An aerial view of the Kassler slow-rate sand filtration plant shows the six basins with one basin emptied for scraping. This plant has served the Denver Water Department for more than 80 years.

The Application and Effectiveness of Slow Sand Filtration in the United States

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A survey of 27 slow sand filtration plants in the United States indicated that most of these plants are currently serving communities of fewer than 10 000 persons, are more than 50 years old, and are effective and inexpensive to operate. A slow sand filtration research facility in Logan, Utah, was compared with the operating plants to determine if locally available, unsieved sand achieved similar results. The 75-m³/d research facility performed well in removing turbidity, coliform bacteria, and particles of a size representative of *Giardia* cysts.

Slow sand filtration for providing potable water has been used since the nineteenth century. However, this technology is not now as widely applied in the United States as rapid sand filtration. Slow sand filters are operated at filtration rates between 0.1 and 0.4 m³/h/m² of filter area, whereas rapid sand filtration uses filtration rates between 5 and 15 m³/h/m².¹ Slow sand filters treat low-turbidity waters (<10 ntu) for weeks or months before accumulated materials clog the top layer of sand, at which time 1 to 2 cm of the

biologically active top layer of sand is scraped away.

Because small communities in the United States cannot take advantage of the economies-of-scale associated with rapid sand filtration, slow sand filtration may be a feasible, economical alternative for treatment of small and rural community drinking water supplies. Accordingly, the research described in this article was conducted to investigate the limitations and potential benefits of using slow sand filters for small community water treatment systems.

There is currently no known source of information concerning application of slow sand filtration in the United States. However, information concerning the design and operating characteristics of slow sand facilities now in use is essential for evaluating the feasibility of future applications of this technology. This type of information should be useful to consulting engineers, regulatory officials, and plant operators. For the purpose of obtaining this information, an attempt was made to locate all slow sand filtration facilities identified by each state regulatory agency. A questionnaire was designed and sent to these facilities in an effort to compile a current summary of slow sand filtration practices in the United States. Forty-seven facilities were identified and were sent questionnaires. Twenty-seven questionnaires were re-

turned, either fully or partially complete. This article summarizes the responses to those questionnaires.

In addition, the article discusses a full-scale slow sand filtration research facility at Logan, Utah, and compares this facility with other operating slow sand filtration facilities. The facility at Logan has a designed capacity of 75 m³/d and will provide long-term operating data that will contribute to an overall evaluation of the performance of slow sand filters. This article evaluates the Logan facility with reference to being typical of operating treatment plant facilities.

Approach

The survey questionnaire was designed to collect information regarding the overall physical characteristics of individual facilities, including age, capacity, and population served; the characteristic quality of influent and effluent water; the design of the facilities; the operating practices; and the costs of treatment.

To ensure a reasonably high percentage of return, the questionnaire was organized simply and required only straightforward responses.

Results of the survey

Geographic distribution of slow sand filtration plants. Table 1 lists the locations of facilities that responded to the questionnaire. Most of these facilities are located in the eastern United States. Thirty-seven percent of the filtration plants in the survey are located in New York. No other state reported more than two slow sand filtration facilities.

Physical characteristics of slow sand filtration facilities. Survey results indicated that most existing slow sand filtration facilities serve communities of fewer than 10 000 persons (Figure 1). Some 31 percent of the facilities serve populations of fewer than 1 000 persons. Some facilities serving larger populations use slow sand filters in parallel with rapid sand filters that were installed after the construction of the slow sand filter plants. Data collected on plant capacities, as expected, closely paralleled the population served. The Logan, Utah, research facility has a plant capacity of 75 m³/d, which is significantly less than most of the operating slow sand filtration facilities.

Figure 2 shows the distribution of the ages of the surveyed slow sand filtration facilities. Some 56 percent of facilities are more than 50 years old, but there has been recent construction activity associated with slow sand filtration. Figure 2 also shows that from 25 to 50 years ago the rate of construction of slow sand filtration facilities declined.

Water quality. Most slow sand filtration facilities use lakes or reservoirs as raw water sources (Figure 3). A few use

Figure 1. Populations of communities served by operating slow sand filter plants

Figure 2. Ages of operating slow sand filtration plants

Figure 4. Average raw water turbidities at operating slow sand filter plants

TABLE 1
Locations of operating slow sand filtration facilities that responded to the survey

City and State	
Ashland, Wis.	Pawhuska, Okla.
Auburn, N.Y.	Peekskill, N.Y.
Denver, Colo.	Port Henry, N.Y.
Gilbertsville, N.Y.	Scranton, Kan.
Hamden, Conn.	Shortsville, N.Y.
Honolulu, Hawaii	Stayton, Ore.
Illion, N.Y.	Stilwell, Okla.
Kelley Island, Ohio	Superior, Wis.
Lanesville, Ind.	Waipio, Hawaii
Little Falls, N.Y.	Watsonville, Calif.
Lyndonville, N.Y.	Waverly, N.Y.
McIndoe Falls, Vt.	West Hartford, Conn.
Ogdensburg, N.Y.	Westfield, Mass.
Parker, Kan.

Figure 3. Raw water sources used at operating slow sand filter plants

Figure 5. Average filtered water turbidities at operating slow sand filter plants

TABLE 2
Filter component depths at operating slow sand filtration facilities

Filter Component	Mean Depth cm	Coefficient of Variation percent	Number of Responses
Water	173	48	25
Sand medium	84	30	24
Support media	56	72	25

TABLE 3
Sand characteristics at operating slow sand filtration facilities

Facility	Effective Size (D_{10})* mm	Uniformity Coefficient $D_{60}^{\dagger}/D_{10}$	Sand Source	Sand Cost dollars/ton
Ashland, Wis.	0.26	1.6	Beach	10.00
Auburn, N.Y.	0.3	1.5	Supplier-sieved	4.69
Denver, Colo.	0.34	2.76	River-sieved	
Gilbertsville, N.Y.	0.40	2.25	Supplier-sieved	
Hamden, Conn.	0.3	2.2	Supplier	
Honolulu, Hawaii	0.45-0.55	1.2-1.7	Beach-sieved	9.25
Ilion, N.Y.	0.2-0.4	<3.5	Supplier-sieved	63.00
Kelley Island, Ohio			Supplier-sieved	4.60
Lanesville, Ind.			Supplier	
Little Falls, N.Y.			Supplier-washed	4.35
Lyndonville, N.Y.	0.25-0.35	2.5-3.5	Supplier-sieved	
Pawhuska, Okla.			Supplier-sieved	
Port Henry, N.Y.			Supplier-sieved	
Scranton, Kan.			Supplier-sieved	5.00
Shortsville, N.Y.	0.35-0.45	1.7	Supplier-sieved	
Stayton, Ore.	1.2-1.4	1.4-1.6	Supplier-sieved	
Stilwell, Okla.			River-sieved	45.00
Superior, Wis.	0.45-0.55	1.35-1.70	Supplier-sieved	28.95
Waipio, Hawaii			Beach-sieved	20.00
Watsonville, Calif.	0.3	2.3		
Waverly, N.Y.	0.12	3.5	Supplier	4.00
West Hartford, Conn.			Supplier-sieved	10.30
Westfield, Mass.	0.3	2.3	Native, washed	

*Size of sieve opening through which 10 percent of sand will pass

†Size of sieve opening through which 60 percent of sand will pass

TABLE 4
Filter cycle durations at operating slow sand filtration facilities

Season	Mean Length of Filter Cycle days	Coefficient of Variation percent	Number of Responses
Spring	42	73	21
Summer	43	63	21
Fall	46	70	21
Winter	60	72	22

TABLE 5
Comparison of slow sand filtration facilities surveyed with Logan, Utah, facility

Parameter	Value for Logan, Utah, Facility	Mean Value From Facilities Surveyed
Plant capacity— m^3/d	75	39 000
Filtration rate— $m^3/h/m^2$	0.20	0.15
Influent turbidity— ntu	5	4
Effluent turbidity— ntu	0.28	0.65
Sand depth— cm	30	33
Water depth— cm	122	173
Sand effective size— mm	0.18	0.38
Sand uniformity coefficient	4.4	2.3
Treatment cost—dollars/1000 gal	0.15	0.20

TABLE 6
Total coliform analysis at Logan, Utah, research facility

Sampling Date	Effluent Temperature °C	Influent Total Coliforms number/100 mL	Effluent Total Coliforms number/100 mL
Oct. 1, 1983	10	50	0
Oct. 21, 1983	8.4	40	1
Nov. 1, 1983	14.4	30	0
Jan. 27, 1984	2.4	12	0
Jan. 31, 1984	1.2	10	1
Feb. 3, 1984	1.1	4	1
Feb. 29, 1984	2.3	4	1

ivers or streams, and one reported using groundwater. Some plants using lakes or reservoirs reported that algae control measures are sometimes required. The Logan, Utah, research facility uses a river as a raw water source.

All facilities reported excellent turbidity removal efficiencies. Figure 4 shows

The slow-rate sand filtration experimental plant at Logan, Utah, consists of a control building, the two-cell filter, and a storage-presedimentation tank.

that about 50 percent of the facilities had influent turbidity levels at more than twice the maximum contaminant level (MCL) of 1.0 ntu. Figure 5 shows that fewer than 15 percent of the plants had effluent turbidity levels in excess of the MCL. Turbidity of raw water at the Logan facility varies from 1.0 to 15.0 ntu and the effluent turbidity is consistently less than 1.0 ntu.

Figures 6 and 7 show coliform removal. As with turbidity, all plants reported good performance. Figure 6 shows that more than 20 percent of the facilities had influent coliform levels in excess of 100/100 mL. Figure 7 indicates that 90 percent of the facilities reported effluent coliform levels of 1/100 mL or less.

Data related to other water quality parameters, such as organic and inorganic species, were not requested in the questionnaire. Responses to questions concerning sampling requirements indicated that most of these analyses are required only a few times a year. One facility indicated that influent manganese and iron caused operational problems. However, it was not specified whether these metals were removed.

Design characteristics. Slow sand filtration is characterized by a relative simplicity of design compared with other water treatment processes. Typically, slow sand filtration units consist of (1) a depth of graded gravel, called support media, that separates filter sand from the underdrains; (2) a depth of filter sand (which may vary because of scraping operations); and (3) a depth of water above the filter sand that provides hy-

draulic head for the process. Table 2 summarizes the reported values for each of these depths. These data show large variations. The range of sand depths reported was 38 to 183 cm.

Size and uniformity of filter medium are known to have a significant effect on filtration performance. Table 3 itemizes responses to questions related to the characteristics of sand used at the facilities. All facilities reported very uniform sands, and most had effective sizes in the range of 0.1 to 0.5 mm. Many facilities purchased sand that was sieved by suppliers. Costs varied from slightly more than \$4/ton to \$63/ton. Many facilities also reported that filter sand, once purchased, has never been replaced because the sand is recycled. The sand used in the Logan facility is the least uniform, and has a smaller effective size, because the plant is used to evaluate the performance of cheaper, locally available unsieved sand.

Operational characteristics. The primary controllable parameter in slow sand filtration is filtration rate. Filtration rates at slow sand facilities are less than those at rapid sand facilities. Filtration at typical rapid sand filtration rates, without chemical treatment, results in unacceptable levels of filter performance. Additionally, lower filtration rates at

A close-up view of the experimental slow-rate sand filter shows the two-cell filter at top of the photo and the storage-presedimentation tank at bottom.

slow sand filtration facilities result in prolonged durations of the filter cycle. Figure 8 shows the distribution of filtration rates used at slow sand filtration facilities. Figure 8 also shows that most plants maintain filtration rates of less than 0.25 $m^3/h/m^2$. The Logan, Utah, facility was operated at 0.20 $m^3/h/m^2$.

Filter cycle durations should be expected to have significant effects on the relative cost and ease of operations. Filter scraping, required at the end of each filter cycle, is a labor-intensive activity. It is usually performed with hand shovels, although a few facilities

Figure 6. Coliforms in raw waters at operating slow sand filter plants

Figure 7. Coliforms in filtered waters at operating slow sand filter plants

Figure 8. Filtration rates at operating slow sand filter plants— $m^3/h/m^2$

Figure 10. Numbers of personnel employed at operating slow sand filter plants

Figure 9. Season of longest filter cycle duration at operating slow sand filter plants

Figure 11. Cost of treatment at operating slow sand filter plants—dollars/1000 gal

have developed custom methods using power tractors. Table 4 shows mean values of reported filter cycle durations for each season. Two facilities reported filter cycles of one year and one facility reported 6-month cycles, except during winter. These three plants are not included in the data summarized in Table 4 and Figure 9. Figure 9 shows which seasons were reported as yielding the longest filter cycles. Generally, Figure 9 and Table 4 indicate that winter yields longer filter cycles, although there are exceptions. Some of the plants reported that filter cycle durations were controlled by regular maintenance procedures; i.e., filters were scraped on a regular basis regardless of the development of head loss. Other facilities allowed filters to run until a certain head loss developed or until adequate flows could not be maintained. The filters that are regularly scraped account for the large percentage of facilities reporting seasonally equal filter cycles (Figure 9). Some plants reported equal winter and summer cycles that were longer than the cycles for spring and fall.

Postchlorination for disinfection of filter effluent was practiced by 93 percent of the facilities studied in the survey. Prechlorination was reported at 22 percent of the plants. Most plants using prechlorination reported that it served solely as a disinfection measure. One plant, however, cited prechlorination for oxidation of influent manganese and iron and for enhanced removal of 0.02 to 0.4- μ m-sized clay particles. Three plants reported using copper sulfate as an algae control measure in prefiltration storage reservoirs. Two facilities aerated water prior to filtration, and one plant adjusted effluent pH for distribution system protection. The facility at Logan, Utah, did not use chlorine disinfection because it was a research facility and did not discharge to public supplies. However, presedimentation reduced suspended materials.

Cost of slow sand filtration. Figure 10 indicates the number of personnel employed at the slow sand filtration facilities surveyed. These facilities are operable with only a few personnel, and low labor requirements reduce costs. Survey responses, in general, indicated that highly skilled personnel are not employed at slow sand filtration facilities, another factor contributing to low costs.

The questionnaire requested an assessment of overall treatment cost per 1000 gallons. Many plants did not respond to this request because of lack of appropriate records or unwillingness to compile a cost estimate. Figure 11 summarizes responses indicating that most plants achieve treatment for less than \$0.10/1000 gal. One plant was reported to have a treatment cost of \$6.50/1000 gal, and dissatisfaction with

Figure 12. Cross section of field-scale facility

Figure 13. Turbidity data from field-scale facility (vertical lines indicate duration of filter cycle)

Figure 14. Average particle size distribution in influent and effluent from field-scale facility

Figure 15. Number of 7-12- μ m-sized particles counted from field-scale study, grouped by time of day (tick marks indicate 95 percent confidence intervals for the means; numbers indicate subsets of means that are statistically the same at 0.05 level of significance)

sand filtration because of excessive head loss was expressed. The Logan facility's overall treatment cost, based on a 10-year design life, was estimated to be \$0.15/1000 gal.

Discussion

Because small communities do not have adequate economic resources for advanced water treatment processes, it is appropriate to evaluate slow sand filtration as an alternative treatment method for such communities. Since most slow sand installations serve small communities, the proposed application is justified. Most operating facilities reported successful performance without any chemical treatment other than chlorination. The plants had few components and seemed to be relatively easy to design. Many of the facilities were from 10 to 100 years old, indicating long design lives. Most plants treat water at a cost of less than \$0.10/1000 gal. Assuming water use of 378 L/d per capita (100 gpd), a cost to the individual user of about \$0.01/d is indicated. Generally, the survey did not provide any evidence against using slow sand filtration for small communities with appropriate water sources.

The facility at Logan, Utah, is intended to provide long-term operational data on slow sand filtration under controlled conditions. The facility is discussed for the purpose of comparing it with operating slow sand filtration facilities, as represented by the survey responses. If the Logan facility is typical of other operating facilities, more confidence can be placed in the long-term data collected from the facility.

The facility at Logan consists of two filtration cells, each with a filtration area of 9.3 m². Each cell is an independent filtration unit so that controlled experiments can be conducted. A cross section of a filtration cell is shown in Figure 12. An elevated presedimentation tank, with a 3.1-h detention time, was provided and can be optionally included in the treatment flow sheet. Logan River water is used as a raw water source. The Logan River is a watershed conduit for a mountain canyon. The filtration facility is located at the mouth of this canyon. Table 5 compares performance and design parameters in the Logan facility with averages of reported values of those parameters collected from the survey. Table 5 indicates that the Logan facility is representative of a typical operating facility. The sand used in this facility is, however, less uniform and of a smaller effective size than those reported in operating facilities because the Logan facility is being used to evaluate the efficacy of using sands of lower than recommended quality. This facility will yield information that can be useful in evaluating the effects of varying clima-

tological and influent water quality conditions on the performance of slow sand filtration facilities.

The research facility was evaluated for its effectiveness in removing turbidity, coliforms, and particles. The results of turbidity analyses from the field-scale facility are shown in Figure 13. The vertical lines in Figure 13 represent the occurrence of filter scraping. The facility consistently produced water with turbidities below the MCL of 1.0 ntu.

The total coliform analyses for the Logan research facility are listed in Table 6. Coliform removal by the facility was good, even with a sand media uniformity coefficient of 4.4 (Table 5).

Particle data were collected during one complete filter cycle. Figure 14 shows the distribution of particle size in the influent and in the effluent of the field-scale facility. The data shown are averages from all of the data collected during the filter cycle. The data indicate that two-log (99 percent) reductions of particle counts occurred for the smallest sizes detected and three-log (99.9 percent) to four-log (99.99 percent) reductions were achieved for larger sizes. Figure 15 shows the results of particle counts grouped by time of day for the 7-12- μ m size range. The 95 percent confidence intervals for the means are plotted with each of the data points.

The results of the particle count analyses show that the field-scale facility removed significant quantities of particles sized from 2.4 μ m upward. The size range of 7-12 μ m is considered to be representative of the size of *Giardia* cysts. Consistent three-log reductions were observed in this study. It should be noted that many small-sized particles passed through the filter bed. Currently, the relationship between particle counts and the potential for the presence of pathogens is unknown. If the ratio of inert particles to pathogens remains the same through filtration, these data indicate that significant reduction in pathogens can be achieved with slow sand filtration.

Filter cycle durations lasted from two to six weeks. The shortest filter cycle was associated with an attempt to scrape a minimum amount of sand to initiate a new filter cycle. Many other factors that were not controllable in the field-scale facility probably affected the length of filter cycles. Influent turbidity, algae growth, and temperature are all expected to have an effect on filter cycle duration. The limited data collected from the field-scale facility thus far do not allow speculation on which of these variables most strongly influences filter cycle durations.

Conclusions

The following conclusions were reached as a result of this research:

- Operating slow sand filtration facilities are serving primarily smaller communities with populations of fewer than 10 000 persons.

- Most slow sand facilities are more than 50 years old; however, there has been a relatively significant amount of slow sand filter construction during the last 25 years.

- Most slow sand facilities operate at filtration rates of less than 0.25 m³/h/m².

- The longest filter cycle durations occur during the winter months at most slow sand facilities.

- Slow sand facilities are inexpensive to operate because few personnel are required and there is only a minimal need for chemicals.

- The slow sand filtration research facility at Logan, Utah, can be considered typical of other operating facilities.

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