rapid sand filters are important in surface water treatment because they remove residual suspended solids following flocculation and sedimentation to produce low-turbidity effluent (Reynolds and Richards 1996). Rapid sand filters also effectively remove pathogenic cysts such as *Cryptosporidium* (Gitis 2008). Rapid sand

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filters are run in the forward (typically downflow) direction to remove solids from the influent water, and must be fluidized and backwashed for cleaning once the bed is fully loaded. One reason rapid sand filtration as practiced in industrialized countries is difficult to implement in resource-poor communities is that high flow rates are necessary to backwash filters, and achieving these flows requires one or more of the following:

- Electric pumps: High-flow velocities can be achieved by pumping backwash water through the filter. Electricity for the pump, however, adds considerable operating cost, and pumping is impractical for communities without reliable electrical service.
- Elevated storage: A tank at a high elevation can be used to generate large flows for backwashing; however, the provision of an additional tank adds to the cost of the filtration system, and the volume of water typically consumed for backwash can significantly reduce the net volume of clean water produced.
- Multiple filter units: A bank of parallel filters is an alternative to pumps or elevated tanks. One filter can be taken offline for backwashing, and flow is diverted to this filter from all of the other filters to produce a high upflow velocity. Because the backwash velocity tends to be seven to eight times the filtration velocity, seven to eight individual filter units are needed, which adds to the capital cost and operational complexity of this scheme.

This study introduces a novel self-backwashing rapid sand filter for municipal-scale water treatment. The stacked rapid sand filter (SRSF) presented here can operate using the same volumetric flow rate for both filtration and backwash. Thus, the SRSF can be backwashed by gravity in any situation where a low elevation drain is available. The SRSF also has a smaller footprint and construction cost relative to multiple filter units. As a result, the SRSF is expected to be a robust and sustainable technology for municipal-scale drinking water facilities around the world. The objective of this study was to validate the SRSF concept in both laboratory and field experiments, by demonstrating adequate filtration-cycle performance and effective backwashing.

Process Theory

Traditional Rapid Sand Filter Design

There are two modes of operation for a rapid sand filter:

1. Filtration: Turbid water passes through the filter media and suspended solids are removed by transport and attachment to the sand grain surfaces (Yao et al. 1971). The filter operates in filtration mode until turbidity removal declines or until the head loss through the filter increases to an excessive level.
2. Backwash: Water passes through the filter in the reverse direction at a velocity sufficient to fluidize the filter bed media, detaching captured solids from the media, and transporting them out of the filter. The filter operates in backwashing mode until the filter bed media has an acceptably low level of attached solids. At the end of backwashing, the filter media settles, and the filtration process begins again. Often, the filter is rinsed to remove any trace of backwash water before effluent is sent to clean-water storage.

In both filtration and backwash modes, the approach velocity or loading rate V is defined as the flow Q per unit area of the bed A_{Bed} as in Eq. (1)

$$V = \frac{Q}{A_{\mathrm{Bed}}} \tag{1}$$

Table 1. Process Variables and Typical Values in Single-Media Rapid Sand Filters

Variable	Unit	Typical range	Reference
Loading rate	m/day	100–230	AWWA 1971
Backwash velocity	m/day	860–1,200	Davis and Cornwell 2008
Influent turbidity	NTU	1–10	Davis and Cornwell 2008
Turbidity removal	percentage	90–98	Reynolds and Richards 1996
Bed depth	m	0.5–0.75	Reynolds and Richards 1996
Media effective size	mm	0.35–0.70	Reynolds and Richards 1996

Typical design parameters for single-media rapid sand filters are shown in Table 1.

Stacked Rapid Sand Filter Geometry

A stacked rapid sand filter consists of a sand bed in a single vessel, with inlets and outlets placed through the wall at several points to create multiple layers (see Fig. 1). During filtration mode, each layer of the SRSF receives a portion of the total flow and acts as an independent filter operating in parallel with the other layers. Depending upon its position relative to the influent and effluent piping, either downward or upward flow will occur through a layer. During backwash, the entire flow moves through the sand bed in the same direction from bottom to top and the layers are fluidized. Fig. 1 illustrates flow through a stacked filter column during both modes of operation.

In a traditional rapid sand filter, the approach velocity can only be changed by varying the total flow through the system. The stacked configuration of the SRSF allows for the scaling of loading rate and backwash velocity by the number of layers, N_{Layer}. The layers of the SRSF operate in parallel during filtration mode so the total flow is divided among the layers and the flow rate $Q_{\mathrm{Filtration}}$ in each layer is

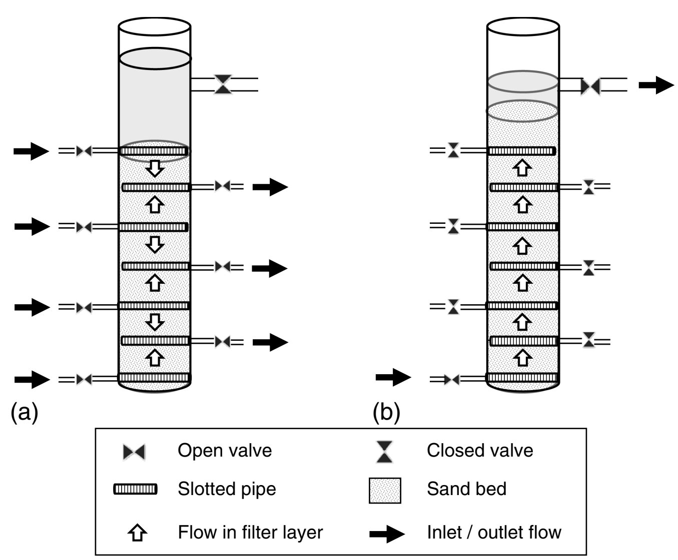

Fig. 1. Conceptual diagram of flow in a six-layer SRSF system during (a) filtration mode and (b) backwash mode, showing both the division and the direction of flow in the filter bed; both cycles can be run at the same total flow rate

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$$Q_{\mathrm{Filtration}} = \frac{Q_{\mathrm{Total}}}{N_{\mathrm{Layer}}} \tag{2}$$

This calculation assumes that each layer receives an equal share of the total flow. It is important to note that flow will be divided equally in parallel among several sand layers of uniform depth and composition as long as head losses in the sand and not head losses in the inlet plumbing control flow distribution. The filtration-cycle approach velocity $V_{\mathrm{Filtration}}$ in each layer can be calculated by substituting Eq. (2) into Eq. (1)

$$V_{\mathrm{Filtration}} = \frac{Q_{\mathrm{Total}}}{N_{\mathrm{Layer}} A_{\mathrm{Bed}}} \tag{3}$$

In backwash mode, the total flow passes through all filter bed layers in series so the number of effective layers is now one. As a result, Eq. (3) becomes

$$V_{\mathrm{Backwash}} = \frac{Q_{\mathrm{Total}}}{A_{\mathrm{Bed}}} \tag{4}$$

Setting the flow rates equal in Eqs. (3) and (4) gives

$$V_{\mathrm{Backwash}} = N_{\mathrm{Layer}} V_{\mathrm{Filtration}} \tag{5}$$

Eq. (5) shows that the SRSF, unlike a traditional rapid sand filter, can use the same total flow rate for both filtration and backwashing, and the backwash velocity will still be N_{Layer} times greater than the filtration velocity. The number of layers in the SRSF can be selected based on the desired ratio of backwash velocity to filtration loading rate. Backwash velocities are typically around six times the filtration loading rate so a six-layer SRSF satisfies this condition.

Stacked Filter Backwash Hydraulics

The head HL_{Backwash} required to backwash the SRSF can be approximated with the same relationship that is typically used to predict backwash head loss for a single-media rapid sand filter

$$HL_{\mathrm{Backwash}} = H_{\mathrm{Filter}}(1-\varepsilon)\left(\frac{\rho_{\mathrm{Sand}}}{\rho_{\mathrm{Water}}} - 1\right) \tag{6}$$

where H_{Filter} = settled depth of the sand; ε = settled-bed porosity; ρ_{Sand} = density of the sand particles; and ρ_{Water} = density of water (Davis and Cornwell 2008). With typical parameters of $\varepsilon = 0.4$ and $\rho_{\mathrm{Sand}} = 2{,}650\ \mathrm{kg/m^3}$, the backwash head loss is 0.99 times or roughly equal to the height of the settled filter bed. This head requirement reflects the energy input needed to suspend the sand particles in the water column and it is independent of velocity provided that the upflow velocity is sufficient to fluidize the particles.

The backwash head loss in the SRSF may differ slightly from the prediction of Eq. (6). It may be higher because of minor losses around the inlet and outlet pipes that are placed through the sand bed or it may be lower because some of the sand in the bed is displaced by these inlet and outlet pipes.

Successful operation of the backwash cycle for the SRSF requires the following conditions:

1. All flow enters through the lowest inlet pipe and exits at a point above the sand bed.
2. Water passes through the sand at a sufficient velocity. As long as the filter has been sized with Eq. (4) to provide a typical rapid sand filter backwash velocity, this velocity is expected to be sufficient to fluidize the sand and provide an adequate degree of expansion.
3. Sufficient head is available over the backwash exit point to suspend the sand grains. This head should be approximately equal to the sand bed height with typical filter sand plus any extra head required to overcome minor losses due to pipes in the sand bed.

Implications for Design and Applications

The costs associated with backwashing are an important limitation to the widespread application of rapid sand filters in municipalities in the developing world. As discussed previously, the infrastructure required to backwash conventional filters represents a significant capital cost. In addition, backwash may require as much as 5–7% of the total volume of water treated by a conventional system (Nasser et al. 2002; Cornwell and McPhee 2001), which adds to the operating cost. Some studies have sought to reduce the net loss of water to backwashing by mixing some of the backwash water with raw water and recycling it through the treatment process (Yang et al. 2006). A survey of 362 water treatment plants in the United States revealed that 226 of these plants recycle their backwash wastewater (Arora et al. 2001).

The SRSF concept is a distinct and novel solution to the problem of improving backwash efficiency. Implementation of the SRSF into a drinking water treatment system presents a number of possible benefits over the implementation of a traditional rapid sand filter. Capital costs are expected to be lower because the SRSF is self-backwashing and no pumps, elevated tanks, or redundant filter units are required. Operating costs and operational simplicity are also likely to improve because the SRSF requires no electrical equipment, and the total flow rate to the filter need not be adjusted to start the backwash cycle.

The benefits listed previously would make the SRSF a preferable option to traditional rapid sand filters for drinking water treatment in many parts of the world. If this novel technology is shown to be viable, it would realize gains in efficiency illustrated

Table 2. Comparison of SRSF with Conventional Rapid Sand Filtration Alternatives

Parameter	Unit	SRSF design	Conventional designs: Pumps	Conventional designs: Storage	Conventional designs: Multiunit
Configuration		Sand bed with six filter layers	Pumps deliver backwash flow	Tank provides backwash flow	Seven filter units in parallel
Special equipment		Inlet/outlet manifolds	Electric pumps and controls	Elevated tank and valves	Header for flow control
Filter boxes	Number	1	1	1	**7**
Filter box area	$\mathrm{m^2}$ per filter box	0.91	**5.46**	**5.46**	0.91
Filter cycle flow	L/s per filter box	10	10	10	1.4
Backwash flow	L/s	10	**60.1**	**60.1**	10

Note: Assumed plant capacity is 10 L/s. Assumed loading rates are 1.83 mm/s (160 m/day) for filtration and 11 mm/s (950 m/day) for backwash. Values marked in bold highlight the implementation advantages of the SRSF compared to conventional filters.

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by the design example in Table 2. This table compares the overall dimensions and flows of the SRSF to conventional alternatives for a hypothetical 10 L/s water plant serving a few thousand consumers in a small city in the developing world.

Some water savings may also be realized by the SRSF system. The placement of inlets and outlets throughout the sand bed in an SRSF creates multiple points of high solids concentration at the end of a filtration cycle. All six filter layers are then backwashed in series with the same water, which should produce a very concentrated waste stream. The concentration of removed solids in the backwash water is anticipated to allow the backwash cycle to be completed in a relatively short amount of time at the same flow rate used for the filtration cycle, which would reduce the loss of treatable water to backwashing waste.

Materials and Methods

Laboratory Stacked Filter System

Two SRSFs (four layer and six layer) were constructed in 10.16-cm (4 in.) polyvinyl chloride (PVC) pipe columns, with inlet and outlet pipes spaced to make 20-cm layers. The filtration and backwash cycles were demonstrated with simulated sedimentation tank effluent using the system illustrated in Fig. 2. During filtration, the SRSF was loaded at 1.4–1.83 mm/s (120–160 m/day) per layer in the range of typical design loading rates for rapid sand filtration. During backwash, similar flow rates were used to achieve upflow velocities of 10–11 mm/s (860–950 m/day) in all layers. These backwash velocities are also in the range of typical design values.

The layer inlets and outlets used a 1.27-cm (0.5 in.) pipe with 0.023-mm (0.008 in.) well-screen slots (Big Foot Manufacturing, Cadillac, MI). Single slotted pipes were sufficient as the inlets and outlets in this small-diameter laboratory filter because this laboratory filter column effectively had one inlet pipe for every 10 cm of filter width. A full-scale SRSF would require slotted pipe manifolds to distribute flow through the sand. To promote uniform flow through the width of the filter layers, these manifolds should have a slotted pipe spacing smaller than the layer depth but large enough for flow to pass between the pipes during backwash. The ratio of pipe spacing (10 cm) to layer depth (20 cm) was 0.5 in this study; future research is needed to optimize this value for a full-scale design.

The head loss in the influent piping was limited to 10% of the head loss through the clean sand bed to promote uniform distribution of flow among the layers of the filter. Specifically, the piping components were sized such that their head losses were small compared to the frictional losses in the sand bed. The filter media was typical rapid sand filtration sand with an effective particle diameter of 0.45 mm and a uniformity coefficient of approximately 1.4 (Ricci Bros. Sand Co., Port Norris, NJ).

Control of Experimental Parameters and Data Acquisition

The laboratory system utilized tap water from the Ithaca, NY municipal system in which hardness is approximately 150 mg/L as $CaCO_3$, alkalinity is approximately 113 mg/L as $CaCO_3$, and pH is approximately 7.7 (Foote et al. 2010). In a reservoir upstream of the SRSF, hot and cold water were blended to achieve a

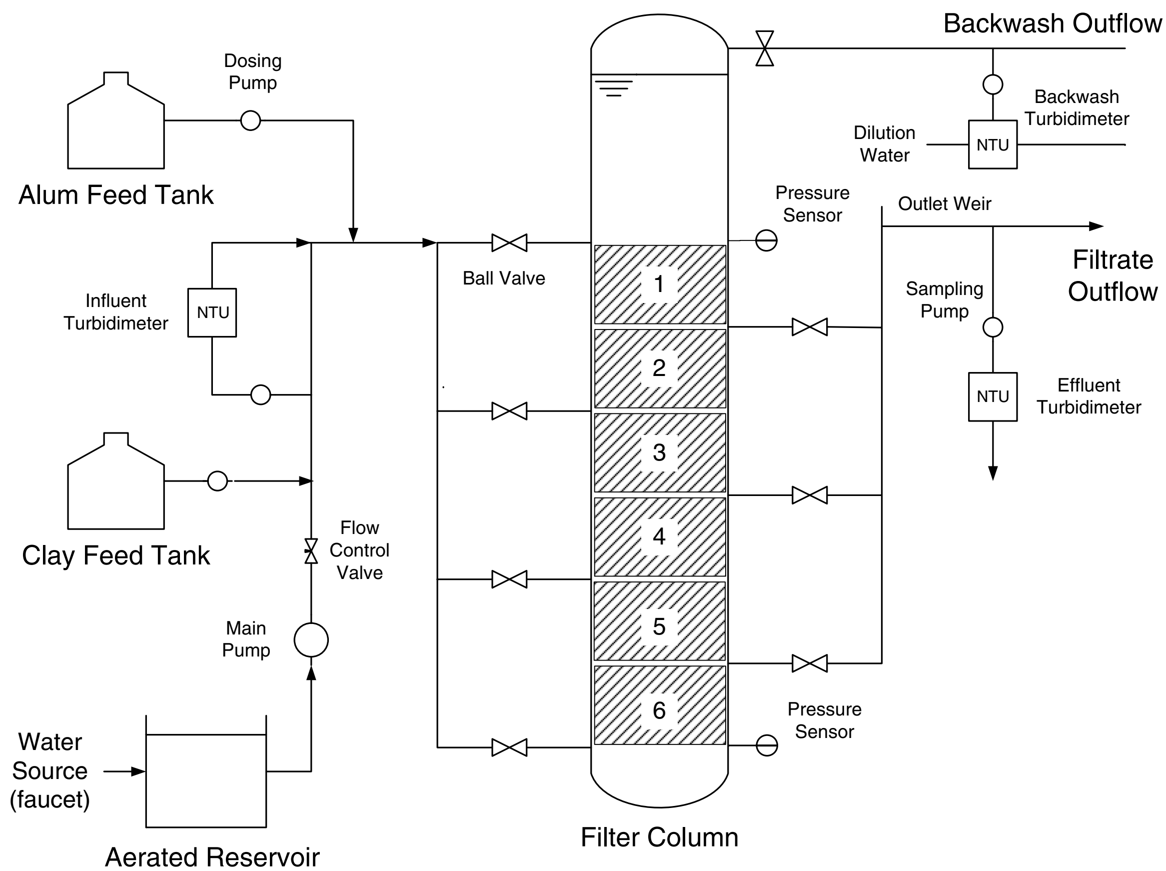

Fig. 2. Schematic for the experimental SRSF system showing a six-layer SRSF column along with the apparatus for alum and clay dosing, the pressure sensors to measure filtration and backwash head losses, and the influent and effluent turbidity sampling systems

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room-temperature mixture, and air was bubbled through the reservoir to strip any excess dissolved gas from the water.

The tap water was modified by addition of kaolin clay and alum to create a model sedimentation tank effluent, which an SRSF system would be treating in practice. Simulated settled-water turbidity in the range of 5–10 NTU (nephelometric turbidity units) was maintained by mixing a concentrated clay stock solution into the influent. Water exiting a sedimentation tank at a coagulation-flocculation plant also typically contains residual coagulant, which is important for the effectiveness of the filtration process because it promotes attachment of suspended particles to the filter media (Yao et al. 1971). Therefore, 1.5 mg/L alum $[Al_2(SO_4)_3 \cdot 14H_2O]$ was added to the filter feed water by dosing from a concentrated stock. This simulated settled water was used for filtration cycles and also for several backwash cycles as a field-scale SRSF might be used.

In-line data logging turbidimeters (MicroTOL, HF Scientific) were used to monitor the influent and effluent turbidity and to assess filter performance. Samples were continuously pumped through the turbidimeters at greater than 0.83 mL/s to prevent settling of particles in the sample lines. A dilution stream of clean water was pumped into the backwash turbidimeter at a constant flow rate to achieve a dilution factor of 9.9 so that the high turbidity in the backwash water could be measured within the turbidimeter's detection range.

Head loss across the filter bed was continuously measured and logged using an electronic pressure sensor with computer data acquisition installed in the column just above the top of the sand bed as shown in Fig. 2. This sensor measured the height of water from its own elevation to the free water surface in the filter column. The sensor was zeroed when the water was at the level over the outlet weir reflecting the clean bed head loss so that it tracked the increase in head loss over the course of a filtration cycle as suspended solids accumulated in the bed of the filter. Because there are multiple parallel paths through layers of the stacked filter, the filtration-cycle head loss is equivalent to the head loss through any one path.

A second pressure sensor was placed at the level of the bottom inlet to the SRSF as shown in Fig. 2. This sensor was used in conjunction with the first pressure sensor to measure the head loss across the sand bed during the backwash cycle. During backwash, as water flowed up from the bottom inlet through the sand bed, the difference between the pressures measured by the two sensors was the backwash head loss.

Performance Analysis

During the filtration cycle, performance of the filter was quantified as the negative logarithm of the fraction of remaining turbidity pC^*, often referred to as log removal, as in Eq. (7)

$$pC^* = -\log\left(\frac{\text{Effluent turbidity}}{\text{Influent turbidity}}\right) \tag{7}$$

The effluent turbidity was also compared to the applicable U.S. drinking water standard, which specifies less than 0.3 NTU in 95% of samples and less than 1 NTU at all times (USEPA 2010).

Performance of the SRSF during the backwash cycle was observed to determine the extent to which the filter bed had fluidized and to monitor whether contaminants had been removed from the bed. The expansion of the bed was measured, and the expanded-bed porosity ε_{Exp} was calculated for each bed expansion according to Eq. (8)

$$\varepsilon_{\text{Exp}} = 1 - \frac{D}{D_e}(1-\varepsilon) \tag{8}$$

where the settled-bed porosity ε was assumed to be 0.4; D = depth of the filter (1.2 m for the six-layer system); and D_e = expanded-bed depth. In addition, data from the backwash effluent turbidimeter, shown in Fig. 2, was used to calculate the amount M_{Removed} of retained contaminants that had been flushed from the bed, as in Eq. (9)

$$M_{\text{Removed}} = Q_{\text{Backwash}} \sum_{t=0}^{t_{\text{Backwash}}} \text{NTU}_t \Delta t \tag{9}$$

where Q_{Backwash} = backwash flow rate; NTU_t = measured backwash turbidity at any time t; and Δt = time interval between data points (5 s in this study). In essence, Eq. 9 is an integral of the turbidity versus time function over the period of t_{Backwash} for which the backwash was run. The result of this calculation has units of NTU-L, which is approximately proportional to contaminant mass because NTU is closely related to volumetric suspended solids concentration (Davis and Cornwell 2008).

Field Demonstration Unit

An additional SRSF unit was utilized for a field demonstration. This filter was constructed using a 7.62-cm (3 in.) clear PVC pipe, with six 20-cm filter layers. The smaller 7.62-cm (3 in.) diameter column was selected for easier transportation and setup at water treatment plants in the field. Otherwise, this field demonstration unit was run under similar conditions as the laboratory SRSF: it was loaded at 1.83 mm/s (160 m/day) per layer during filtration, backwashed at 11 mm/s (950 m/day), and used the same filter media and inlet/outlet pipes as the laboratory filter.

The filter was tested at several municipal drinking water treatment plants in Honduras that were designed and built in conjunction with the Cornell University AguaClara program. These facilities treat surface water supplies by coagulation/flocculation, sedimentation, and disinfection. The plants have capacities ranging from 6–55 L/s. They are located in small towns and cities, and each plant serves several thousand residents (AguaClara 2012b). Additional information about the AguaClara program can be found from AguaClara (2012a).

The demonstration SRSF was connected via a siphon to the top of the upflow sedimentation tanks at each plant, as shown in Fig. 3. The filter then treated settled waters with turbidities from 1–5 NTU. The settled water was also used for backwashing. The filter was positioned so that sufficient head would be available to fluidize the sand bed; that is, a head of HL_{Backwash} was available over the height of the backwash trough to provide for expansion of the sand bed as illustrated in Fig. 3. In this demonstration SRSF, the settled sand bed occupied the 1.2-m distance H_{Filter} between the lowest and highest inlets so about 1.2 m of head was required to backwash the filter as shown in Eq. (6). During filtration cycles, samples were taken from the filtered effluent and measured for turbidity using hand-held turbidimeters (MicroTPW, HF Scientific) to assess the performance of the SRSF.

Results and Discussion

Filtration-Cycle Performance

The laboratory SRSF treated water over a range of influent turbidities and filtration velocities comparable to typical conditions for rapid sand filtration, as shown in Table 3. The filtration test results

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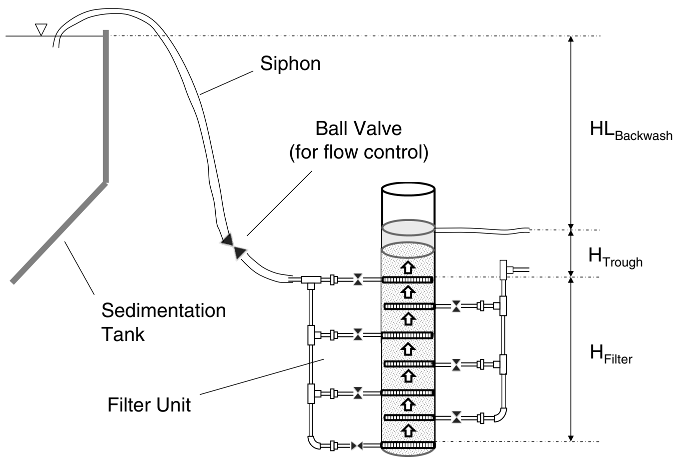

Fig. 3. Diagram of the SRSF field demonstration unit showing its connection to the water treatment plant sedimentation tank; the flow directions and head requirement for the backwash cycle are shown here to illustrate the constraint on vertical placement of this filter; the filter bed is drawn in expanded form, but the height H_{Filter} is defined as the settled bed height

presented subsequently show that the SRSF can effectively treat settled water and can meet applicable standards for water quality. The SRSF treatment process performs at or near the level of conventional rapid sand filters, and acceptable performance is possible with the novel stacked configuration.

The SRSF removed suspended solids in experiments with influent turbidity as high as 12 NTU and produced treated effluent around 0.1–0.3 NTU, showing that the SRSF process is appropriate for the typical range of rapid sand filter influent turbidities. Observations for an example experiment are shown in Fig. 4(a) where influent and effluent turbidities are plotted as a function of time and reveal a ripening period (Region A) leading to a consistent effluent turbidity of around 0.2 NTU (Region B). After 10 h of run time, the performance decreased with the onset of particle breakthrough from the filter bed (Region C). In Fig. 4(b), the calculated pC^* shows performance consistent with conventional filters. The SRSF achieved a pC^* of 1.6–1.8, which corresponds to a high percent removal of turbidity (97.5–98.5%). This percent removal is within the expected range for rapid sand filters (Reynolds and Richards 1996). Conventional filters are expected to produce better quality water than the SRSF because each layer of the SRSF is shallower than a conventional filter bed, but the turbidity removal performance of the SRSF is still satisfactory for drinking water treatment applications.

Increased head loss accompanies particle removal by a filter as the suspended particles and coagulant retained in the sand

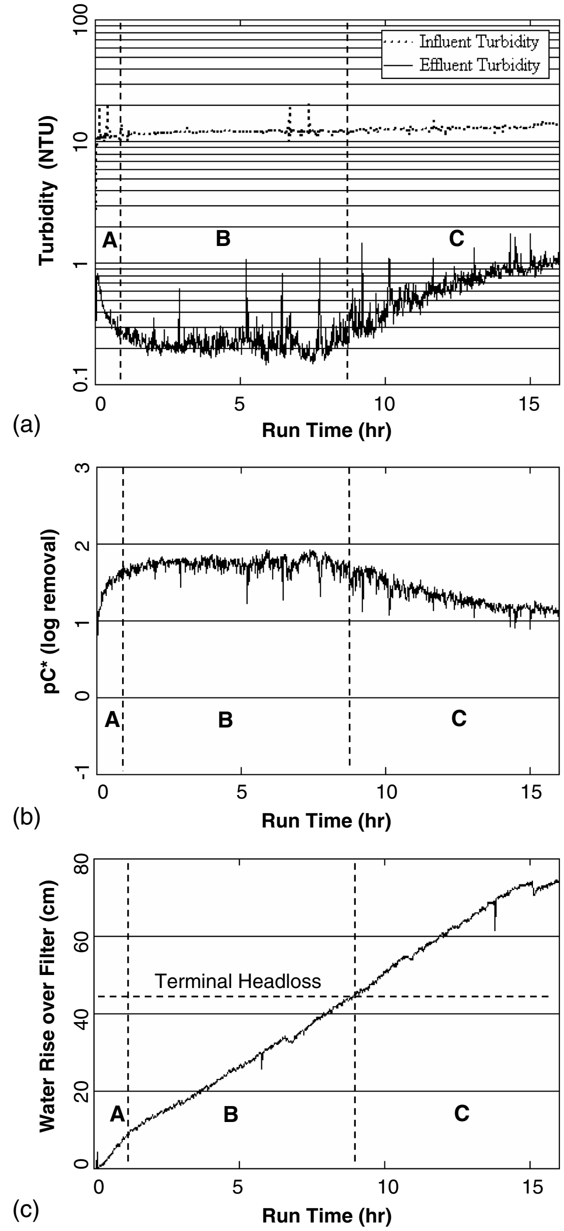

Fig. 4. Data from an example filtration cycle run at 144 m/day, including (a) influent and effluent turbidity; (b) log turbidity removal; and (c) head loss increase over the initial 15 cm clean bed head loss; the three regions demarcated on these graphs are (A) a ripening period, (B) a period of good filter performance, (C) a decline in turbidity removal; these regions are demarcated with respect to the U.S. Environmental Protection Agency drinking water standard of 0.3 NTU

Table 3. Bench-Scale SRSF Performance under Various Filtration-Cycle Conditions

Filtration velocity (m/day)	Previous backwash cycle water	Postripening averages: Influent (NTU)	Postripening averages: Effluent (NTU)	Postripening averages: pC^*	Samples above 0.3 NTU (%)	Length of run (h)
120	Clean (tap)	5.53	0.14	1.61	0.2	24.3
160	Clean (tap)	5.84	0.13	1.65	0.8	25.2
160	5 NTU	5.22	0.11	1.69	0.1	20.9
144	Clean (tap)	10.7	0.16	1.84	4.4	10.1
144	Clean (tap)	12.0	0.24	1.70	13.5	9.6
144	10 NTU	11.6	0.17	1.83	6.4	9.8

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bed create a greater resistance to flow. Fig. 4(c) shows a roughly linear head loss increase during the course of the filtration cycle, which is the head loss pattern that is expected for effective depth filtration (Baumann and Oulman 1970). In design of rapid sand filters, the head loss increase is an important parameter governing the length of the filtration cycle: a terminal head loss is specified, and the filter is to be backwashed when the head loss reaches this value. The filtration cycle shown in Fig. 4 would produce water of appropriate quality with less than 43 cm specified as the terminal head loss, and a similar terminal head loss was observed for the other filtration trials. The head loss during filtration mode through the SRSF is lower than in a conventional rapid sand filter because the filter media depth per layer is smaller in the SRSF, and total head loss is proportional to depth.

Over the course of several trials, the performance study yielded a consistent filter bed capacity, defined here as the product of turbidity removed and run time, of around 100 "NTU-h." The treated effluent in the example in Fig. 4 meets Environmental Protection Agency (EPA) drinking water standards of <0.3 NTU for a period of approximately 10 h with 12 NTU influent, while other experiments with influent turbidity of 5 NTU allowed the SRSF a run time of more than 20 h before needing backwash. The NTU-hr parameter is a property of the particular influent water used in these trials so terminal head loss is considered a better determiner of filtration cycle time. However, the SRSF is expected to have a shorter cycle time than a conventional filter. The SRSF has reduced bed capacity because of its shallower layers and smaller total sand volume compared to conventional technology, as shown in Table 2.

Backwashing Bed Expansion

A stacked filter can be effectively fluidized for backwashing just like a conventional rapid sand filter. The novel concept of performing backwash and filtration at the same total flow rate is viable from the perspective of the physical process of backwashing. There are some physical backwashing characteristics, however, that are unique to the SRSF system.

Typical backwash velocities of 10–12 mm/s (860–1000 m/day) were found to be effective in achieving bed expansion within the recommended design range of 15–30% (Davis and Cornwell 2008). Traditional rapid sand filter design relates backwash velocity to expanded-bed porosity with an empirical power-law equation of the following form (Weber 1972):

$$V_{\text{Backwash}} = K_e(\varepsilon_{\text{Exp}})^{n_e} \tag{10}$$

The bed expansion of the laboratory SRSF was measured across a range of upflow velocities. A regression analysis generated the values $K_e = 114.33$ mm/s and $n_e = 3.46$ (Fig. 5), and the experimental data fit the model in Eq. (10) quite well ($R^2 = 0.997$). While the specific values of K_e and n_e are a function of the particular sand medium used in a given filter, the SRSF displays the same general relationship between backwash velocity and bed expansion as in conventional rapid sand filters.

The measured head loss for backwashing was around 1.18 m, also consistent with typical rapid sand filters and with the prediction of Eq. (6). The head required to fluidize the SRSF is slightly less than the 1.2-m height of the sand bed, which reflects the volume of sand displaced by the inlet and outlet pipes in the sand bed.

A unique property of the SRSF system is that its fluidization can be controlled to occur two layers at a time. Table 4 shows the observed expansion as the six-layer laboratory SRSF was fluidized in two-layer increments. This feature stems from the configuration of inlets and outlets; each layer will fluidize when it experiences the full backwash velocity at the inlet below it, regardless of the status of the other layers of the filter. This, in turn, depends on the state of the inlet valves during backwash mode, as illustrated in Fig. 6. Similar observations were made for settling the sand bed after backwashing: (1) opening an inlet valve allows the layers below that inlet to settle, and (2) opening an outlet allows the layers above that outlet to settle. Opening an inlet valve reduces the flow to layers below that inlet and therefore the velocity that these layers experience; similarly, opening an outlet allows flow out of that outlet and reduces the velocity experienced in the layers above.

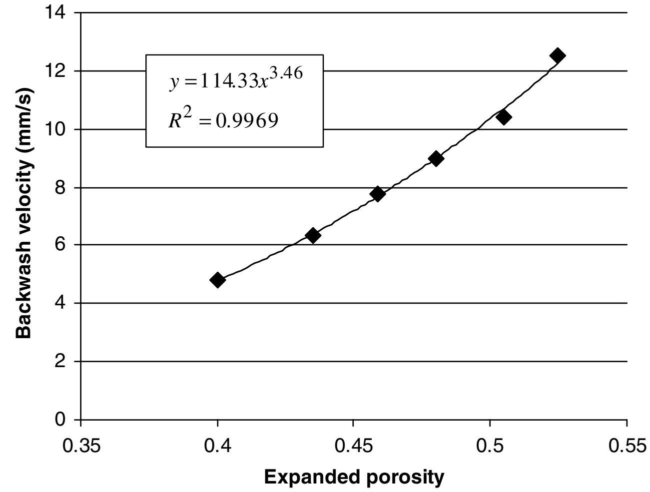

Fig. 5. Plot of expanded porosity for increasing backwash velocities showing experimental data points and a power-law regression equation; the initial porosity of the bed when fully settled during a filtration cycle was 0.4, and expanded porosity was calculated from measured bed expansion using Eq. (8)

Table 4. Observed Bed Expansion at Two Backwash Velocities

Inlets closed	Layers fluidized	Bed expansion (%) 10 mm/s	Bed expansion (%) 11 mm/s
1	2	9	11
1 and 2	4	16	20
1, 2, and 3	6	21	27

Note: Inlets are numbered as in Fig. 6. Bed expansion is reported as a percentage of the total 1.2-m sand bed depth.

Contaminant Removal During Backwash

The removal of contaminants from the filter bed was successfully demonstrated with the laboratory SRSF, and the bed fluidization was sufficient to clean the sand bed in preparation for another filtration cycle. In Fig. 7, the turbidity of backwash effluent is shown over the course of a backwash cycle with all six filter layers fluidized to illustrate the removal of suspended solids that had been retained in the sand bed during filtration. The contaminants were flushed out over a relatively short period of time, producing a concentrated waste stream with a turbidity as high as 6,200 NTU at its peak.

Virtually all of the contaminants loaded to the filter bed were removed during this test. During the filtration cycle preceding the filter backwash, 110 NTU influent was pumped into the filter over a period of 1.5 h at 4.8 L/min (144 m/day), while the filter produced 1 NTU effluent. These observations correspond to a total solids loading of 47,000 NTU-L. A total suspended solids recovery

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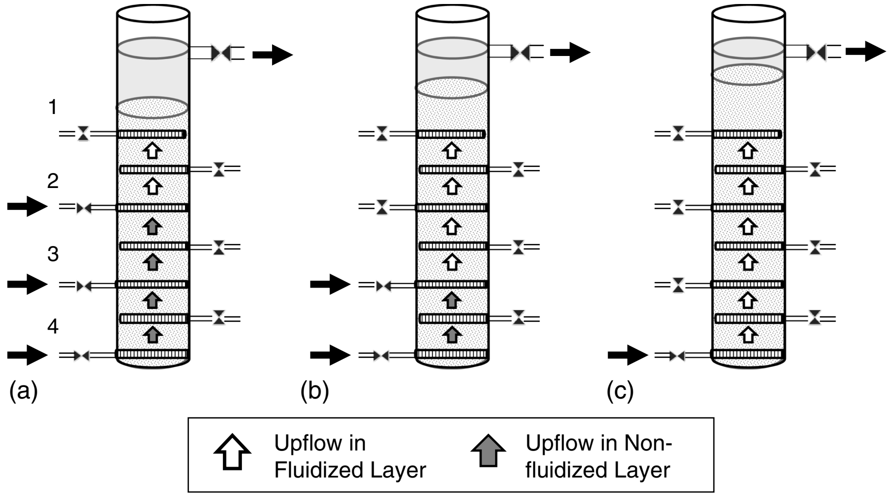

Fig. 6. Configuration of the inlet valves of an SRSF to fluidize (a) two layers; (b) four layers; (c) all six layers; when the inlet valves are set such that the entire backwash flow is passing upwards through a pair of layers, these layers will fluidize because they are experiencing the full backwash velocity

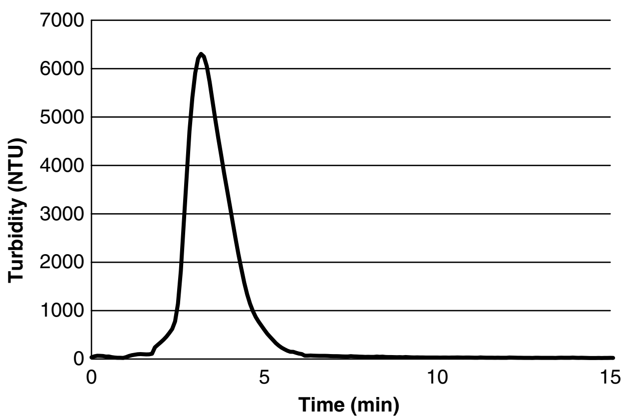

Fig. 7. Plot of effluent turbidity over time during a 950 m/day backwash cycle; the readings from the backwash turbidimeter were scaled by the sampling system dilution factor to produce the curve shown in this graph

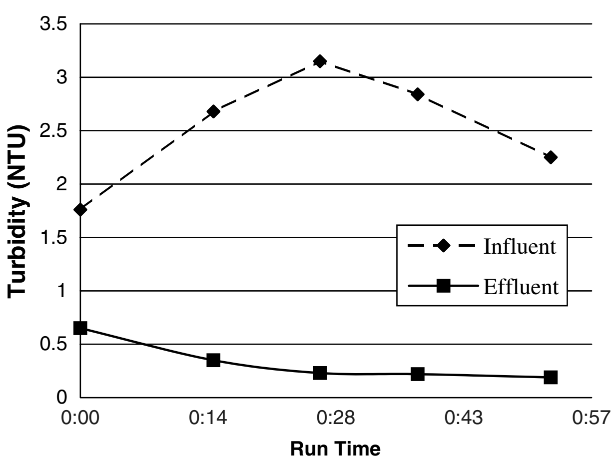

Fig. 8. Results of the first SRSF field demonstration at the Támara water treatment plant in Francisco Morazán, Honduras, where the filter was loaded at 160 m/day with sedimentation tank effluent for around 1 h to gauge the turbidity-removal performance of the system

of 46,500 NTU-L, i.e., 98.9% recovery, was observed during the backwash cycle in Fig. 7.

In practice, the length of the backwash cycle should be minimized to reduce loss of water to backwash effluent. Fig. 7 shows that a 15-min backwash cycle, as used in this test, is much longer than needed. About 94% of the solids loaded to the bed had been removed after 5 min of backwash, and about 97% had been recovered at 7 min. This suggests that for the conditions used in this research, a 7-min backwash cycle time would be sufficient, and any additional backwashing would consume water without providing much added benefit in the form of cleaning the sand bed.

Use of Settled Water for Backwash

Loss of filtered water during operation of the SRSF in the field can be reduced if sedimentation tank effluent is used to backwash the filter. When a filtration cycle ends, water would continue flowing from the sedimentation tanks into the filter at the same flow rate, but it would be redirected to the bottom inlet to fluidize and backwash the SRSF. This backwash method was evaluated to determine if it diminished the performance of the filter.

In several laboratory experiments, the SRSF was backwashed with the same 5–10 NTU simulated settled water that served as influent during the filtration cycle. Results suggest that a stacked filter can be effectively backwashed with settledwater without its performance being affected. As shown in Table 3, the pC^* and effluent turbidity achieved during a filtration cycle did not change significantly after backwashing with 5–10 NTU water. The ripening time also was not noticeably affected. An interpretation of this result is that the turbidity in the settled influent water is small compared to the large amount of turbidity in the filter bed at the onset of backwash and does not significantly affect the flushing of contaminants from the filter. In addition, most suspended particles introduced into the filter bed with the backwash water are effectively retrained by the filter media when the filtration process resumes.

If backwash is to be performed with settled water in the field, eliminating contact of backwash water with clean-water plumbing becomes an important design consideration. The placement of a trough or channel for filtered water must be such that backwash effluent will not have a path to mix with treated water for distribution. In addition, a short "filter-to-waste" period, lasting perhaps

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1–2 filter residence times, is recommended to rinse the SRSF inlet and outlet pipes that were exposed to backwash water. These practical issues must be addressed as the SRSF system moves toward full-scale implementation.

Field Demonstration Results

The field demonstration was carried out to test the performance of the SRSF at operating drinking water treatment facilities under the conditions it would face at a full-scale installation. The results from the laboratory studies indicate that both the filtration and backwash cycles can be successfully carried out in the field, and the SRSF field test was expected to produce water meeting EPA standards for turbidity. Some variation from laboratory results was anticipated because parameters such as the total sand bed capacity vary depending on the nature of the suspended particles in the influent water.

The first test site for the SRSF demonstration unit was the AguaClara water treatment plant in Támara, Francisco Morazán, Honduras. Settled water from the Támara plant had turbidity in the 2–3 NTU range, which meets the Honduran standard of 5 NTU for treated water, with about 0.5 mg/L alum residual. Filtration of this water was quite effective; in the first test (Fig. 8), the filter ripened in about 20–25 min to produce water less than 0.3 NTU, and achieved effluent quality as low as 0.19 NTU. In the second test (results not shown), the filter ran overnight producing water around 0.5 NTU. The run concluded after about 18 h as the head loss in the filter increased 28 cm and the effluent turbidity approached 1 NTU.

At the AguaClara water treatment plant test site in Agalteca, Francisco Morazán, Honduras, settled-water turbidity was in the 0.5–1 NTU range. The SRSF filtration was initially not effective with the cleaner influent water in Agalteca, and a 1 mg/L dose of alum was then added to the filter influent for part of the test. In samples without alum addition, there was no discernable or consistent difference between the influent and filtered water; with alum added, the filter performed consistently better and achieved as low as 0.31 NTU effluent. These results indicate that addition of alum to the influent can improve filter performance when needed. Similar results for coagulant addition to rapid sand filters have been demonstrated in laboratory and full-scale pilot tests reported by Lin et al. (2011).

Conclusions

Stacked rapid sand filtration is presented in this paper as a robust and sustainable technology that can address the limitations of conventional rapid sand filtration for municipal drinking water treatment facilities around the world. Backwashing conventional rapid sand filters requires expensive systems such as electric pumps, elevated storage tanks, or large banks of parallel filters. A stacked rapid sand filter, meanwhile, is self-backwashing at the same flow rate used for filtration, and it does not require pumps or other electrical equipment.

Effective backwashing bed expansion, efficient removal of contaminants from the sand bed during backwash, and adequate filtration-cycle performance of the SRSF system have been demonstrated in the laboratory and in field tests. Because the SRSF concept has been shown to be viable, it could be used at full-scale to realize significant benefits relative to conventional filters: reduced complexity of implementation and operation; savings in capital and operating costs; and possible reductions in water lost to backwashing.

Further research should consider the design and operational details required for implementation of a full-scale stacked rapid sand filter. In addition, laboratory investigation of issues such as alum-filter interaction, flow distribution among filter layers, and backwashing hydraulics can help to optimize the technology.

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References

AguaClara. (2012a). ⟨http://aguaclara.cee.cornell.edu/⟩ (Feb. 4, 2012).

AguaClara. (2012b). "Project Sites." ⟨https://confluence.cornell.edu/display/AGUACLARA/Project+Sites⟩ (Jul. 24, 2012).

Ahrens, B. T., and Mihelcic, J. R. (2006). "Making wastewater construction projects sustainable in urban, rural, and peri-urban areas." *J. Eng. Sustain. Dev.*, 1(1), 13–32.

American Water Works Association (AWWA). (1971). *Water quality and treatment*, 3rd Ed., McGraw Hill, New York.

Arora, H., Giovanni, G. D., and Lechevallier, M. (2001). "Spent filter backwash water contaminants and treatment strategies." *J. Am. Water Works Assn.*, 93(5), 100–112.

ASCE. (2009). "2009 report card for America's infrastructure." ⟨http://www.infrastructurereportcard.org/⟩ (May 24, 2011).

Baumann, E. R., and Oulman, C. S. (1970). "Sand and diatomite filtration practices." *Water quality improvement by physical and chemical processes*, E. F. Gloyna and W. W. Eckenfelder, eds., University of Texas Press, Austin, TX.

Cornwell, D. A., and MacPhee, M. J. (2001). "Effects of spent filter backwash recycle on Cryptosporidium removal." *J. Am. Water Works Assn.*, 93(4), 153–162.

Davis, M. L., and Cornwell, D. A. (2008). *Introduction to environmental engineering*, 4th Ed., McGraw Hill, New York.

Foote, J., Baker, C., and Bordlemay, C. (2010). "Drinking water quality report 2010." ⟨http://www.egovlink.com/public_documents300/ithaca/published_documents/Public_Works/Water_and_Sewer/Water_Treatment_Plant/2010_Annual_Drinking_Water_Quality_Report.pdf⟩.

Gitis, V. (2008). "Rapid sand filtration of Cryptosporidium parvum: Effects of media depth and coagulation." *Water Sci. Technol. Water Supply*, 8(2), 129–134.

Hokanson, D. R., Zhang, Q., Cowden, J. R., Troschinetz, A. M., Mihelcic, J. R., and Johnson, D. M. (2007). "Challenges to implementing drinking water technologies in developing world countries." *Environ. Eng. Applied Res. Pract.*, 43(1), 2–9.

Lin, P.-H., Lion, L. W., and Weber-Shirk, M. L. (2011). "Comparison of the ability of three coagulants to enhance filter performance." *J. Environ. Eng.*, 137(5), 371–376.

Mihelcic, J. R., Fry, L. M., Myre, E. A., Phillips, L. D., and Barkdoll, B. D. (2009). *Field guide to environmental engineering for development workers*, ASCE, Reston, VA.

J. Environ. Eng., 2012, 138(10): 999-1008

Mintz, E., Bartram, J., Lochery, P., and Wegelin, M. (2001). "Not just a drop in the bucket: Expanding access to point-of-use water treatment systems." *Am. J. Public Health*, 91(10), 1565–1570.

Nasser, A., Huberman, Z., Dean, L., Bonner, F., and Adin, A. (2002). "Coagulation as a pretreatment of SFBW for membrane filtration." *Water Sci. Technol. Water Supply*, 2(5–6), 301–306.

Reynolds, T. D., and Richards, P. A. (1996). *Unit operations and processes in environmental engineering*, PWS, Boston.

Stillwell, A. S., King, C. W., Webber, M. E., Duncan, I. J., and Hardberger, A. (2010). "The energy-water nexus in Texas." *Ecol. Soc.*, 16(1), 2.

U.S. Environmental Protection Agency (USEPA). (2010). "Drinking water contaminants." ⟨http://water.epa.gov/drink/contaminants/index.cfm⟩ (Jul. 24, 2012).

Weber, W. J. (1972). *Physicochemical processes for water quality control*, Wiley-Interscience, New York.

Whittington, D., and Hanemann, W. M. (2006). "The economic costs and benefits of investments in municipal water and sanitation infrastructure: A global perspective." *CUDARE working paper series 1027*, Dept. of Agricultural and Resource Economics and Policy, Univ. of California at Berkeley, Berkeley, CA.

Yang, C. B., Cheng, Y. L., Liu, J. C., and Lee, D. J. (2006). "Treatment and reuse of backwash water in Taipei water treatment plant, Taiwan." *Water Sci. Technol. Water Supply*, 6(6), 89–98.

Yao, K. M., Habibian, M. T., and O'Melia, C. R. (1971). "Water and waste water filtration: Concepts and applications." *Environ. Sci. Technol.*, 5(11), 1105–1112.

J. Environ. Eng., 2012, 138(10): 999-1008