Factors affecting filtered water turbidity

A study of 75 filtration plants found that operator awareness and commitment to excellence may be more important to performance than key water quality, design, and operational variables.

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Approximately 8 million of Pennsylvania's 12 million residents receive water from 329 surface water treatment plants. This study evaluated the performance of a subset of these plants to determine whether they are prepared to meet the turbidity treatment technique requirements of the Enhanced Surface Water Treatment Rule. Using 75 filtration plants, the authors reviewed key water quality, design, and operational variables to determine their effect on filtered water turbidity. Except for plants that did not use a coagulant, served populations of < 3,300 people, or used streams for source water, there was no strong statistical correlation between any of the variables and filtered water turbidity. Many plants were able to consistently achieve low turbidity levels despite limitations such as small system size, plant age, or high source water turbidity. The results of this study show that intangible variables such as commitment to achieving low turbidity, operator skill level, and operator attention appear to be more important than tangible variables such as source water quality, ownership type, plant age, coagulant type, and other operational or design factors.

Over the past 10 years, optimizing the performance of surface water treatment plants has received considerable attention in the United States. Several major waterborne disease outbreaks have narrowed the focus even more. Now, many public water systems, public health officials, regulatory agencies, news media, and others are discussing the risks associated with microbial contaminants such as *Giardia* and *Cryptosporidium*. Because of these organisms in particular, both design considerations and operational procedures at surface water treatment plants have recently changed. These organisms are among the most difficult pathogens to remove and inactivate in water treatment plants and thus serve as the "yardstick" for reducing health risks. That is, if a plant can remove and inactivate *Giar-*

For executive summary, see page 178.

Operators at 75 treatment plants were asked to complete monthly monitoring forms and to report the highest raw water turbidity of the day as well as the highest finished water turbidity of the day.

dia cysts and *Cryptosporidium* oocysts, it is probably removing and inactivating other known waterborne, disease-causing organisms. Both *Giardia* and *Cryptosporidium* are protozoa. Epidemiological investigations have determined that protozoa, as a group, are responsible for more waterborne disease outbreaks than any other waterborne pathogen.[1]

The Pennsylvania Department of Environmental Protection (DEP) is concerned about the performance of filtration plants and their ability to remove bacteria, viruses, and protozoa. About 8 million of the state's 12 million residents—plus out-of-state visitors—receive water from 329 surface water treatment plants. Even a short-term breakdown in treatment at one of these facilities could lead to a widespread disease outbreak because of the "acute" nature of microbial pathogens. Furthermore, consumers served by filtered surface water systems may be especially vulnerable to a major pathogen breakthrough. These individuals, who normally receive either pathogen-free water or water with low concentrations of pathogens, may have immune systems that are susceptible to some organisms if they suddenly occur in elevated concentrations in drinking water.[1] More important, individuals with weakened immune systems may be more vulnerable to contracting waterborne diseases as well as experiencing more serious illnesses. These individuals include people who have undergone organ transplant operations, are receiving treatment for certain cancers, or have human immunodeficiency virus or acquired immunodeficiency syndrome; elderly individuals; or anyone who otherwise has a weakened immune system.[2] Opportunistic pathogens such as *Cryptosporidium, Mycobacterium avium,* and microsporidia may present a risk to people who are immunocompromised.[3]

Consumers served by filtered surface water systems may be especially vulnerable to a major pathogen breakthrough.

Turbidity levels examined at 75 plants

To assess the current performance of Pennsylvania's surface water treatment plants, this study examined the long-term raw water and finished water turbidity at 75 plants. The information from the study will help determine the current performance status of filtration plants and whether these water systems are prepared to meet the turbidity treatment technique requirements of the Interim Enhanced Surface Water Treatment Rule (IESWTR) and perhaps the Long-Term Enhanced Surface Water Treatment Rule (LTESWTR).

In addition, it will help assess the ability of the plants to meet performance expectations outlined in the voluntary Partnership for Safe Water program. This program provides water systems with a means of self-assessing their filtration plants to minimize breakthrough of pathogens into finished water. The authors also reviewed key water quality, design, and operational variables to determine their effects on filtered water turbidity. Finally, an attempt was made to uncover problems with collecting and managing turbidity data.

Factors Evaluated for Their Effects on Finished Water Turbidity Levels

Coagulant type
- Alum
- Polyaluminum chloride
- Ferric salt
- Polymer
- None

Population served
- ≤3,300 people
- 3,301–10,000 people
- 10,001–100,000 people
- >100,000 people

Ownership
- Municipal
- Investor

Source type
- Reservoir
- River
- Stream

Plant type
- Conventional
- Direct filtration
- Package—gravity filters
- Package—pressure filters

Plant age in years
- ≤10
- 11–25
- 26–50
- >50

Type of filter media
- Sand
- Anthracite
- Mixed media—sand and anthracite
- Multimedia—garnet, sand, and anthracite

Filtration rate—gpm/sq ft (m/h)
- 0–1 (0–2.5)
- >1–2 (>2.5–5)
- >2–3 (>5–7.5)
- >3–4 (>7.5–10)

Comparing plant-to-plant turbidity data

For surface water treatment plants, turbidity is the primary surrogate for determining the removal of waterborne, disease-causing organisms. Turbidity measurement is quick, relatively inexpensive, and easy for water system operators to understand. Whether they use a grab-sampling technique or online instrumentation, almost all operators know the basic processes involved in turbidity measurement.

Limitations to consider. Still, several limitations must be considered when turbidity data obtained from multiple plants are compared. First, staff at surface water treatment plants have historically selected instruments from a variety of manufacturers, which could cause some differences in results. Also, operations personnel may have chosen sampling points from a number of locations within the treatment plant. For example, DEP specifies that the preferred sampling point for finished water turbidity is the combined filter effluent before water reaches the clearwell or receives additional treatment. Some filtration plants, however, do not provide accessible piping at this location. Thus, operators have had to obtain turbidity measurements from each filter or even the clearwell itself, which could influence analytical results.

This study examined long-term raw water and finished water turbidity at 75 plants, to assess the current performance of Pennsylvania's surface water treatment plants.

Other problems can lead to plant-to-plant variations in recorded turbidity levels because of inconsistencies in the way data are recorded. For example, current Pennsylvania regulations stipulate that turbidity must be recorded every 4 hours, but they do not specify that the highest value within the 4-hour period should be recorded. Operators must decide whether they should record the highest turbidity result of the day, an average of multiple readings, or perhaps each of the required 4-hour measurements during the day. Some instruments lack recording devices (e.g., strip charts, circular charts, data loggers, or supervisory control and data acquisition systems). Thus, the value recorded on a daily monitoring form may depend on when the plant personnel observed the readings on the instrument panel.

Instrument calibration is another factor that could affect turbidimeter performance.[4] At turbidity levels < 0.1 ntu, calibration and quality control are extremely critical for accuracy. Particularly at medium and small water systems, operators may not have the time, expertise, and tenacity to pursue quality assurance procedures. Consequently, not all water systems use instruments that are properly maintained or calibrated.

Turbidity most practical measure of filter performance. Despite these shortcomings, turbidity is still the most practical physical parameter with which to gauge filtration plant performance. Other water quality parameters such as pH and alkalinity can indicate optimal performance of chemicals or individual major unit processes, but they do not serve as an adequate surrogate for particle and microbial removal. Although particle counters can provide valuable filter performance data, there are difficulties with on-site calibration and instrument-to-instrument standardization. Particle counters are extremely sensitive and are quite effective in establishing an in-house performance baseline; however, they are not yet conducive to performing plant-to-plant comparisons.

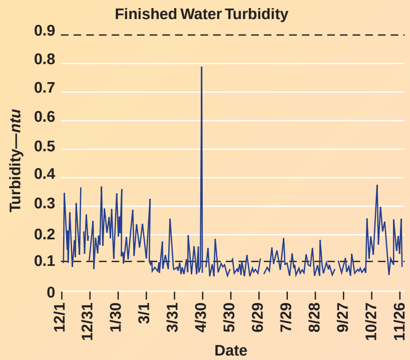
For surface water treatment plants, turbidity is the primary surrogate for determining the removal of waterborne, disease-causing organisms.

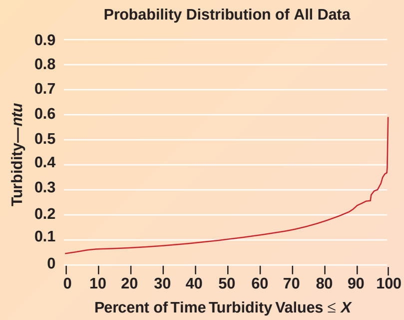
During DEP's statewide filtration plant performance evaluations (FPPEs)—an ongoing 11-year program to evaluate filtration plants for microbial removal—comparisons between plant turbidimeters and calibrated DEP turbidimeters have demonstrated fairly good accuracy of most plant turbidimeters over the past three years. Typically the results achieved were within 0.03 ntu of DEP's turbidity measure-

FIGURE 1 Example of a Partnership for Safe Water spreadsheet showing data in turbidity-versus-time output and probability-of-distribution output

Daily finished water turbidity

Percentile	Yearly	Dec-98	Jan-98	Feb-98	Mar-98	Apr-98	May-98	Jun-98	Jul-98	Aug-98	Sep-98	Oct-98	Nov-98
50	0.10	0.16	0.19	0.17	0.10	0.08	0.07	0.07	0.08	0.07	0.07	0.08	0.16
75	0.15	0.24	0.25	0.21	0.14	0.10	0.09	0.09	0.10	0.09	0.09	0.13	0.23
90	0.23	0.28	0.29	0.29	0.18	0.16	0.16	0.11	0.13	0.12	0.10	0.18	0.29
95	0.28	0.35	0.33	0.34	0.25	0.16	0.19	0.11	0.15	0.13	0.11	0.20	0.30
96	0.29	0.35	0.33	0.34	0.25	0.16	0.19	0.11	0.15	0.13	0.11	0.20	0.30
97	0.30	0.36	0.37	0.36	0.33	0.20	0.80	0.13	0.18	0.16	0.19	0.25	0.37
98	0.33	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
99	0.36	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Average	0.12	0.19	0.20	0.18	0.12	0.09	0.11	0.08	0.09	0.08	0.08	0.10	0.17
Minimum	0.05	0.08	0.08	0.10	0.06	0.06	0.05	0.05	0.06	0.05	0.05	0.05	0.06
Maximum	0.80	0.36	0.37	0.36	0.33	0.20	0.80	0.13	0.18	0.16	0.19	0.25	0.37
RSD	63.3%	40.1%	34.3%	37.2%	49.0%	38.2%	126.9%	27.2%	30.4%	33.2%	33.4%	48.9%	47.3%





Start year	98	365 = Total days
Month	12	12.00 = Total months
Day	1	

Utility name
Plant name
Plant street address
Plant city, state, zip
Plant contact name
Plant phone

Spreadsheet is from the Partnership for Safe Water; RSD—relative standard deviation, NA—not available

FIGURE 2 **Pennsylvania map showing location of the study's 75 surface water treatment plants**

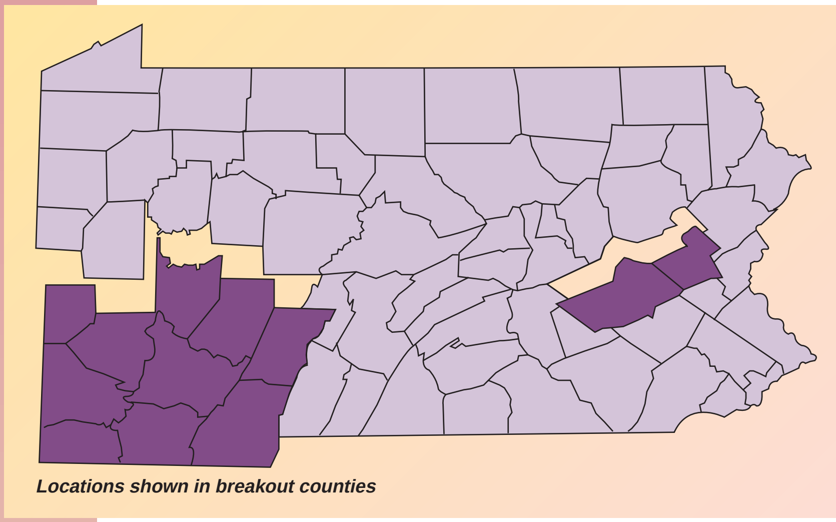


FIGURE 3 **Frequency distribution of maximum monthly turbidity values in finished water at 75 filtration plants**

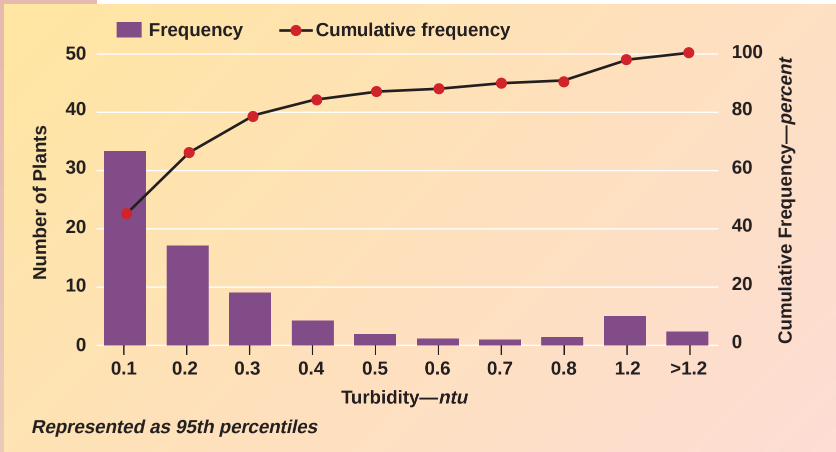
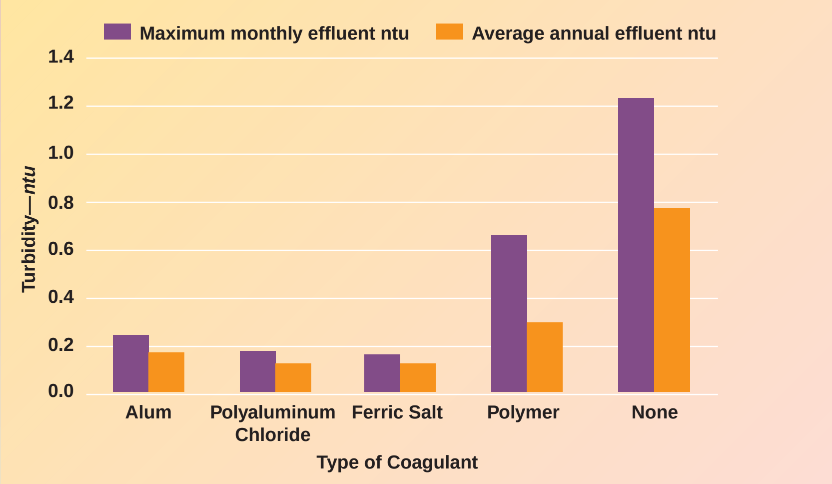


FIGURE 4 **Effect of coagulant type on effluent turbidity**



ments. This was especially remarkable during recent FPPEs because turbidimeter inaccuracy was a problem at many plants in the early years of the program. Although these comparisons do not fall within the bounds of a rigorous study, they show that the quality of turbidity information in Pennsylvania is generally improving.

Compiling turbidity data

In support of the national Partnership for Safe Water program, staff in the US Environmental Protection Agency's (USEPA's) Cincinnati, Ohio, office developed a spreadsheet to analyze and graph turbidity data. The spreadsheet* summarizes up to 365 days of information in monthly and yearly percentiles.[5] It also shows the data in a turbidity-versus-time output as well as a probability distribution output (Figure 1).

Operators asked to collect data. To acquire the data, staff in DEP's Uniontown, Greensburg, and Ebensburg offices in southwestern Pennsylvania and in the Pottsville office in northeastern Pennsylvania telephoned or visited operators at 75 water plants. Staff in the Allegheny County Health Department also contributed data from their FPPEs. Figure 2 shows the represented areas of the state. DEP asked the operators to voluntarily complete monthly monitoring forms and instructed them to report the highest raw water turbidity of the day as well as the highest finished water turbidity of the day (except postbackwash turbidity spikes). The forms were returned to DEP, where

*Available in several versions of Excel, Microsoft Corp., Redmond, Wash.; Lotus 1-2-3, Lotus Development Corp., Cambridge, Mass.; or QuattroPro, Corel Corp., Ottawa, Ont.

the data were entered into spreadsheets (two for each filtration plant—one for raw water and one for finished water). Although these data collection efforts were part of special projects, the turbidity graphs and percentiles were so valuable to both DEP staff and water system operators that the data collection and graphing efforts continue today. In fact, some operators began entering the data and graphing the information on their own.

Plants had to meet minimum standards. To be included in the study, the 75 water plants had to meet minimum standards. First, they had to use conventional or package rapid sand filtration technologies. Slow sand and diatomaceous earth filtration plants were excluded from the study because the turbidity standard for these plants is different. In addition, at least six months of turbidity data for raw water and finished water had to be available from the participating water plants in 1997 and submitted to DEP.

TABLE 1 **Turbidity data summary for 75 filtration plants**

Category	Average Annual 95th Percentile Turbidity	Maximum Monthly 95th Percentile Turbidity
Average value—*ntu*	0.2	0.3
Plants > 0.3 ntu	8 (11 percent)	16 (22 percent)
Plants > 0.1 ntu	18 (24 percent)	32 (43 percent)

TABLE 2 **Analysis of variance within each factor for maximum monthly and average annual effluent turbidity**

Factor	Maximum Monthly Effluent Turbidity		Average Annual Effluent Turbidity	
	F-ratio*	*P*-value†	*F*-ratio*	*P*-value†
Coagulant type‡	16.52	0.00	8.17	0.00
Coagulant type§	1.10	0.34	1.19	0.31
Population served	3.58	0.02	3.47	0.02
Ownership	0.87	0.36	0.56	0.46
Source type	4.17	0.02	4.00	0.02
Plant type	2.03	0.12	0.76	0.52
Plant age	2.90	0.04	1.83	0.15
Media type	0.51	0.68	0.99	0.40
Filtration rate	0.64	2.76	1.33	0.27

*A high *F*-ratio indicates that the variability between groups is greater than the variability within groups.
†*P*-values test the significance of differences between the turbidity values for various groups within a factor. *P*-values < 0.05 are assumed to be indicative of a statistically significant difference between the mean turbidity values of groups within a factor.
‡Includes seven plants that did not use coagulant
§Excludes seven plants that did not use coagulant

Additional filtration plant information on the 75 plants was collected through DEP's FPPE program. This information, which was obtained from reliable database files, included population served, type of source water, date of construction, ownership, and various design and operational factors (see the sidebar on page 30). Because these factors—as well as raw water turbidity levels—could affect the finished water turbidity levels, the authors compared the variables with the annual 95th percentile of the finished water turbidity levels (the 95th percentile means that 95 percent of the turbidity values were below the particular number). This percentile was selected because it would provide a good picture of daily conditions while removing unusually low or high extremes in turbidity. The variables were also compared with the highest monthly 95th percentile of finished water turbidity levels to gain a worst-case perspective. The 95th percentile matches turbidity reporting requirements of the Surface Water Treatment Rule (SWTR) and the Pennsylvania Filtration Rule.

Whether they use a grab-sampling technique or on-line instrumentation, almost all operators know the basic processes involved in turbidity measurement.

Finished water turbidity compared with other variables. The finished water turbidity levels were compared with operational, design, and other variables for the 75 filtration plants (see the sidebar on page 30). The two turbidity values used in the study were the highest monthly 95th percentile and the annual 95th percentile numbers for 1997. The highest monthly data were derived from a smaller number of sample results and were greater in value than the annual data. In other words, the highest monthly value was based only on the values recorded during one month, whereas the annual value was based on all the values recorded during the study, which had a minimum time of six months.

A high monthly value may indicate a short-term upset at the plant, whereas a high annual value signifies consistent poor performance. The IESWTR specifies the monthly turbidity level for water sys-

TABLE 3 Raw water and effluent turbidity data for each factor

Factor	Number for Each Group		Maximum Monthly Turbidity > 0.1 ntu		Maximum Monthly Turbidity > 0.3 ntu		Annual Average Turbidity > 0.1 ntu		Annual Average Turbidity > 0.3 ntu		Turbidity* Average Raw Water	Turbidity* Maximum Monthly Effluent	Turbidity* Average Annual Effluent
	n	*percent*	*n*	*percent*	*n*	*percent*	*n*	*percent*	*n*	*percent*	*ntu*	*ntu*	*ntu*
Coagulant type													
Alum	33	45	13	39	6	18	6	18	3	9	15.8	0.2	0.2
Polyaluminum chloride	28	38	12	43	3	11	5	18	0	0	19.1	0.2	0.1
Ferric salt	6	8	1	17	1	17	1	17	0	0	28.4	0.2	0.1
Polymer	4	5	3	75	3	75	3	75	2	50	14.5	0.7	0.3
None	3	4	3	100	3	100	3	100	3	100	2.5	1.2	0.8
Total†	74		32		16		18		8				
Population group													
<3,300	31	41	16	52	11	35	12	39	7	23	14.2	0.4	0.3
3,301–10,000	23	31	10	43	3	13	5	22	1	4	15.2	0.2	0.1
10,001–100,000	17	23	6	35	2	12	1	6	0	0	22.2	0.2	0.1
>100,000	4	5	0	0	0	0	0	0	0	0	32.1	0.1	0.1
Total	75		32		16		18		8				
Investor-owned?													
Yes	4	5	1	25	0	0	0	0	0	0	29.4	0.1	0.1
No	70	95	30	43	15	21	17	24	7	10	16.4	0.3	0.2
Total‡	74		31		15		17		7				
Source type													
Reservoir	35	47	18	51	9	26	13	37	3	9	7.9	0.3	0.2
River	28	37	7	25	2	7	1	4	1	4	32.4	0.2	0.1
Stream	12	16	7	58	5	42	4	33	4	33	9.2	0.5	0.3
Total	75		32		16		18		8				
Plant type													
Conventional	38	51	12	32	7	18	5	13	4	11	25.0	0.3	0.2
Direct	3	4	1	33	0	0	0	0	0	0	2.1	0.1	0.1
Package—gravity	26	35	11	42	5	19	7	27	2	8	10.1	0.2	0.2
Package—pressure	8	11	8	100	4	50	6	75	2	25	9.1	0.5	0.4
Total	75		32		16		18		8				
Plant age—*years*													
<10	38	51	14	37	4	11	9	24	3	8	12.0	0.2	0.2
11–25	11	15	6	55	5	45	4	36	2	18	16.2	0.4	0.2
26–50	12	16	6	50	5	42	3	25	2	17	19.8	0.7	0.2
>50	14	19	6	43	2	14	2	14	1	7	30.2	0.3	0.1
Total	75		32		16		18		8				
Filter media type													
Sand	11	15	6	55	5	45	5	45	3	27	15.8	0.4	0.2
Anthracite	8	11	4	50	2	25	1	13	1	13	27.5	0.3	0.2
Mixed	24	32	7	29	3	13	2	8	1	4	25.4	0.2	0.1
Multimedia	30	40	13	43	4	13	8	27	1	3	9.5	0.2	0.1
Total	73		30		14		16		6				
Filter rate—*gpm/sq ft (m/h)*													
0–1 (0–2.5)	10	13	5	50	4	40	3	30	3	30	20.6	0.4	0.3
>1–2 (>2.5–5)	30	40	11	37	6	20	5	17	2	7	21.9	0.2	0.1
>2–3 (>5–7.5)	17	23	6	35	1	6	3	18	0	0	15.8	0.2	0.1
>3–4 (>7.5–10)	10	13	3	30	2	20	2	20	1	10	7.8	0.2	0.1
Total§	67		25		13		13		6				

*All turbidity values < 0.1 ntu are assumed to be 0.1 ntu.
†Filter plant that uses sodium aluminate was not included in coagulant evaluation.
‡Filter plant that serves electric power–generating facility was not included in ownership evaluation.
§Filter rate evaluation does not include pressure filters and plants with no flow data given.

tems serving ≥ 10,000 people; combined filtered water turbidity at each plant must remain ≤ 0.3 ntu in at least 95 percent of the measurements taken each month.

The plants participating in the study recorded turbidity values to two decimal places, but because of limitations in the accuracy of turbidity measurements, turbidity values were rounded to the nearest tenth. This was also in keeping with the regulatory limits that are specified to one decimal point (e.g., 0.3 ntu). It was assumed for the various data comparisons used in the study that all values < 0.1 ntu were equal to 0.1 even though many of the finished water turbidity values in the study were below this level. This assumption was made because differences in turbidity levels below 0.1 ntu have a limited meaning, owing to limitations in turbidity instruments when values this low are measured. These limitations have been described[4] and include difficulties in calibrating instruments to read such low values. The inclusion of values below 0.1 ntu in the data could have obscured the statistical impact of higher turbidity values associated with some of the filtration plants. Eight systems reported monthly maximum 95th percentile turbidity values of ≤ 0.05 ntu.

Results and discussion

Regulatory mark missed by several facilities. The average maximum monthly and annual 95th percentile turbidity values for the facilities participating in the study were 0.3 and 0.2 ntu, respectively. The data in Table 1 show that 16 (22 percent) of the 75 facilities would not have met IESWTR or LTESWTR requirements for at least one month during the study. (For this study, the authors assumed that the LTESWTR, which affects surface water systems that serve smaller populations, would also entail a 0.3-ntu limit.) For instance, the combined turbidity must be ≤ 0.3 ntu in at least 95 percent of the measurements taken each month. Of these, eight plants (11 percent) had an annual 95th percentile turbidity > 0.3 ntu, which may signify chronic noncompliance. All turbidity values were rounded to the nearest 0.1 ntu; thus, plants reporting values between 0.30 and 0.35 ntu were assigned values of 0.3 ntu and were not included in the number of plants projected to be noncompliant. Forty-three percent of the facilities would not have met the Partnership for Safe Water 0.1-ntu optimized performance goal for at least one month of the study, and 24 percent would not meet the annual goal. Figure 3 shows the maximum monthly turbidity values at the 95th percentile for finished water at the various plants.

FIGURE 5 Effect of population served on effluent turbidity

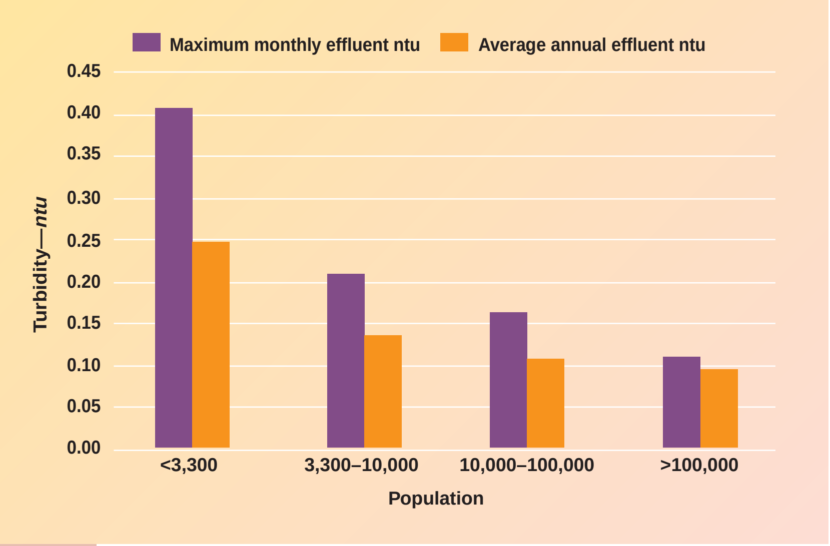
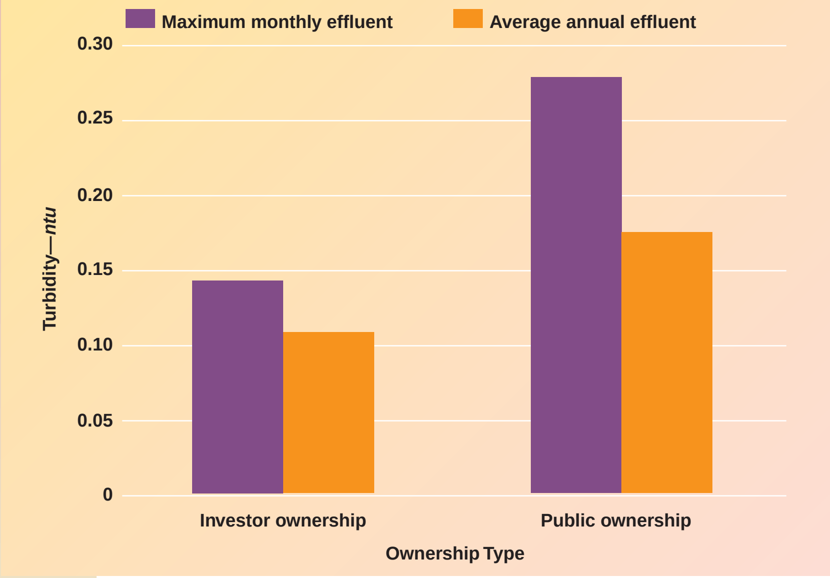


FIGURE 6 Effect of ownership on effluent turbidity



The estimates of noncompliance in this study may be conservative because of the methodology used by the plants to record turbidity data. As discussed earlier in this article, participants were asked to record the highest daily finished water turbidity value (excluding postbackwash turbidity spikes). These values were then used to derive the 95th percentile values. Compliance with the IESWTR and probably the LTESWTR for many facilities will, however, be based on multiple daily values rather than just the highest daily value. Thus, the data in this study may overestimate the degree of noncompliance. Still, the highest value represents a potential weak point because if pathogens are present in substantial concentrations in the raw water, a brief increase in turbidity in the finished water could signify pathogen breakthrough.

Variability within each of eight factors analyzed. Table 2 shows an analysis of variability within each factor to determine the significance of the turbidity variability of each group within a factor. For example, for filter media, the variability in finished water turbidity among the sand, anthracite, mixed media, and multimedia groups was analyzed to determine whether it was statistically significant. For average annual effluent turbidity, three factors—coagulant, population served, and source type—had a significant difference among the groups within the

FIGURE 7 **Effect of source type on effluent turbidity**

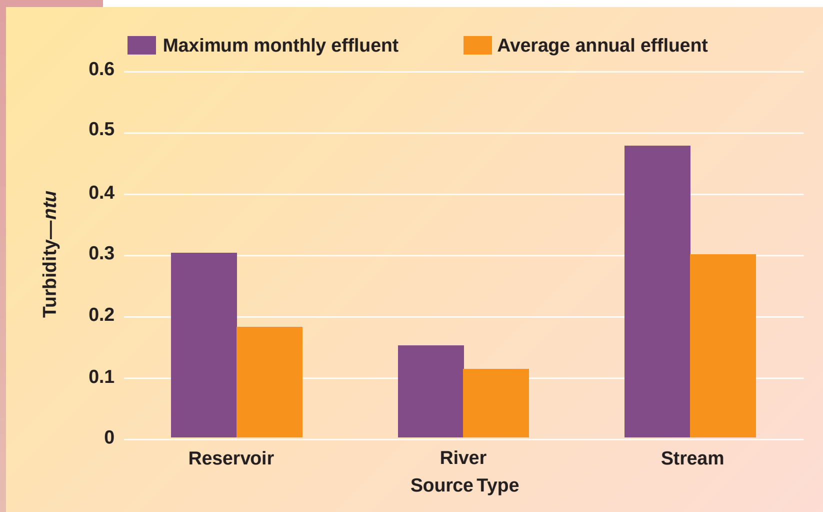
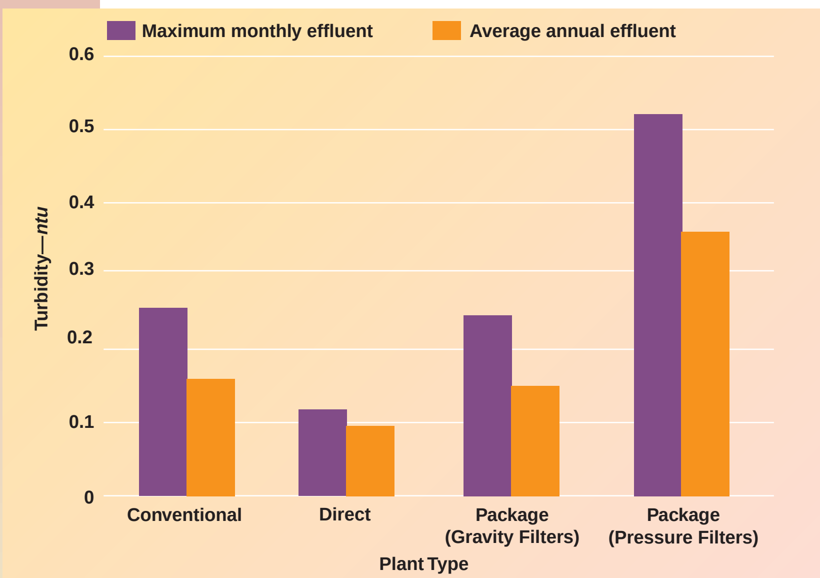


FIGURE 8 **Effect of plant type on effluent turbidity**



factor at the 95 percent confidence level. If the plants not using a coagulant are excluded from the analysis, then there is no significant difference in maximum monthly turbidity among the various types of coagulants.

For each of the eight factors, the average turbidity values were calculated for the facilities in a particular group along with the number of systems that had values > 0.3 and 0.1 ntu (Figures 4–11 and Table 3). When these results are assessed, small increases in filtered water turbidity can be associated with increases in concentrations of protozoa, viruses, and bacteria.[6]

Coagulant type. The coagulants used by the water systems in this study were broken down into five categories: alum, polyaluminum chloride, ferric salt, polymer, and none. Although polymers are not coagulants per se, DEP records showed that four systems used polymer instead of a coagulant. In this study, the data for plants using only polymer were compared with those for plants using coagulants. Records for the three plants in the "none" category show that no coagulant or polymer is used. Although there are differences in the various polyaluminum chloride products used in the water industry, for the purpose of this study they were lumped into one category. One of the plants used sodium aluminate as a coagulant; this plant was not used in this part of the evaluation because it represented only one data point. Additionally, the study did not consider other operational variables that affect coagulation such as dosage, pH, mixing conditions, and frequency of jar testing.

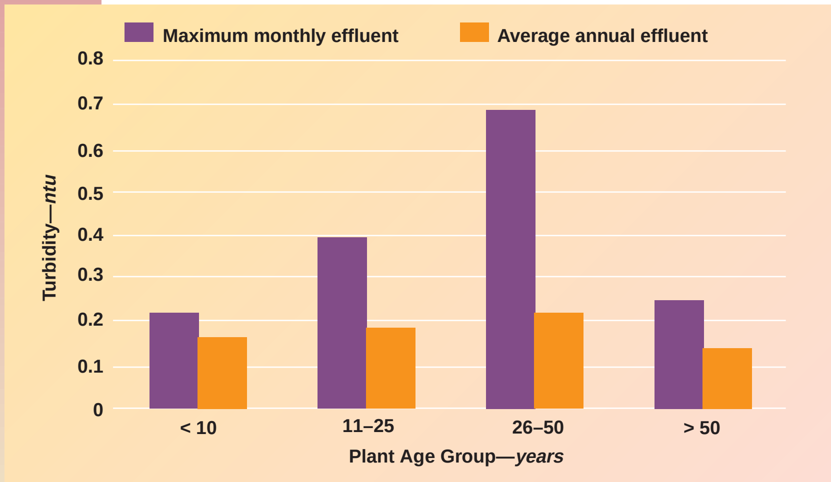
The results in Figure 4 and Table 3 show poor performance for the systems that used only a polymer or no coagulant at all. All of the systems in the "none" category as well as three of four systems using only a polymer exceeded the 0.3-ntu limit. This was not surprising because all the facilities evaluated in this study were rapid sand filtration plants, which require effective chemical coagulation to provide proper treatment. All of the systems in the "polymer" or "none" category served < 3,300 people (i.e., small systems as defined by USEPA).

There was no significant difference in the turbidity data for the other three categories: alum, polyaluminum chloride, and ferric salt. The average raw turbidity of the systems using ferric salts was, however, substantially higher than that for the systems using alum and polyaluminum chloride. Most of the plants used either alum or polyaluminum chloride, and the performance of the two coagulants appeared to be almost identical.

Population served. The filtration plant data sets were evaluated with respect to the population served using four categories: ≤3,300, 3,301–10,000, 10,001–100,000, and >100,000. USEPA generally uses these population ranges for regulatory purposes. The plants serving the smallest systems (i.e., ≤3,300 people), which made up the largest (41 percent) portion of the study participants, had the poorest turbidity values (Figure 5). Thirty-five percent of these plants had maximum monthly 95th percentile turbidity values > 0.3 ntu, and 52 percent had values > 0.1 ntu (Table 3). By contrast, none of the plants serving populations > 100,000 people had maximum monthly turbidity values > 0.1 ntu even though the larger systems experienced average raw water turbidity twice that of the smallest systems. There was little difference in the data for the plants in the 3,301–10,000- and 10,001–100,000-population categories. The percentage of plants with maximum monthly turbidity values > 0.3 ntu for these categories was 13 and 12 percent, respectively.

In some cases, a feature of small systems that affects performance is insufficient capital for major construction or renovation. In this study, the median age of the plants for the smallest systems was 10 years—the same median age for all the plants in the study. Once again, plant age does not explain the poorer performance of the smallest systems and suggests that operational factors may play more of a role than physical facilities in determining the performance of the smallest systems.

FIGURE 9 **Effect of plant age on effluent turbidity**



Slow sand and diatomaceous earth filtration plants were excluded from the study because the turbidity standard for these plants is different.

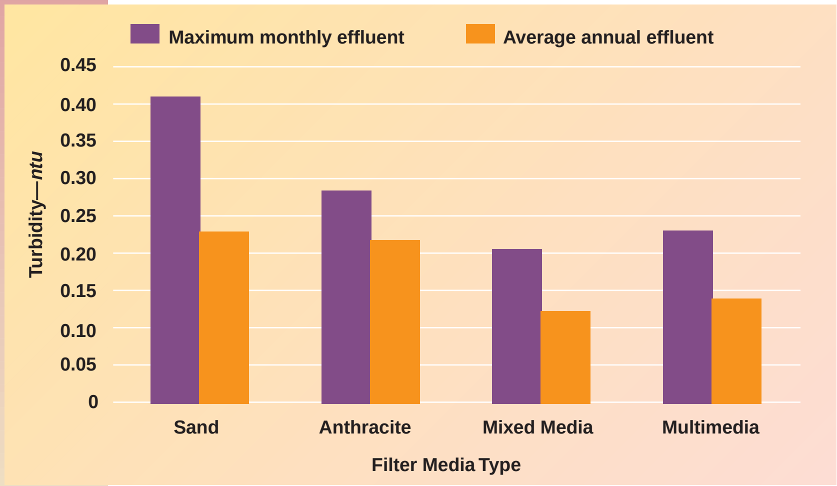
Ownership. Turbidity data from plants that were investor-owned and those that were publicly owned were compared. The publicly owned plants were owned and operated by government entities such as cities, boroughs, and municipal authorities. Only five of the plants were investor-owned. One of these facilities, a noncommunity water supplier serving workers at a power station, had extremely poor turbidity data that skewed the results in the investor-owned category. For this reason, it was excluded from the ownership evaluation, leaving only four plants in the private category, all of which were owned by one company.

The four investor-owned plants had lower effluent turbidity values relative to the publicly owned plants, but the difference was not statistically significant. The average of the highest monthly turbidity values for the investor-owned plants was 0.1 ntu, compared with 0.3 ntu for the publicly owned plants (Table 3 and Figure 6). The four privately owned plants were constructed in 1906, 1922, 1965, and 1991 and tended to be located on larger streams and rivers with higher raw water turbidity values relative to the average facility participating in this study.

Croker et al[7] assessed one of the privately owned plants evaluated in this study. The study describes how the plant was able to substantially improve finished water turbidity through operational changes and minor capital improvements (primarily for instrumentation) even though the plant was constructed in 1906. Because all of the investor-owned plants in the study had the same owner, no conclusions should be drawn about the general performance of private versus public plants. However, the fact that the private owner was consistently able to provide excellent performance despite a variety of conditions shows that a commitment to maintaining low turbidity levels may be equally as important if not more important than other variables evaluated in this study.

Source type and source water turbidity. Water sources were classified as reservoir, river, or stream. Almost half of the sources were reservoirs, 37 percent were rivers, and 16 percent were streams. Staff at each filtration plant recorded raw water turbidity values once each day for the duration of the study. The average raw water turbidity for each source type and finished water turbidity data are given in Table 3. The data show that the plants using river sources seemed to perform better than those using reservoirs and streams. The difference is statistically significant (Table 2).

FIGURE 10 **Effect of filter media type on effluent turbidity**



Approximately 26 percent of the plants using reservoirs and 47 percent of those using streams had the highest monthly turbidity values (>0.3 ntu), compared with only 7 percent of the plants using rivers. These results occurred even though the river sources had much higher average raw water turbidity values than the streams and reservoirs. The average raw water turbidity for the rivers was 32 ntu compared with 7.9 and 9.2 ntu for the reservoirs and streams, respectively. The median river water turbidity was 35 ntu, indicating that the high average value was probably not skewed by a few high values.

Pennsylvania rivers tend to have highly variable water quality relative to reservoirs. River water turbidity, pH, and alkalinity levels generally fluctuate rapidly, depending on flow conditions. Consequently, river sources are almost always more difficult to treat than reservoir sources. Nevertheless, the performance data for the river plants appear to be superior to those for the reservoirs and streams, indicating that source type is a poor predictor of plant performance.

A minimum of six months of turbidity data for raw water and finished water had to be available from the participating water plants in 1997.

A comparison of turbidity data for raw water and finished water from each plant using a regression analysis provides an R^2 value of 0.05, which means that there is no correlation between the two values. Thus, systems with poorer-quality water are able to provide treatment on a par with systems that have better water quality. Perhaps the plants treating higher-turbidity water place more emphasis on filtration plant performance because of their concerns regarding the poor quality of the source. Low-turbidity water, however, does not necessarily have low concentrations of *Giardia* cysts and *Cryptosporidium* oocysts. A study of the Allegheny River near Pittsburgh under varying water quality conditions did not find a correlation between *Giardia* and *Cryptosporidium* and turbidity or any other water quality factor.[8] National studies, too, have not uncovered a good physical or biological surrogate for *Giardia* or *Cryptosporidium* presence.[9] The findings in this Pennsylvania study may suggest that surface water systems treating low-turbidity source water may need to place more emphasis on maintaining low finished water turbidity levels.

Plant type. Filtration plants were placed into four categories: conventional, direct, package (gravity filters), and package (pressure filters). The plants in the package (gravity) category include plants in which one manufacturer provided the flocculation, clarification, and filtration processes in a complete unit. Two of the plants using pressure filters used a clarification process before the filters. The remaining six pressure filtration plants did not use a clarification process. As discussed previously, diatomaceous earth filtration plants were not included in this study.

Most of the plants in the study were conventional or package (gravity). The results of the analysis (Figure 8 and Table 3) show little difference in performance between the conventional and package (gravity) plants. The direct filtration plants had lower turbidity values than the conventional and package (gravity) plant, but only three direct filtration plants were included in the study. Additionally, the average raw water turbidity for direct filtration plants was much lower than that for the other categories.

The package (pressure) plants had higher turbidity values relative to the plants in the other categories, but the difference was not statistically significant. Fifty percent of the package (pressure) plants would not have complied with the 0.3-ntu standard for at least one month during the study. None of the package (pressure) plants would have complied with a 0.1-ntu standard. All of the package (pressure) plants served < 5,000 people; five out of eight plants served < 1,000 people.

Plant age. To evaluate the effect of plant age on filtration plant performance, four classifications of plant age were used: ≤10, 11–25, 26–50, and >50 years. About half the systems were < 10 years old, with approximately equal numbers of systems in the other three age categories (Table 3). The large number of recently constructed filtration plants is attributed to Pennsylvania's regulations enacted in response to the federal SWTR. Pennsylvania's regulations require that all surface water sources be filtered. As a result, more than 100 filtration plants were constructed in the 10-year period preceding this study.

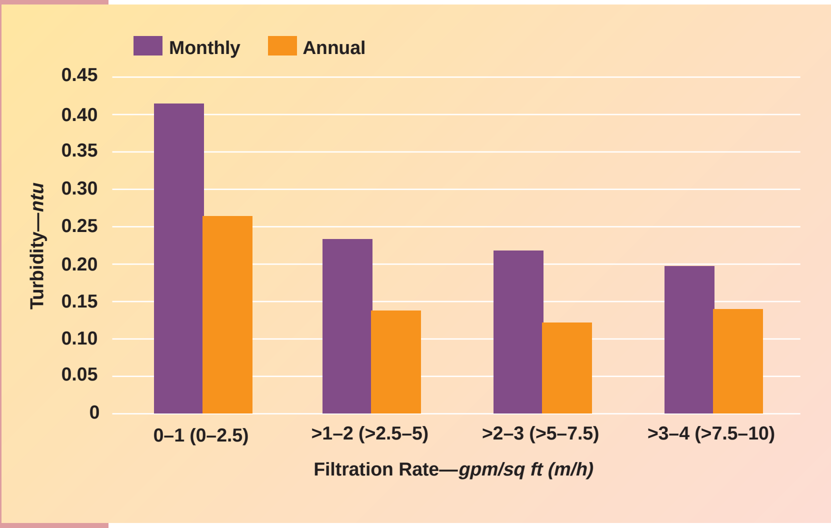
There is no obvious correlation between plant age and performance for the plants participating in this study. The lowest percentages of plants that exceeded 0.3- and 0.1-ntu levels were in the newest and oldest groups. Conversely, the middle two age groups had a higher number of systems predicted to be noncompliant. A comparison of plant age and maximum monthly finished water turbidity data for each plant using regression analysis provides an R^2 of 0.002. This shows that there is no relationship between turbidity and plant age. The fact that the newest plants did not appear to have much better performance than the oldest plants is somewhat surprising because the newer plants were constructed in accordance with stricter regulatory standards. This finding may suggest that operational considerations are just as important or more important than plant design characteristics.

Media type. There were four classes of filter media for the plants in this study: sand only, anthracite only, mixed media (sand and anthracite), and multimedia. The filters in the multimedia category had at least three types of media, such as sand, anthracite, and garnet. Two plants using pressure filters were excluded from the media evaluation because they used a proprietary type of monomedia.

The plants that used sand only and anthracite only appeared to have higher finished water turbidity values than the mixed media and multimedia plants. There were more single-media plants in excess of the 0.3-ntu limit and the 0.1-ntu optimization goal than plants using two or more types of filter media, but the differences do not appear to be statistically significant. Various studies have shown that there is a lower rate of head loss and consequently longer filter run times for mixed and multimedia filters compared with sand-only filters, but the benefit provided in terms of improved filtrate quality has not been fully demonstrated.[10]

Filtration rate. Filtration rates were divided into four categories: 0–1 gpm/sq ft (0–2.5 m/h), >1–2 gpm/sq ft (>2.5–5 m/h), >2–3 gpm/sq ft (>5–7.5 m/h), and >3–4 gpm/sq ft (>7.5–10 m/h). Public water supply permits in Pennsylvania limit filtration rates in gravity plants to a maximum of 4.0 gpm/sq ft (10 m/h), and none of the gravity plants exceeded this rate. Five of the pressure filtration plants, however, had filtration rates in the range of 4–7 gpm/sq ft (10–17.5 m/h.) Pennsylvania's filtration rate limit of 4.0 gpm/sq ft (10 m/h) was established for gravity filters and is not necessarily applicable to pressure filters. Pressure filtration plants were not included in the filtration rate evaluation for this reason.

FIGURE 11 Effect of filtration rate on effluent turbidity



Forty-three percent of the facilities would not have met the Partnership for Safe Water 0.1-ntu optimized performance goal for at least one month of the study.

The plants with the lowest filtration rates (0–1 gpm/sq ft [0–2.5 m/h]) appeared to have the worst performance (Table 3 and Figure 11). There was no obvious relationship between filtration rate and turbidity for plants in the other three categories. This seems to indicate that the most conservatively designed filters do not necessarily have the best performance. The R^2 value is 0.02, which seems to show that there is no relationship between filtration rate and turbidity performance. Some studies have shown that the effect of filtration rate on filtrate quality does not become apparent until rates exceed 4.0 gpm/sq ft (10 m/h), which is higher than the rates used by plants in this study.[10] There may, however, be other advantages to lower filtration rates, such as longer filter run times and less water used for backwashing.

Conclusions

This study examined the long-term finished water turbidity data at 75 surface water treatment plants in Pennsylvania. The average maximum monthly and annual 95th percentile turbidity values for the facilities participating in the study were 0.3 and 0.2 ntu, respectively. Twenty-two percent of the plants would have not complied with a 0.3-ntu standard for at least one month of the study.

When turbidity data from multiple plants are compared, several potential limitations that could be crucial to data collection required under new regulations must be considered. Staff at surface water treatment plants have historically selected instruments from a variety of manufacturers, have the option of choosing sampling points from a number of locations within the treatment plant, and face instrument calibration issues that could affect turbidimeter performance. All are important considerations when filtration plant performance is monitored and plant-to-plant variations are compared. For plant-to-plant comparisons, data collection must be consistent as to whether the data represent highest, average, or routine sampling (values from once every four hours).

This study also reviewed key water quality, design, and operational variables to determine their effects on filtered water turbidity. Plants that did not use a coagulant, served small systems, or treated water from streams had, on average, poor turbidity removal relative to the plants overall. Variations in performance among the rest of the plants cannot be explained statistically by the differences in the variables evaluated as part of the study. Many plants were able to consistently achieve extremely low turbidity levels despite limitations such as small system size, plant age, or high source water turbidity. This suggests that small systems are not condemned to having poor performance. Nontangible variables such as commitment to achieving low turbidity, operator skill level, and operator attention appear to be equally as important if not more important than tangible variables such as source water quality, plant age, and type of coagulant. The few private plants evaluated were consistently able to provide excellent performance despite a variety of conditions, which further shows that commitment to excellence is extremely important. The oldest filtration plants seemed to perform as well as the newest ones, indicating that some water systems without state-of-the-art facilities can significantly improve performance by optimizing operations without making major capital expenditures. Efforts by regulatory agencies that increase owner and operator awareness of the importance of filtration plant performance and optimization are obviously valuable.

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