Emission of Microbial Aerosols From Sewage Treatment Plants That Use Trickling Filters

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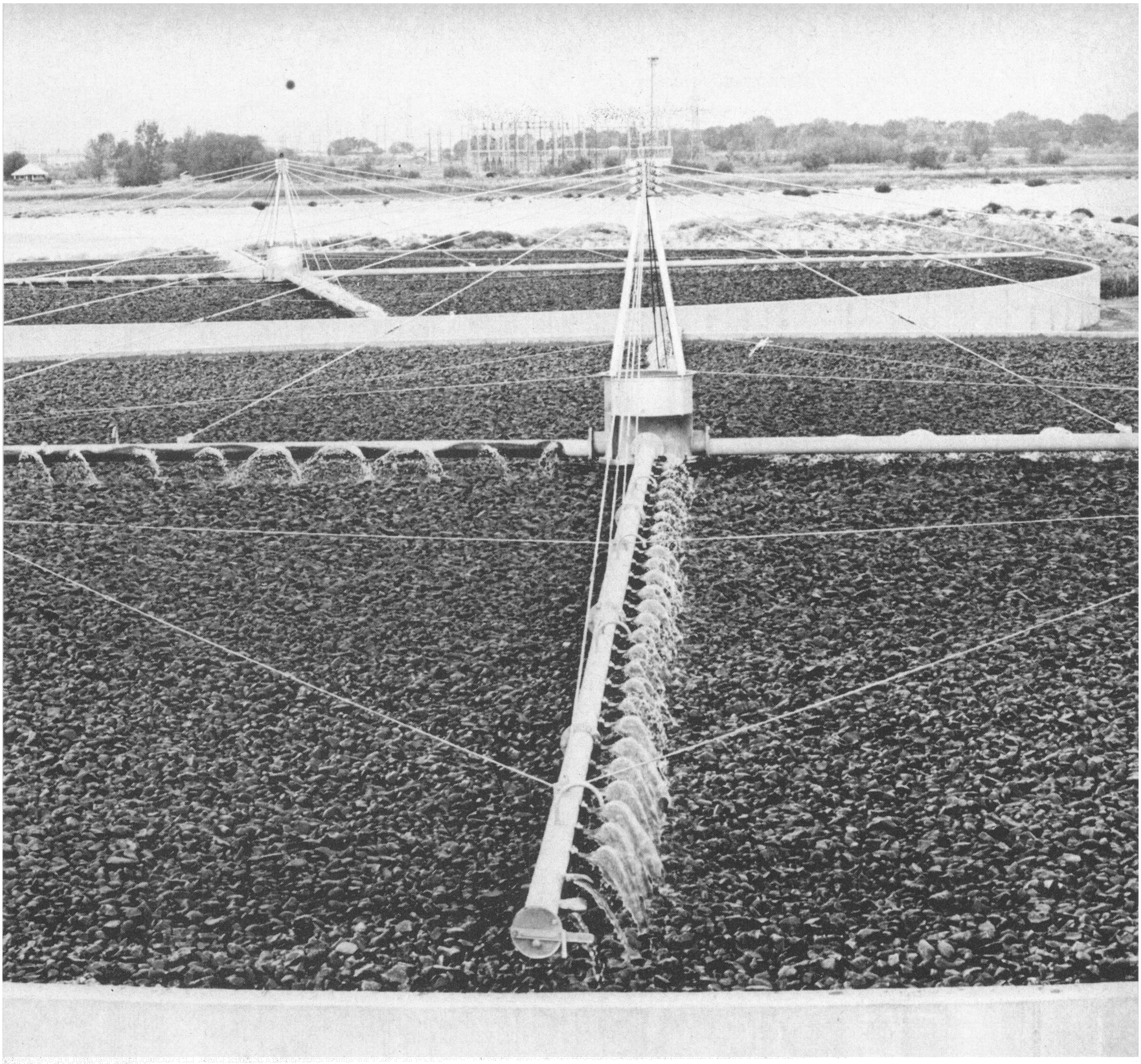
VIRTUALLY every city in the United States of more than 2,500 population has some kind of communal sewage treatment facility. These facilities vary from only primary settling treatment to sewage lagoons to the more sophisticated secondary methods of activated sludge and trickling filter processes. The modern secondary treatment plants, because of their design, are a major source of aerosolized microorganisms that may contaminate the air of surrounding populated areas.

A sewage plant that concentrates and processes the wastes of thousands of people may act as a continuous point source generator of microbial aerosols. The possible public health danger of aerosolized sewage organisms can be visualized when one considers the great number and variety of pathogens that may be present in raw sewage (*1*).

The universal indicator of fecal pollution in water, *Escherichia coli,* serves equally well in the examination of aerosols from sewage treatment plants. An early investigation into microbial air pollution associated with sewage treatment (trickling filter) is reported in a thesis by Albrecht (*2*). The spraying action and the splashing of the liquid sewage as it is delivered into the trickling filter rock bed produces numerous aerosolized particles ranging in size from 1 to 5 microns, and it is known that particles in this size range can be effectively deposited in the deepest recesses of the human lung.

Napolitano and Rowe (*3*) compared the emissions of coliform organisms from sewage plants that were using an activated sludge process and the high-rate trickling filter. These authors sought to establish the survival distance of coliform organisms as related to wind velocity and other weather conditions and to determine the size distribution of the areosolized particulate matter. They concluded that activated sludge facilities yielded approximately 10 times as many coliform organisms per volume of air sampled as high-rate trickling filters. They also reported that about 50 percent of the aerosol particles given



(*U.S. Army photograph*)

Figure 1. Trickling bed filters of sewage plant 1

off by both kinds of plants were more than 5 microns in diameter and hence were less likely to penetrate the human lung than the smaller particles (*4*). The larger particles are deposited in the nasal-pharynx region and swallowed.

Randall and Ledbetter (*5*) also studied bacterial air pollution from activated sludge facilities. Their results showed that the bacterial population of the air was significantly increased by passage over an activated sludge unit. An average of eight organisms per cubic foot was recorded in control samples taken upwind of the sewage facility; as many as 1,170 organisms per cubic foot were recorded in test samples taken downwind of the facility. Despite an initial rapid die-off, the aerosolized bacteria persisted in a viable state for a considerable time and a considerable distance downwind and were found to increase in numbers with increasing wind velocity. These authors concluded that there was a definite

Total bacterial and coliform aerosol recoveries on individual trials from plant 1

Trial No. and time of trial	Meteorological conditions: Distance downwind from source (meters)	Wind-speed (mph)	Relative humidity (percent)	Temperature (°F)	Total bacteria—particles per m³ (Casitone agar)[1]	Coliforms—particles per m³ (Endo agar)[1]
1.—day	15	6–8	35	86	59	294
2.—day	15	6–8	55	71	1,195	141
3.—night	15	6–8	50	71	1,848	647
	50				633	232
	100				306	60
4.—night	15	15–20	95	65	4,856	2,354
	50				656	299
5.—day	15	10–12	70	42	476	247
	50				71	33
6.—night	15	4–6	65	42	1,050	530
	50				381	113
7.—day	15	4–6	40	51	466	(2)
	15				424	
	50				31	
	50				10	
8.—night	15	1–3	85	33	456	(2)
	15				399	
	100				51	
	100				137	
9.—day	15	8–12	89	43	(2)	280
	15					236
10.—night	15	8–12	93	39	(2)	217
11.—day	15	10–15	44	60	530	111
	50				360	15
12.—night	15	10–15	45	58	378	130
	50				(2)	18
13.—day	15	20–25	60	41	906	706
	50				121	119
	100				145	104
14.—night	15	10–15	74	38	679	693
	50				111	(2)
	100				(2)	25
15.—day	15	15–25	13	65	631	100
	50				255	49
16.—night	15	10–15	57	49	629	657
17.—day	15	8–10	35	68	358	220
	50				(2)	84
	100				492	64
18.—day	15	Calm...	35	90	134	(2)
	15				250	
	100				414	
19.—night	15	Calm...	49	77	3,206	(2)
	15				3,645	(2)
	15				3,929	(2)
	100				(2)	251
	100				(2)	381

[1]Data represent net downwind counts after upwind control counts have been subtracted. Total bacteria include all organisms that grew on Casitone agar. Coliforms were grown on Endo medium.
[2]No data collected.

Total bacterial and coliform aerosol recoveries on individual trials from plant 2

Trial No. and time of trial	Distance downwind from source (meters)	Wind-speed (mph)	Relative humidity (percent)	Temper-ature (°F)	Total bacteria—particles per m (Casitone agar)[1]	Coliforms—particles per m (Endo agar)[1]
	Meteorological conditions					
20.—day	100	16–22	15	85	815	(2)
	100				(2)	620
	700				(2)	79
	3,000				(2)	0
21.—day	100	10–15	95	38	2,091	723
	100				2,114	965
	100				2,007	(2)
	700				293	349
	700				449	487
	700				529	(2)
22.—day	100	10–15	85	45	536	676
	100				803	438
	700				0	15

NOTE. See opposite page for explanation of footnotes.

possibility of airborne infection from activated sludge plants and that organisms of the genus *Klebsiella* were present in large numbers. Their conclusion supports the possibility, already mentioned, of a public health hazard from aerosols emitted from trickling filters.

Glaser and Ledbetter (*6*) investigated the number and size of aerosol particles generated by activated sludge treatment. They concluded that in 1 cubic foot of air emitted from the activated sludge chamber more than 15,000 particles were greater than 1 micron in diameter. Of this total, 40 percent of the particles had diameters of less than 10 microns. Using Andersen samplers, Adams and Spendlove (*7*) sought to determine the numbers of total bacterial particles and coliform particles emitted from a trickling filter source. Positive coliform samples were recovered from the aerosol samplers in the immediate vicinity of the trickling filter and to a point 0.8 mile downwind.

Recent interest in the sources of environmental pollution, together with developments in the science of aerobiology during the past decade, have provided the technology to investigate trickling filters as a source of microbial aerosol pollution of the atmosphere. The purpose of our study was to examine the effects of various environmental conditions upon the emission of *E. coli* and total bacterial forms from two typical trickling filter processing plants serving a metropolitan area. An attempt was made to gain information regarding the magnitude of emission of potentially hazardous aerosols as they might vary with changing environmental conditions.

Materials and Methods

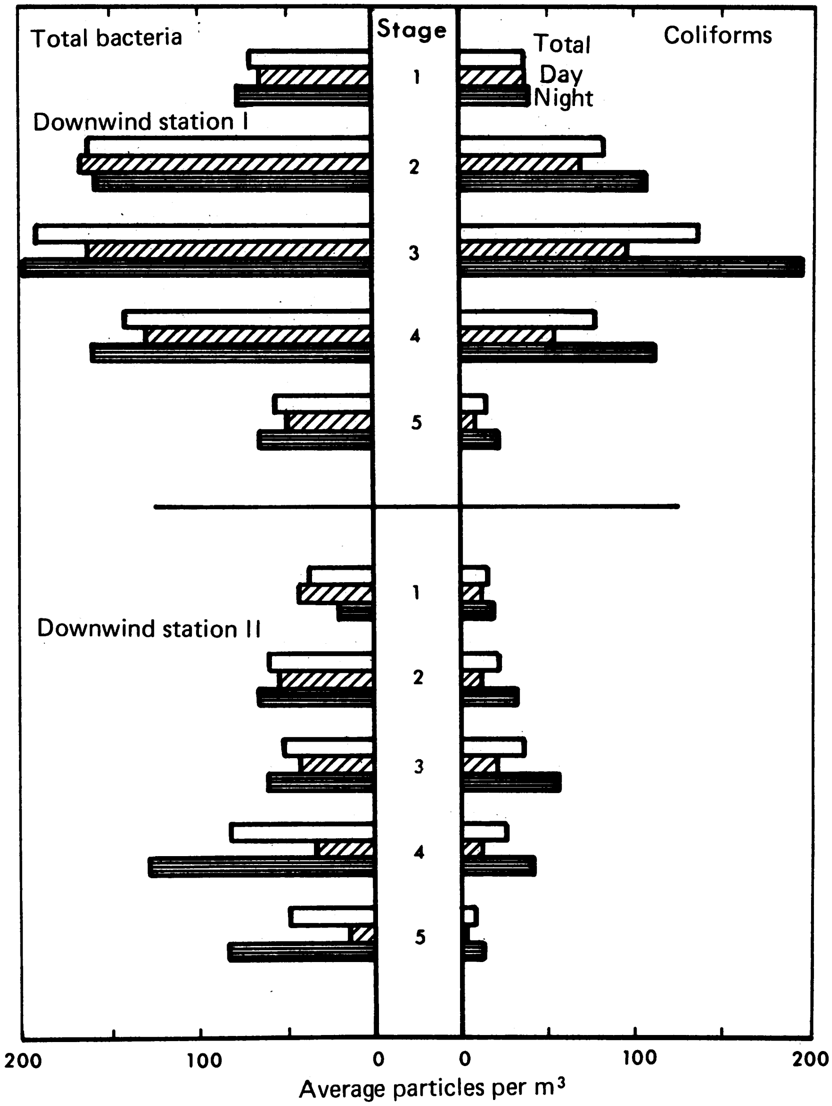
Sewage plants studied. Two sewage treatment plants located in the intermountain West were studied over the period July 1970 through December 1971. Each plant included both primary and secondary sewage treatment facilities.

Plant 1 has a design capacity of 15 million gallons per day and serves a suburban population estimated at approximately 100,000. A bank of four trickle bed filters is in constant operation; the bank forms a square, with a filter in each corner. Two of the four filters are shown in figure 1. This plant is located adjacent to a built-up industrial area.

Plant 2 is larger than plant 1. It serves a metropolitan population of approximately 200,000 and processes an average of 35 million gallons of sewage per day. This plant has two banks of four filters each, located close together. A business district is located 5 to 7 kilometers southeast and downwind of the prevailing winds of plant 2. Directly south is a large housing development. An oil refinery occupies the area to the north.

Sampler used and techniques. Aerosol samples were taken with the Andersen sampler (*8*), a cascading sieve-type device that is widely used in characterizing the number and size of viable aerosol particles. In the field trials, each sampler was attached to a vacuum source calibrated to aspirate at the rate of 1 cubic foot (28.3 liters) per minute. Sampling stations were located from as close as 5.0 meters from the downwind edge of the filters to a distance of 3 to 5 kilometers downwind. The petri plates removed from

Figure 2. Numbers of particles recovered per Andersen sampler stage during day and night sampling trials

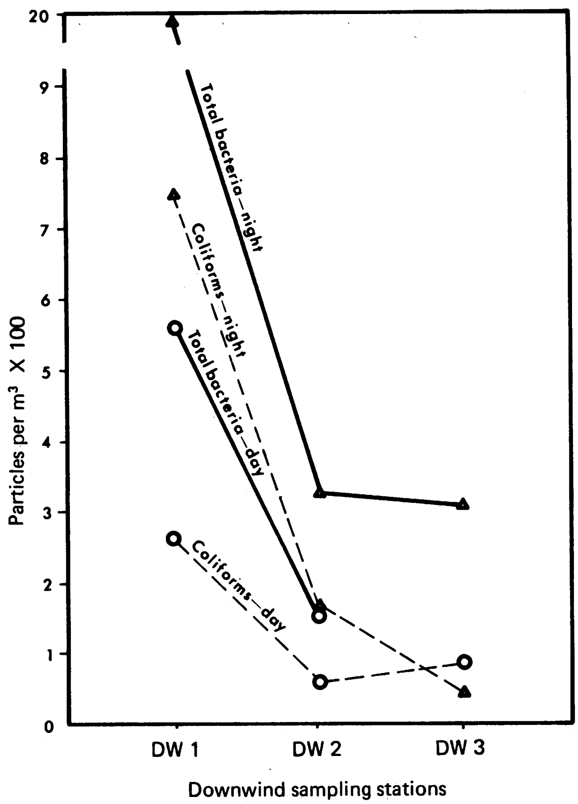


the sampler following completion of a field trial were incubated aerobically at 37° C for 24 hours for Casitone agar and 48 hours for Endo agar. Casitone agar was used for the total bacterial count and Endo agar for the assessment of coliforms. Viable particle counts were obtained by correcting for the positive hole count as reported by Andersen (*8*).

Each trial, except 1, 2, and 10 (see tables), was conducted with two or more test sampling stations. In addition, an upwind control was always taken to establish a background count of airborne organisms. Each downwind station usually consisted of two Andersen samplers, one containing Casitone and the other containing Endo agar plates or duplicate sets of Casitone plates.

At plant 1, the downwind 1 (DW1) station was located in the center area of the trickling filter complex, approximately 15 meters downwind from the center of one of the trickling filters. All distances were measured from the center of the filter apparatus. This procedure precluded sampling the airborne output of the other three filters operating in the complex. At plant 2, downwind 1 stations were set up at varying distances downwind to a maximum of 100 meters. Downwind 2 (DW2) and 3 (DW3) stations ranged from 700 meters to 3 kilometers

Figure 3. Effect of solar radiation and downwind distance



downwind. During cold weather either 2.5 percent carboxy methyl cellulose or 3 percent cornstarch was added to the agar of the Andersen sampler plates to prevent freezing.

The table shows the trials that were completed and the numbers of samples taken, together with the existing meteorological conditions. Plots given in figures 2 through 8 were taken from data supplied by these trials.

Standards and controls. The results of the upwind control samples for all trials were averaged. Determination of the numbers of coliforms was made by direct sampling onto Endo selective media. Colonies showing fermentation of lactose on the medium were considered to be coliforms.

The microbial population of the liquid sewage at the point of aerosolization indicated the number and types of organisms that are theoretically available for aerosolization. Bacterial counts of liquid sewage were made at intervals throughout the investigation. The counts reported represent all the microorganisms present in the liquid sewage that were able to grow under the conditions of the experiment.

Liquid samples for total bacteria and coliforms were collected into a sterile flask directly from the boom of the trickling filter. Each sample was iced and returned to the laboratory; there serial dilutions were prepared, and spread plate techniques for both the total count and coliforms were carried out. Casitone agar was used for the total count determinations and Endo agar for the coliform counts. The plates were incubated for 24 hours for total counts and 48 hours for coliform counts.

Results

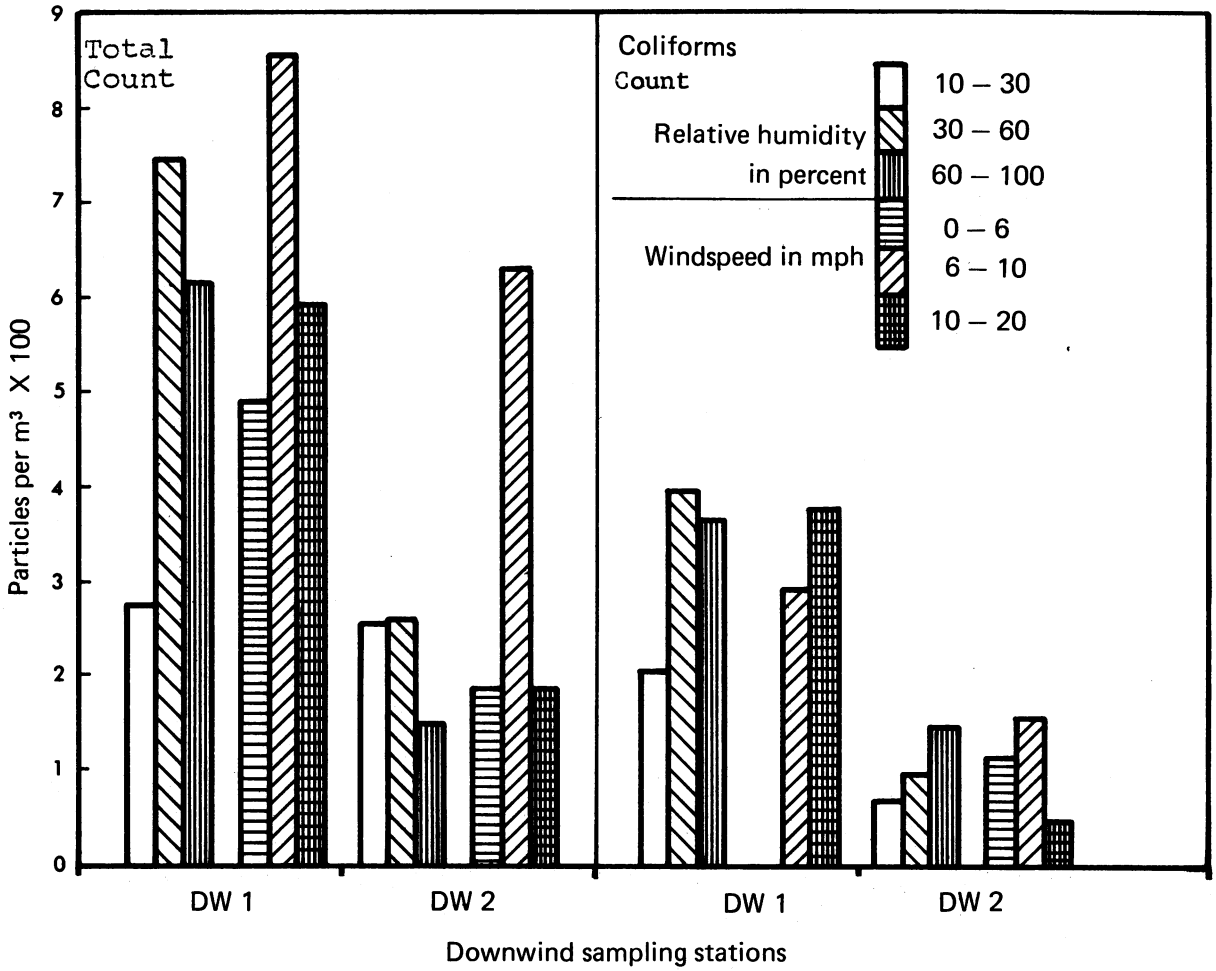
Controls. The number of bacteria present in the air immediately upwind of the sewage treatment plants averaged 180 viable particles per cubic meter of air (particles per cubic meter). Throughout the series of sampling trials (see table), the background level remained fairly constant. In 88 percent of the trials the count was less than 350 particles per cubic meter, and in 59 percent it was less than 150. The standard deviation of the upwind controls was 110 with a 63 percent coefficient of variation.

Only occasional coliform bacteria were seen on the upwind controls. The overall numbers collected throughout the series averaged 2.12 particles per cubic meter of air; during most of the trials, however, no coliforms at all were observed on the upwind control plates. Both total and coliform upwind counts were subtracted from downwind counts to determine the numbers of microorganisms being emitted by the trickle filter and being carried to the sampler (table 1).

Liquid sewage samples were taken in 14 of the 22 trials shown in the table. The total bacterial population at the point of aerosolization ranged from 1.5×10^6 to 4.0×10^6 viable cells per milliliter. Coliforms taken from the same point averaged 2.1×10^4 per milliliter.

Characterization of aerosols. The overall average net count of viable airborne particles at the DW1 station was 620 per cubic meter. At the DW2 station it was 247, and at the DW3 station it was 236. The counts include both day and night sampling trials (see table). Standard-deviation (s) and coefficient-of-correlation (v) calculations were performed on viable particle counts for DW1 and DW2. The standard deviation at DW1 was 416 and at DW2 it was 197; the coefficient of variation was 67 percent for DW1 and 80 percent for DW2. The counts from the downwind stations exceeded the upwind control counts in every sampling trial.

Figure 4. Effect of relative humidity and windspeed, taken separately



At the DW1 sampling station, an average of 347 coliforms per cubic meter was collected for all the trials; at DW2 the average was 90. The standard deviation of the DW1 coliform results was 222; *v* was equal to 64 percent. At the DW2 site, *s* equaled 86.90 and *v* was 71 percent.

The results of investigations of aerosol particle size are shown in figure 2. As these data indicate, both total bacterial and coliform particles were most numerous in the sizes that were collected by the third stage of the Andersen sampler (3.0-6.0 μ diameter). Particles collected on stages 2 (5.0-10.4 μ) and 4 (2.0-3.5 μ) were essentially identical at DW1. At DW2, however, more viable particles were found on stage 4. This result was to be expected since some of the large particles that would have been collected on stage 2 (5.0-10.4 μ) would have settled out before reaching DW2.

Environmental and meteorological conditions. Also as expected, the aerosol concentration of both the total bacteria and the coliforms decreased with distance from the filter. An average of all counts (fig. 3) showed that greater numbers of particles were recovered at night than during the day at all sampling locations, for both total count and *E. coli* aerosols. The slope of the lines indicates a rapid and large reduction in the counts of all organisms by the time the DW2 station is reached. If the slopes of the lines are compared, a somewhat steeper initial slope can be observed during the night. This condition is even more pronounced when the coliform counts for the day and the night are compared. It indicates that solar radiation has its greatest effects in the first few seconds of cloud travel.

Relative humidity (RH), windspeed, and temperature were measured during the course of each trial. Figure 4 illustrates the results of analysis of the effects of RH and windspeed separately as related to the numbers of aerosolized particles recovered during the trials. Two sampling stations, DW1 and DW2 at plant 1, were considered in each case.

Midrange relative humidities of 30 to 60 percent and midrange winds of from 6 to 10 miles per hour appeared to produce the highest counts immediately downwind from the trickling filter. At the DW2 location a smaller reduction in the counts obtained under the low 10 to 30 percent RH was seen, while nearly equal losses were seen at higher humidities.

The coliform counts under these same meteorological conditions followed an expected pattern. Higher humidities and windspeeds contributed to the highest counts at the DW1 site. High windspeeds appeared to have about the same effect on particle counts as mid- to high-range RH; no data on low wind speeds, however, were available. As the downwind distance increased, the higher humidities and midrange winds when taken separately seemed to produce the highest counts. In view of the data on aerosol concentration, low RH combined with low winds would probably be the condition that would preclude as much aerosol travel as possible from this type of sewage treatment facility.

To examine the effects of environmental conditions on the airborne particles, the meteorological conditions of interest were combined to determine their effect. Figure 5 illustrates the average counts obtained at the three downwind stations under conditions of high RH (defined as all RH readings over 50 percent) and low RH (less than 50 percent). The windspeeds were not plotted but were left variable.

Figure 6 is the reverse of these data; the RH is variable and two ranges of windspeed are considered. The points in both figures 5 and 6 are averages. Our analysis indicated that coliform aerosols were more adversely affected by low RH than the total bacterial aerosol as the aerosol moved downwind. This effect is shown in the wider spread of the regression lines in figure 5. The slope of the line indicates a greater adverse effect on coliform survival at the low RH condition. The total bacterial aerosol was not as sensitive as the coliform aerosol to low relative humidities.

High and low winds seem to have much less effect on both the total bacterial aerosol and the coliform aerosol than intermediate winds. The largest variation in coliform counts was noted at the DW2 site; close counts were seen at DW1 and DW2 under both levels of windspeed. The slope of the lines indicates a slight decrease in coliform counts collected under lower wind conditions at the DW2 site. When figures 5 and 6 were superimposed on one another, the slopes of the high wind line and the low humidity line for the coliform aerosols were nearly identical.

Figure 7 illustrates four combinations of windspeed and RH. At the DW1 site high RH and low winds were conducive to aerosol travel; high RH and high winds were second best. At the DW2 site the total bacteria count at high and low humidities and at high and low winds was nearly the same. High RH and both levels of windspeed produced the highest aerosol counts. Low values of RH were definitely not conducive to downwind survival of the coliform aerosol.

The effect of the ambient temperature on recoveries of total bacteria and coliform bacteria is illustrated in figure 8. Three temperature ranges were considred, and the average number of organisms recovered at the downwind stations was determined. These data indicate that greater numbers of coliforms are aerosolized at temperatures above 50° F than below. Temperature in the ranges studied seemed to have no effect on total bacteria counts.

Discussion

The results of our study show that as air travels over an operating trickling bed filter, its bacterial content is significantly increased because of aerosolization of part of the liquid sewage. This aerosol is continually produced as long as the filter is in operation, and it follows that the more filters in operation at a given plant, the greater will be the bacterial content of the air downwind of the filter complex. The majority of particles emitted were found on stages 3 and 4 of the Andersen sampler, indicating that they were $<5.0\ \mu$ in diameter and thus, according to Hatch (*4*), presented the greatest chance of being deposited in the human lung.

The numbers of both coliform and total organisms collected were considerably greater during the night at both plants. This result indicates the detrimental effect of solar radiation on viable aerosol survival, since the nighttime change in bacterial count of the liquid sewage did not ac-

Figure 5. Effect of high and low relative humidity on downwind counts, with windspeed variable

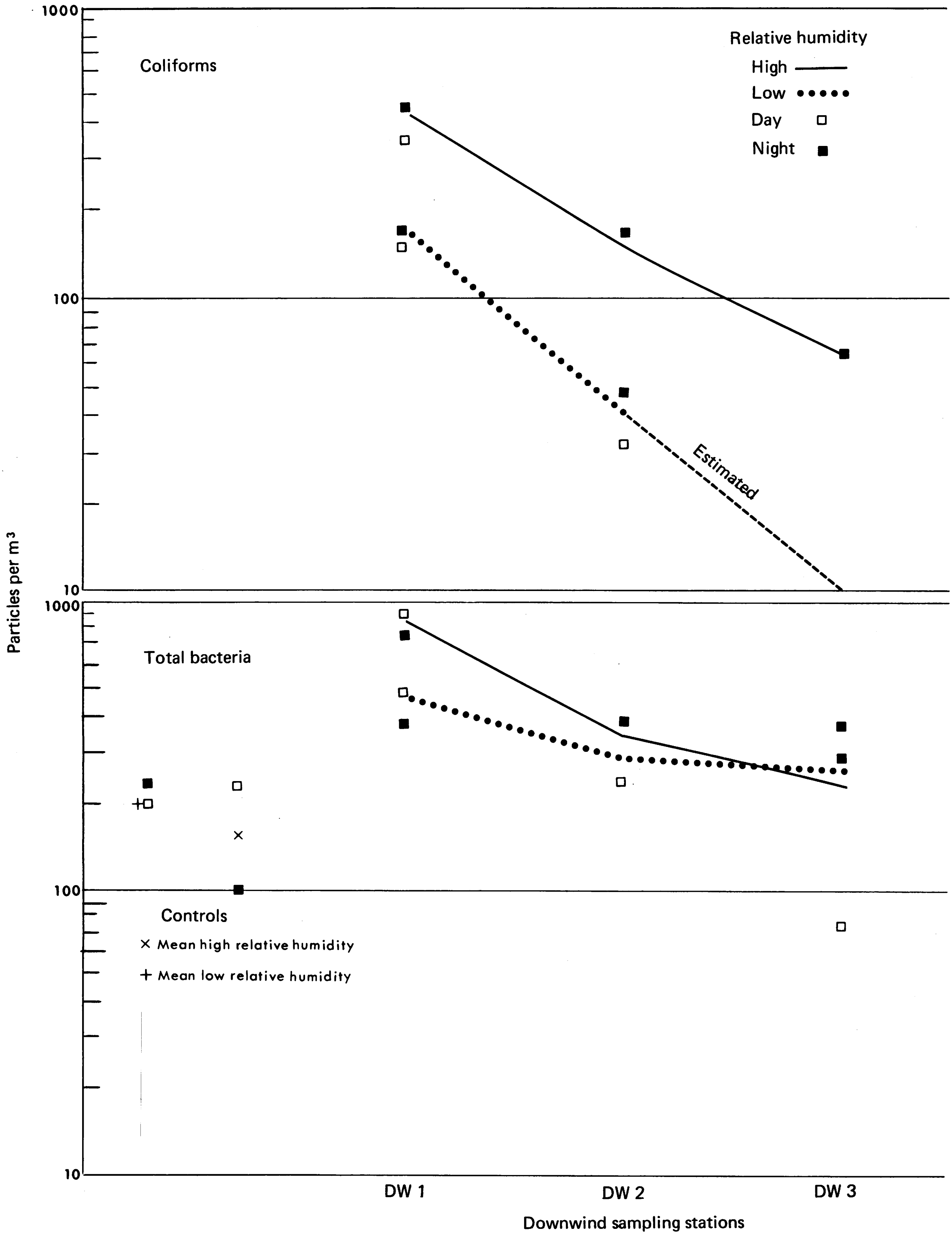


Figure 6. Effect of high and low windspeeds

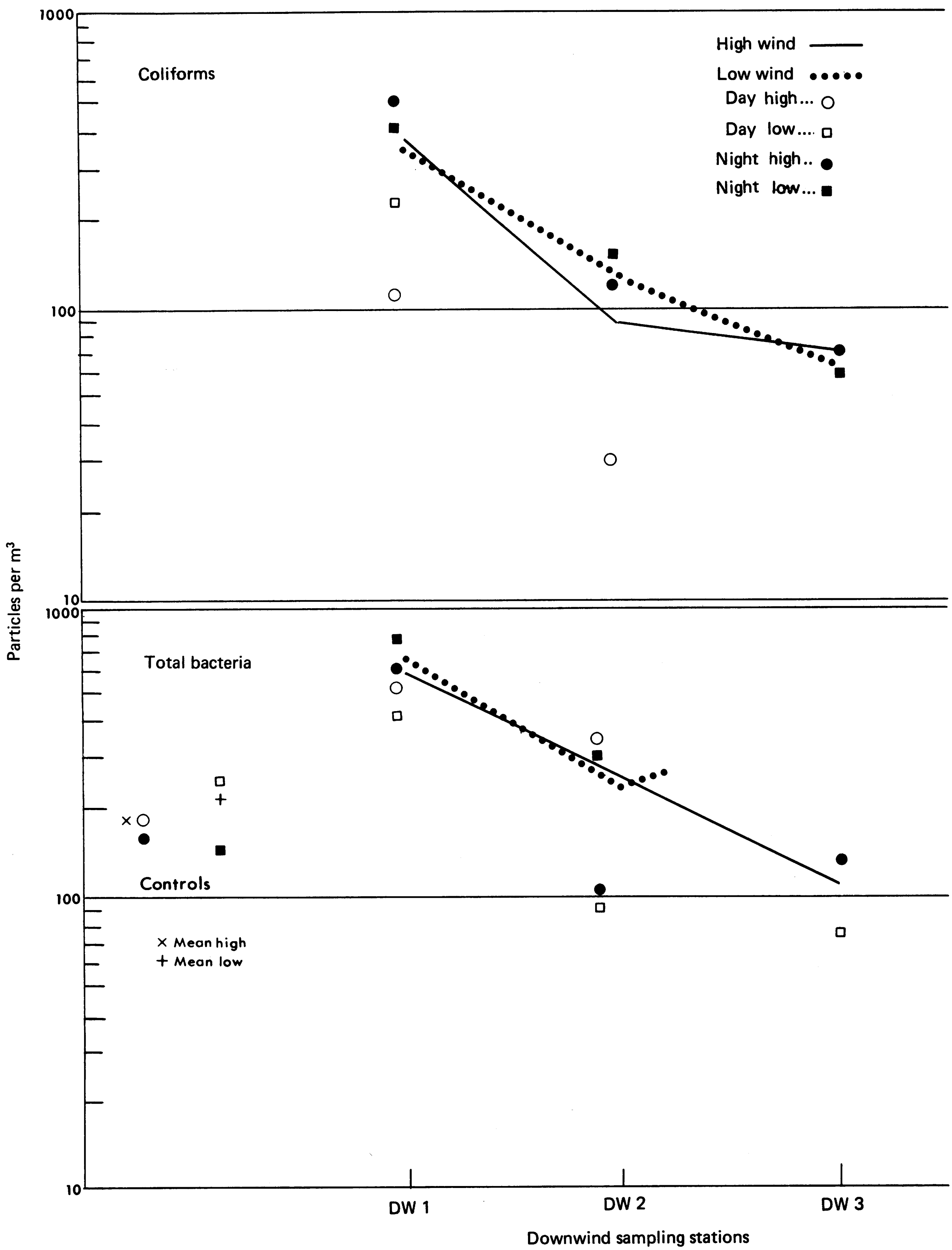
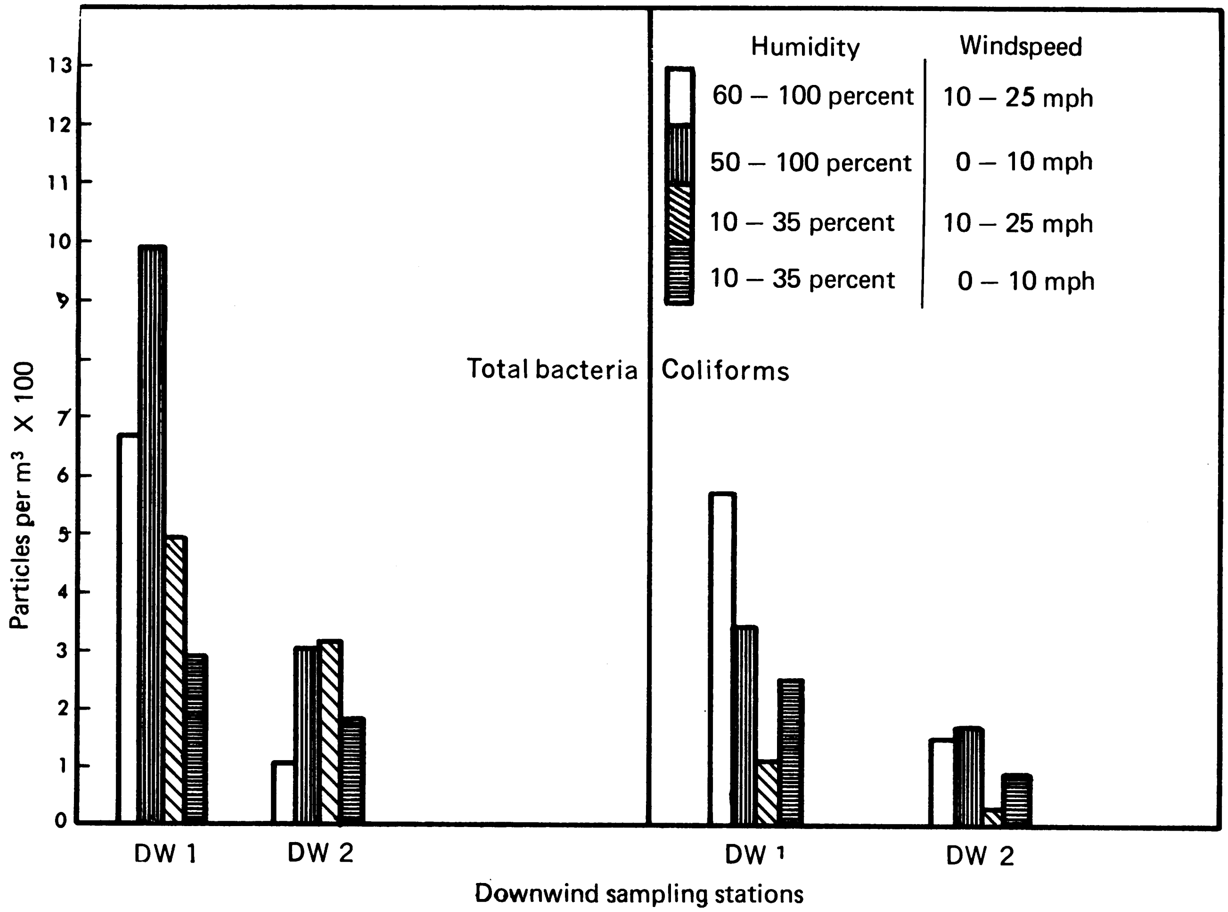


Figure 7. Effect of combinations of relative humidity and windspeed



count for this effect. Even though during daylight some of the organisms (probably spore-formers) may have survived the lethal effect of this radiation, a large number apparently were rapidly killed.

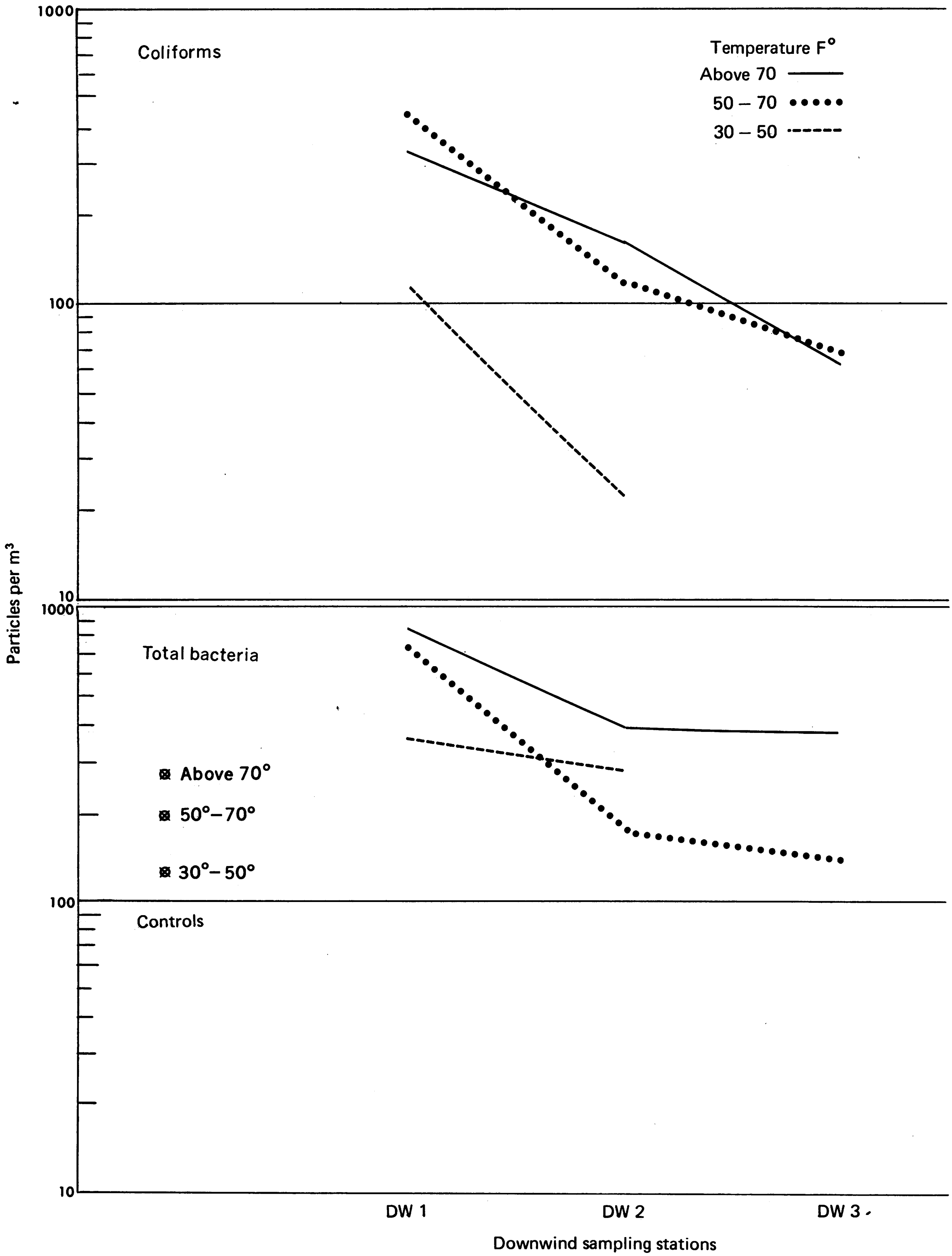
The meteorological conditions of windspeed and relative humidity were shown to directly affect the behavior of the aerosol cloud. Nevertheless, the inherent difficulty of attempting to establish the effect of a single meteorological or environmental parameter on the numbers of organisms collected is confounded by the interactions of all parameters, measured and unmeasured. Thus, the effect of individual parameters is difficult to evaluate. No direct assessment of the effect of one condition independent of all other conditions could be made.

A midrange windspeed of 6 to 10 miles per hour, however, apparently produced greater aerosol emission than did higher or lower windspeeds. The data indicate that the number of coliform particles sampled increased as the relative humidity increased. Yet this observation was only 50 percent reliable, as is seen in the coefficient of correlation of the data, which was 0.44. Our analysis showed that conditions of RH below 35 percent could be expected to produce lower counts.

The unpredictability of the uncontrollable effects of the many meteorological parameters can be reduced by combining two environmental parameters. Therefore, data on windspeed and relative humidity were combined. The coliforms behaved as expected. The rate of die-off reduced as the downwind distance increased under conditions of high humidity (above 50 percent). The nighttime counts were also higher.

Windspeed alone, with variable relative humidity, had less effect on the recovered aerosol than did the effect of RH alone. This observation held true for both the total bacterial count and coliforms. Downwind counts were, with one exception, very close, a result which indicates that at close range windspeed does not affect the counts

Figure 8. Effect of 3 temperature ranges on number of particles recovered at downwind stations



in the same manner as do other factors.

An important meteorological parameter not studied in this investigation, but which profoundly affects the behavior of aerosol clouds, is the temperature gradient during the time of sampling. Of the three gradients (neutral, lapse, and inversion), the most important as far as the aerosol cloud is concerned is inversion. Under this condition the vertical dispersion of the cloud is minimized, thus keeping the greatest concentration of the aerosol near the ground. Inversion conditions may be of a large scale in which the inversion layer extends upward to 1,000 feet or more, or they may exist on a smaller, localized scale, with the top of the layer 50 to 100 feet above ground level. Such a localized condition, coupled with other favorable meteorological conditions, tends to concentrate the aerosol cloud near the ground and keep it there for long distances downwind. Such conditions could produce unusually high numbers of airborne organisms at the human level and increase the hazard of potentially dangerous airborne microorganisms. Further investigations of airborne sewage organisms should attempt to define these conditions.

Conclusion

The extent to which microbial aerosols are emitted and travel downwind from trickling filter sewage treatment plants depends upon a number of factors that relate to the volume of sewage processed and various environmental conditions. Solar radiation, as expected, significantly reduces viable aerosol emission, as does low RH and low windspeed. Conversely, the coliform aerosol count increases with an increase in RH. Windspeeds between 6 and 10 miles per hour favor emission of microbial aerosols as compared with windspeeds above and below this range. *E. coli* may be used as an indication of the air pollution from sewage plants and other fecal sources.

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Recent interest in sources of environmental pollution, together with developments in the science of aerobiology during the past decade, have provided the technology to investigate trickling filters as a source of microbial aerosol pollution of the atmosphere. A study was undertaken to examine the effects of various environmental conditions upon the emission of *Escherichia coli* and total bacterial forms from municipal sewage treatment plants. Two typical trickling filter processing plants serving a metropolitan area were selected for the study. An attempt was made to gain information regarding the magnitude of the potential hazard as it might vary with environmental conditions.

The majority of particles emitted were found to be $<5.0\mu$ in diameter, a size presenting maximum opportunity for deposition in the lung when inhaled by man. The extent to which aerosols are emitted and travel downwind is influenced by windspeed, relative humidity (RH), solar radiation, and probably the temperature gradient. Solar radiation, as expected, was found to significantly reduce viable aerosol emission, as did low RH and low windspeed. Conversely, the coliform count increased with increased RH. Windspeeds between 6 and 10 miles per hour favored emission of aerosols, as compared with windspeeds above and below this range. Use of *E. coli* as an indicator of the air pollution from sewage plants and other fecal sources is suggested.