EPA/600/A-92/184

PROCEEDINGS

Water Quality for the New Decade

ANNUAL CONFERENCE
Philadelphia, Pennsylvania
June 23–27, 1991

Sponsored by
American Water Works Association

FOUNDED 1881

6666 W. Quincy Ave., Denver, CO 80235

MICROBIOLOGICAL CHANGES IN SOURCE WATER TREATMENT: REFLECTIONS IN DISTRIBUTION WATER QUALITY

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INTRODUCTION

Microbial barriers in treatment processes are the major block to the passage of waterborne pathogens from raw source waters. Many of the processes utilized in water supply treatment have some impact on microbial densities and survival. For instance, raw water storage for 24 to 48 hours can generally reduce the bacterial load by 50%, coagulation-sedimentation by 60% and filtration by 99.9 percent under favorable conditions. Combining these processes in a series of successive treatments can provide a cumulative reduction in waterborne organisms so that the burden on final disinfection to achieve a 6 log reduction of bacteria, 4 log reduction in virus and 3 log reduction in protozoan cysts is possible on a continuous basis. The key variable in this case is fluctuating source water quality that can impact treatment barrier effectiveness.

Treatment barrier effectiveness can also change as a consequence of operational changes at the plant. Many water utilities are seriously reviewing the need to modify treatment operations in an attempt to reduce the formation of disinfectant by-products either by reducing organic precursors or changing the type of disinfectant for less reaction products. These moves must be considered carefully because of possible adverse repercussions on treatment barrier effectiveness and ultimately on coliform compliance for the water supply, the worst case scenario being a waterborne outbreak.

FACTORING SOURCE WATER QUALITY IN DISTRIBUTION COMPLIANCE

It is obvious that without adequate treatment, there will be non-compliance problems with distribution water. Treatment needs to be designed to adequately process any given water supply with a wide margin of public health safety. Excluding those situations where filtration has been found to be an essential treatment component for Giardia control in many "protected" surface water supplies, there are other more subtle water characteristics that may degrade treatment barriers and release coliforms into the distribution system.

CHLORINE DEMAND IN SOURCE WATER

Sudden chlorine demand changes in raw source water that are not adjusted for during treatment operations may result in ineffective disinfection for some time interval, thereby providing opportunities for coliforms to pass into the distribution system. Springtime snow melt, major storms over the watershed, seasonal turnovers in impoundments, algal blooms, drought conditions and applications of agricultural fertilizers to fields in the watershed can introduce a variety of substances that exert a chlorine demand and reduce chlorine availability to treat water. Of course, immediate attention to increasing chlorine dosage is necessary but may not be applied promptly to adjust to the changing water quality. Two case histories illustrate possible scenarios that lead to coliform biofilm problems in distribution systems.

Case History No. 1: This city utility is in New York State. Most of the raw source is obtained from two lakes (Hemlock and Canadice) with a lesser amount derived from Lake Ontario. The water is chlorinated, fluoridated and gravity fed into the city's storage and distribution system. Ninety percent of the monthly turbidity averages for a recent five year period were less than 2 NTU, with a maximum monthly average of 3 NTU. However, in late winter (1986) there were periods of exceptionally heavy rains resulting in elevated turbidity and increased chlorine demand, that at times exceeded 1 mg/L. Compensating increases in chlorine applied were not promptly made to these changing source water conditions. By February, coliform occurrences started to increase substantially to the point that the coliform MCL was exceeded for two consecutive months. Coliforms had penetrated the unfiltered treatment process and within the next few months these organisms proceeded to become established in the nutrient rich pipe sediments. With onset of warm water conditions of late spring and summer, colonization was evident by releases of coliforms from the biofilm throughout the distribution network.

Case History 2: Source water for this utility is a small stream, the White River, in Indiana. Upstream of the water intake there are few municipal and industrial discharges to the river; however, the watershed is an intensive agricultural area that is the cause of spring time elevated turbidities, high bacterial counts and ammonia nitrogen concentrations from fertilizers that reach 7 mg/L. This seasonal change in raw source water created an elevated chlorine demand, as well as a troublesome taste and odor problem. In the past, the conventional treatment plant carried a combined chlorine residual throughout the treatment train and into the distribution system during this seasonal period of high ammonia levels. In this situation breakpoint chlorination had been successful. Chlorine dioxide (0.5 mg/L) was applied as a partial substitute for the normal 2 mg/L combined chlorine in past disinfection to minimize taste and odor formation. The first coliform positive samples appeared in the distribution system shortly after the seasonal application of chlorine dioxide–combined chlorine disinfectants ended and the utility was back to a detectable free chlorine residual. This situation suggested that the application of chlorine dioxide as a partial substitute for combined chlorine had not been fully effective, resulting in coliforms passing through the treatment barrier in late February or early March during the first heavy spring runoff. Subsequently the distribution system was colonized with an active biofilm that went into accelerated growth during seasonal warm water with bacterial releases into the main flow of distribution water.

RAW WATER pH SHIFTS

Seasonal changes in raw water pH may contribute to the instability of sediments coating the pipe walls. This change in sediment stability can lead to sporadic releases of coliform bacteria and other viable organisms in the attached biofilm or entrapped in the accumulation of particulate deposits.

Case History: Such a situation was created at one utility in Illinois, serving 32,000 people. Attention to a problem began when coliforms were noted to appear only during the cold water months of December to June. This winter occurrence of coliforms was unusual since most coliform biofilm release problems have been observed to take place during warm water periods. An on-site review of treatment practices and plant records indicated that there had been a pronounced shift in the Lake

Michigan source water pH during the winter. Inspection of data on raw water characteristics revealed water pH of 7.7 in summer shifted to pH 8.2 by December, followed by a rapid decline to pH 7.4 during January to March each year. The reason for these seasonal changes in water pH was thought to be related to near shore turnover of bottom water containing partially decayed vegetation debris (humic matter). Water treatment measures used to process the lake water had little impact on stabilizing the water pH, so this characteristic was passed on into the distribution system.

Implementation of recommendations to adjust the water to pH 8.3 prior to release from the plant and to add lime slowly in the process basin to form a more stable, firm coating on the pipe walls, apparently resolved the coliform occurrence problem in the following year. Successful follow-up treatment may also have been aided by the suggestion to increase the disinfectant concentration during cold water periods to compensate for the increased chlorine demand and reduced disinfectant effectiveness at near-freezing water temperatures.

COLD SOURCE WATER TEMPERATURES

Cold water temperatures have an influence on disinfectant effectiveness. At temperature of 5°C and below, inactivation of organisms by disinfectants requires a longer contact time or an increase in concentration to achieve the same kill rate as at 20°C. The problem is of particular concern for surface water supplies in northern latitudes. Since contact time is generally fixed the only method available to achieve adequate contact time (C·T) values is to increase the disinfectant concentration applied in the contact basin.

Case History: A utility experience in Alaska provided an example of this situation. In this instance, the utility is part of a military base that supplies water to two separate military communities. Surface water is generally processed by conventional treatment most of the year. However, in late autumn surface source water is passed through a rapid sand filter without the benefit of coagulation, then disinfected prior to entry into the two distribution systems.

With raw water temperatures in January and February stabilized to approximately 1 to 5°C at the intake, the applied chlorine dosage in the contact basin was not increased. As a consequence, a species of Klebsiella began to be detected in one of the distribution systems nearest to the utility and the water supply was in non-compliance for 2 to 3 months. The other distribution system, serving the second military base was not affected. This response was probably a result of the extended contact time for chlorine exposure before water arrived at the first customer location, miles further away from the treatment plant. Under winter-time conditions in northern latitudes, the applied chlorine dosage to surface source waters should be increased to achieve effective inactivation of bacteria and viruses.

TREATMENT MODIFICATIONS REFLECTED IN DISTRIBUTION WATER QUALITY

Modifications in water treatment unit processes or in their sequential placement to optimize reductions in disinfection by-product formation, must be cautiously evaluated and monitored for impact on microbial barriers and on distribution water quality. Four major treatment concepts either in pilot plant or full scale, may cause changes in microbial quality: (a) changing the point of free chlorine application;

(b) applying granular activated carbon (GAC) adsorption for organic removal; (c) use of biological activated carbon (BAC) for further reduction of dissolved organics through microbial activity; and (d) employment of alternative disinfectants (chloramines, chlorine dioxide and ozone) to reduce trihalomethane (THM) formation.

DISINFECTION - POINT-OF-APPLICATION

In the trade-off to minimize disinfection by-product formation while maintaining microbial integrity, (by moving the point of disinfection application) some migration of organisms deeper into the treatment train may occur or changes in the microbial flora of process waters will evolve. In the worst case scenario, microbial colonization of the process media materials may result in periodic releases of biofilm aggregates containing coliform bacteria into the finished water.

Case History: Changing the site for chlorine application was investigated at the Cincinnati, Ohio Water Works (Table 1) in a series of two week study periods (1). During routine treatment plant operations, chlorine was applied to the source water after 48 hours of open reservoir storage (Table 1). Adequate retention time of raw source waters is a beneficial first step in microbial population reductions through self-purification processes and can be a buffer against temporary impairment of water quality from an upstream accidental spill of industrial chemicals. In the Cincinnati water treatment operation, coagulant was added to the water as it exited the open-reservoir and chlorine was routinely applied ahead of in-plant treatment processes. In the modified treatment operation, chlorination was delayed (Table 1) until after an additional four-hour clarification process consisting of coagulation and settling.

The results of both the routine and modified treatment schemes showed that 48 hour source water storage with alum treatment reduced the total coliform densities by approximately 97 percent and turbidities by approximately 90 percent. The coagulation and settling process, however, had little effect on further turbidity reductions and further decrease in the coliform population was only approximately 50 percent when chlorination was delayed until after this process (Table 1). Moving the point of chlorination to after coagulation and settling resulted in an intrusion of coliforms into early stages of water treatment. This change placed increased importance on providing a high quality process water at this point, so that final disinfection would be effective in the inactivation of residual densities of various organisms of public health concern. Neither a measurable change in the bacterial quality of the finished water nor any apparent in-plant problems developed.

GRANULAR ACTIVATED CARBON (GAC) ADSORPTION

Carbon filtration, either in the GAC or BAC (biological activated carbon) treatment process, may provide opportunities for specialized microbial populations to become predominant, some of which may be less effectively controlled by conventional disinfection practices. This consideration, coupled with the fact that there are health risk limitations on chlorine dioxide concentration and slower inactivation rates for chloramines, make it apparent that disinfection concentration and contact time values are of critical importance.

Granular activated carbon (GAC) has been in use for many years to remove a variety of synthetic organics and naturally occurring taste and odor compounds. Optimizing removal of organics in process water to lessen disinfection product formation would suggest the GAC process be placed early in the progressive treatment of polluted surface waters. In fact, powdered carbon is often applied in source water impoundments to control taste and odor problems but is not adequate for removal of many other organic compounds (2). Obviously, the GAC filtration process cannot be applied directly to raw surface waters with significant turbidities (above 1 NTU) because silt in these raw waters quickly coats the carbon particles and rapidly reduces organic adsorption capacity. Thus, settling of raw water and chemical treatment with clarification, generally precedes the GAC process. These treatment processes also remove much of the turbidity-associated, microbial flora which include a wide range of environmental organisms, some of which are capable of aggressive colonization of GAC particles.

In the adsorption of organic substances, including those that may be trihalomethane precursors, granular activated carbon particles become focal points for bacterial nutrients and also provide suitable attachment sites for habitation. Although the portion of organic removal in the GAC process possibly attributed to biodegradation is small (compared with physical adsorption to the activated carbon surface) there is a substantial microbial population present at the water-activated carbon surface interface. This process can, therefore, be of concern in that the treatment barriers must remain effective against bacterial population densities that can include regrowth of indicator organisms and selective adaptation by some organisms known to be disinfectant resistant, opportunistic pathogens or antagonists to coliform detection.

Case History: Installation of a GAC filter adsorber on-line after chemical clarification (Figure 1) did result in an approximate 85 percent reduction in turbidity to values ranging from 0.3 to 0.9 NTU (Table 2) and also reduced the chlorine residual to virtually zero, at Jefferson Parish, Louisiana (3). The occasional wide differences in residual turbidities reflect the entrapment of coagulant particles on the GAC bed and their migration through the filter prior to backwashing. Application of chloramines to the clarified water, before passage through the GAC filter adsorber, did not result in a complete reduction of total coliforms in the influent to below the one organism per 100 mL detection level, except for the autumn 1979 period. Disinfectant concentration and contact time become more critical when chloramines are applied, since these agents are slower acting than free chlorine. Total chlorine residual data included not only the active disinfectant components but also some complexes that have no disinfection power. Consequently, a few coliforms were often found in the GAC filter adsorber effluent except during the winter period of 1979.

Moving the GAC adsorber treatment process to a point following sand filtration (Table 3) resulted in an improvement (0.1 to 0.3 NTU) of effluent turbidity. The most beneficial effect was an improvement in the bacteriological quality of the influent. Heterotrophic bacterial densities were below 75 organisms per mL and no total coliforms were found in any of the effluent samples. This water quality improvement was a result of sand filtration effectiveness and increased contact time with chloramines added after clarification. As a result of better quality influent water to the GAC adsorber, no coliforms were detected in the GAC effluent over a three year study period. However, little

difference was observed in the cyclic rise and decline of the heterotrophic bacterial population in the adsorber effluents associated with either treatment arrangements.

While granular activated carbon is often used in conventional treatment beds designed originally for sand filtration, GAC may also be used in pressure contactors. In pressure contactors, GAC bed depth is usually more than 36 inches (0.9 m) to provide the contact time necessary to remove certain classes of organics as the water is pumped through each unit. Factors to be considered were the extent of bacterial colonization in fast flowing water through a deeper GAC bed and containment in a closed cylinder.

Two aspects of microbial response in GAC contactors were explored: amplification potential for heterotrophic bacteria, including coliform persistence, and species profile for various Pseudomonas and Flavobacterium strains that could be opportunistic pathogens. Inspection of data in Figure 2 reveals that chloraminated influent source water (used as feed water through the GAC contactors in series) had standard plate counts (SPC) ranging from 4 to 170 organisms per mL. Lower maximum densities occurred during late autumn and winter cold water temperature conditions. After the influent water passed through the first GAC contactor, densities of heterotrophic bacteria increased by 3 to 4 logs and remained at these higher levels with subsequent serial passage through following contactors.

Residual coliform populations surviving the impact of source water chloramination recovered sufficiently to pass from one contactor to the next resulting in colonization and occasional release in the effluents from each contactor. Apparently, assimilable nutrients in the GAC contactors were the limiting factor that prevented a more aggressive growth of coliforms and higher densities of heterotrophic bacteria in a stepwise fashion from one contactor to another. Conversely, once the limiting density of bacteria was reached in the first contactor, there was no decline in bacterial numbers that might suggest that lower nutrient levels were available after passage of process water to the third contactor in series. From these data, it quickly becomes obvious there are a large number of other organisms present in this process water that we know little about in terms of public health significance.

Does the GAC contactor environment become a habitat for various Pseudomonas species? Periodic speciation of isolated bacteria from GAC contactor effluent water indicate that a variety of Pseudomonas species (Table 4) colonized the GAC and persisted for months in the contactor environment with recurrent or continuous releases to the process water. Occasional quantitation of these organisms over a three year period (1985 to 1987) suggested that all Pseudomonas species represented only one to two percent of the entire population of heterotrophic bacteria detected in effluent waters from GAC contactors. The extent of regrowth and density amplification of Pseudomonas species were not measurable because of numerous indeterminate high counts in the contactor effluents. However, these events appeared to increase as the water passed through contactors in series, suggesting that expanding colonization occurred as a consequence of increased inputs of accumulated organisms from the preceding contactors.

One of the areas of greatest confusion in studying the microbial ecology of GAC adsorbers has been the selection of a cultural protocol (medium, incubation time and temperature) to optimize recovery of these

organisms. In many of the pilot- and full-scale studies reported here and elsewhere in the literature, the standard plate count procedure (plate count agar (PCA), 35°C incubation for 48 hours) has been used until recent years. A comparative analysis of the same process waters by two different culture media and extended incubation time illustrates the problem (Table 5). The traditional standard plate count procedure does not adequately detect either the magnitude of bacterial growth in adsorber beds or in other process waters. These organisms need a medium with a diversity of nutrients in low concentration, such as found in the R2A agar formulation (4). Increasing the length of incubation time at a lower temperature (28°C) further enhances the recovery of a wide spectrum of organisms that may be present in GAC adsorber effluents, other stages of water treatment, finished water, and water in distribution.

ENHANCED BIOLOGICAL DEGRADATION

Many of the industrial chemical compounds found in polluted source waters and naturally occurring organics released to surface waters by decaying vegetation and algal blooms are non-biodegradable and are poorly adsorbed in GAC filtration. Since these organics may also react with disinfectants to form undesirable by-products, attention has been directed toward the conversion of these complex, refractory compounds into more readily biodegradable substances that can be adsorbed by GAC (5-8) or consumed by microorganisms established in the filter. This combined process is sometimes described as biological activated carbon (BAC) treatment (9-10), which frequently involves the use of ozone to enhance the BAC process.

Case History: A 10 gpm pilot plant (Figure 3) was constructed at the Shreveport Treatment Facility to evaluate THM precursor removal through a conventional treatment train using a "Waterboy" package plant (without disinfection) plus GAC adsorption, or with ozonation prior to GAC adsorption in a biological activated carbon (BAC) mode (27). The purpose of investigating BAC in this pilot study was to enhance the biodegradation of high levels of THM precursors in Cross Lake water, the principal water supply for Shreveport, LA. The microbiological concern was the possible loss of effective barriers to coliform penetration further into the system, so that final disinfection was the only barrier to coliform migration and elevated heterotrophic bacterial densities reaching the distribution system.

While preozonation of the process water was used primarily to convert recalcitrant organics to shorter chain carbon compounds, the process, as applied, did have some impact on bacterial population densities and profile of organisms entering the GAC filter bed (Table 6). During the cold water periods of autumn and winter, there was a 2 to 3 log reduction in the source water bacterial densities applied to BAC as compared to non-ozonated raw water. Smaller reductions were noted during warm water months and on one occasion (July 16, 1981) the ozonated influent contained 4 times the density of heterotrophic bacteria found in non-ozonated influent water. Ozonation exposure may have caused the breakup of bacterial aggregates or algal masses in the source water with a release of individual bacteria.

The biological activated carbon mode intentionally encourages greater microbial activity in the BAC bed for the purpose of assimilating much of the recalcitrant organic conversions by ozonation. While ozonation exposure initially suppressed heterotrophic bacterial densities in the

effluent released from the detention basin, there was an expected 10-fold increase in these organisms in the effluent from the second BAC contactor because of the increase in biodegradable organics created by ozonation. Coliform growth was not detected in the BAC contactors probably because the general population of other heterotrophic organisms rapidly became dominant in this environment and suppressed coliform development and detection. In both GAC and BAC treatment modes, the pilot study revealed no treatment barrier protection was provided at these latter stages of water processing. In such situations, final disinfection must be 100% effective at all times to achieve the necessary 6 log reduction of bacteria for a safe water supply.

Examination of process water examinations for coliform bacteria was also done at Shreveport, Louisiana (12) and provided evidence that total coliforms may persist in both BAC and GAC columns (Table 6). The raw source water contained 10^2 to 10^4 coliforms per 100 mL which were not completely inactivated in the pretreatment (package-plant processed) of influent waters going to the pilot plant, nor by preozonation in BAC treatment. Coliforms were also occasionally isolated from BAC treated in a similar pilot plant study conducted in Philadelphia, Pennsylvania (12). In the Philadelphia study, the river source water contained 48,000 total coliform organisms per 100 mL and pretreatment was not very effective in the inactivation of coliforms. It is important to note that the ozone concentration used was selected to obtain maximum removal of dissolved organic carbon and was not necessarily optimum for disinfection of the raw source water.

Identifying the coliform strains isolated from the GAC filter effluents revealed that Klebsiella, Enterobacter and Citrobacter were the genera involved. These organisms are the same coliforms that have been reported to predominate in biofilm growth within some water distribution systems (13). How much of a case can be made for limiting coliform occurrences in distribution systems to treatment barrier penetration by coliforms from a process water is unknown, but should not be overlooked.

The observation that profiles of bacterial groups and species in BAC effluents show a remarkable similarity to those present in GAC effluents is not surprising. The reason for the similarity in bacterial profiles is a reflection of the way BAC technology is studied in this country. Rather than extending service life of the filter to encourage development of specialized bacterial populations that are more efficient in assimilation of dissolved organics, greater reliance was placed on the carbon adsorption aspect with more frequent reactivation of the carbon media. The Shreveport pilot study (14) demonstrated that after 52 weeks of BAC operation, only microbial metabolism was responsible for removal of organics and the rate of trihalomethane formation potential was not sufficiently reduced to meet a 0.1 mg/L maximum contaminant level (MCL) for trihalomethanes.

Amplification and acclimatization of a diverse and specialized microbial population through extended service life of a BAC filter presents another concern. Under these conditions, a biofilm of specialized organisms develops through successional changes in dominant species and is similar to biologically active floc development in sewage treatment processes. While final disinfection can be effective in inactivating many of these diverse organisms, others will be resistant to applied disinfection and will pass into the distribution system. Neither the health effect significance of this diversified population of organisms entering the potable water supply nor the contribution these organisms

make to the development of biofilm in the distribution pipe network and associated reservoirs has been clearly demonstrated.

APPLICATION OF DISINFECTANT ALTERNATIVES

Another approach to minimize trihalomethane production in water treatment is the use of a disinfectant alternative to free chlorine. Preformed chloramines (chloramination), chlorine dioxide and ozone have been proposed as practical disinfectant alternatives. In addition, potassium permanganate has been suggested as a pre-oxidant for some raw source waters. Because of the desire to maintain a disinfectant residual in distribution water, chloramines and chlorine dioxide have received considerable attention. Some surface water systems are seriously considering ozonation because of its more favorable disinfection C·T values, particularly with regard to its effectiveness to oxidize recalcitrant organics and inactivate Giardia cysts. While ozone is a powerful inactivating agent for waterborne pathogens, it does not have a lasting residual to provide protection in distribution water and is known to create more assimilable organics that stimulate the growth of heterotrophic bacteria. Each alternative disinfectant candidate has specific advantages over free chlorine application but also some significant disadvantages that must be understood in the trade-off.

CHLORINE DIOXIDE

Case History No. 1: The Western Pennsylvania Water Company, Hays Mine plant presented an opportunity to study the alternative use of chlorine dioxide as the primary disinfectant (15). For this investigation, the routine practice (Table 7) was source water chlorination, potassium permanganate treatment, coagulation, settling, activated carbon filtration/adsorption and free chlorine application in the clear-well. Later, the treatment train was modified (Table 7) to inject chlorine dioxide and potassium permanganate into the source water entering the coagulation basin, with free chlorine used as a secondary disinfectant in the clearwell prior to distribution. Chlorine dioxide dosage to the source water was 1.5 mg/L and contained less than 0.1 mg/L chlorine.

Bacteriological data indicated that in the source water, 1.5 mg/L of chlorine dioxide was not as effective a disinfectant as 2.6 mg/L chlorine. During source water chlorination, mean total coliform and standard plate count densities in the activated carbon/filter adsorber influent were one per 100 mL and 50 per mL, respectively. When chlorine dioxide was the applied disinfectant prior to coagulation and settling, a disinfectant residual could not be maintained. As a result, mean bacterial densities reaching the activated carbon filter/adsorber were 43 total coliforms per 100 mL and 7,100 standard plate count organisms per mL. In-plant survivors of the total coliform population passed through the two and one-half year old granular activated carbon filter/adsorber essentially unchanged in density. In both treatment trains, the secondary application of chlorine in the clearwell was, however, an effective barrier to total coliform penetration into the distribution system.

From these data, 1.5 mg/L of chlorine dioxide was not equal to the disinfection effectiveness of free chlorine during source water disinfection. Increasing the dose of chlorine dioxide was not economically feasible and might exceed the limit of 0.5 mg/L residual chlorine dioxide, chlorite, and chlorate recommended by the U.S.

Environmental Protection Agency (14). New information on disinfection by-product formation may further reduce this total oxidant limit to 0.3 mg/L in the future.

A further modification of treatment that utilized source water disinfection with a low concentration of both disinfectants was effective in reducing the bacterial densities in the GAC filter/adsorber influent at the Hays Mine plant, although some regrowth of total coliforms and the heterotrophic bacterial population did occur in the filter/adsorber and appeared in the effluent. With the application of chlorine at the clearwell, however, the finished water met the bacteriological standard for total coliforms and a low mean standard plate count of eight organisms per mL was present.

Case History No. 2: In a similar experience, the Evansville (Indiana) water utility has been successful in substituting chlorine dioxide for chlorine as a predisinfectant to their raw source water. With an average chlorine dioxide dosage of 1.2 mg/L applied in pretreatment, total oxidants of 2.1 mg/L applied in the clearwell provided an acceptable bacteriological quality in the distribution system (16).

POTASSIUM PERMANGANATE

Potassium permanganate is most often used in the water supply utility for taste and odor control or for removal of iron and manganese (17, 18). Since it is an oxidant other applications suggested have been the disinfection of process basins (concrete, cement mortar lining, asbestos cement surfaces) and water lines after repairs (19, 20). Because potassium permanganate has a limited disinfection efficacy, (21) application in the disinfection of water lines is not as effective as use of chlorinated water (22). Nevertheless, there may be some measurable benefit achieved in using potassium permanganate as a pre-oxidant in early stages of the treatment train. In this situation the pre-oxidant may reduce growth of algae and slime bacteria in the treatment basins plus provide some abatement in the bacterial population.

Case History No. 1: St. Joseph, Missouri Water Company uses clarification, sedimentation, filtration and chlorine disinfection in the processing of Missouri River water (23). In August 1982, 1.1 mg/L potassium permanganate was applied for four weeks (Table 8) at the discharge of the clarifiers (Fig. 4), prior to entering settling basin No. 1. On the fifth week no potassium permanganate was applied so as to provide percent reduction data for settling alone. Data in this preliminary study suggest that settling produced 59% of the bacterial reduction. Application of potassium permanganate apparently accounted for an additional 40.9%. While potassium permanganate would not be satisfactory for application in final disinfection, use as a pre-oxidant early in the treatment train provides some early in-plant bacterial reductions in addition to controlling interference from algal blooms and bacterial slimes. The impact that this pre-disinfectant has on shaping the resultant microbial flora entering the distribution system is unknown.

Case History No. 2: The Davenport, Iowa Water Company processes raw water from the Mississippi River (Figure 5) using clarification, sedimentation, filtration through GAC and disinfection. In 1983, 0.61 mg/L potassium permanganate was added to control odor in the flocculator basins and keep the sedimentation basin sludge from turning septic (23).

Data collected over ten months (Table 9) indicate that the combination of pre-oxidant application and settling for 35.9 hours could provide a significant reduction in both total coliforms and the standard plate count. How much of this reduction was due to settling vs pre-oxidant contact time of 35.9 hours was not determined. The treatment approach did eliminate odor in the flocculator buildings which appeared after the discontinuance of prechlorination. The changes this pre-oxidant might have had on selective survival of bacteria and conversion of various chemical complexes to assimilable organic compounds released to the distribution system is not known.

OZONATION

Ozone has frequently been used in water supply treatment to remove taste, odor and color because many of the compounds responsible for these characteristics are unsaturated organics (24). Other uses include the removal of iron and manganese, or as a coagulant aid to reduce coagulant requirements and increase filtration rates (25, 26).

Since ozone does not react with organic residuals found in source waters for water supply to produce trihalomethanes, there is a growing interest in the use of ozone as a disinfectant. For instance, ozone is also far more effective in the inactivation of Giardia cysts than is chlorine. Unfortunately ozone residuals are quickly dissipated with a lifetime of less than an hour in most drinking water systems (26). As a result, secondary application of chlorine is necessary to provide disinfectant residual protection in the distribution system.

Treatment train application of ozone generally includes GAC filter-sorbers. Ozone exposure maximizes the breakdown of complex organics to shorter chain compounds which are then either absorbed in the GAC filter bed or degraded by the bacterial flora in a biologically activated carbon filter. The net result will be less THM precursors to react with chlorine in final disinfection. However, there is a trade-off to consider: increased bacterial densities released from the GAC contactor and increased levels of assimilable organic carbon in the finished water support seasonal regrowth of the heterotrophic bacteria in the pipe network.

IMPACT ON DISTRIBUTION SYSTEM WATER QUALITY

Major changes in source water quality, treatment modifications and operational practices are reflected in distribution water quality. The beneficial aspects of some treatment modifications may, in the long term, lead to reduced assimilable organic carbon and biofilm development in the pipe environment. However, adverse effects as a result of reduction in treatment barrier redundancies may eventually lead to biofilm colonization of pipe sections, taste and odor complaints and increased coliform occurrences. Therefore, it is essential to carefully monitor the microbial quality of water in distribution, particularly at the end of the system and in areas of slow flow where disinfectant residuals are marginal or non-existent. Several examples will help illustrate this concern.

Case History: The Cincinnati Water Works stopped chlorination of the Ohio River source water and began chlorination at the influent to the treatment plant (Table 1) on July 14, 1975, as an initial step in changing the in-plant water treatment process to control trihalomethane concentrations. Chlorination at the clearwell was used to

inactivate any residual coliform population that might have penetrated other processes in the treatment chain. With careful control of chlorine dose, point of application, and water pH, a significant decrease in trihalomethane concentration was realized. The impact that this treatment modification might have on the bacteriological quality of drinking water at the distribution system dead-ends and other slow-flow sections in the distribution network was determined from an intensive 2-year study.

With the cooperation of the Cincinnati Water Works Water Distribution Maintenance Section, samples from 32 dead-end water mains were examined on a rotating basis of eight sites per week. These sites are among a number of troublesome dead-end water mains that are flushed out each week to clear accumulated sediments and bring fresher water with free chlorine residuals into these distribution lines. Samples from these flushes were iced immediately and processed within 5 hours of collection. Analyses of 613 water samples over the 2 year period included a 10 tube, three dilution total coliform most probable number (MPN) test and a standard plate count incubated at 35°C (95°F) for 48 hours. Physical/chemical parameters measured were free chlorine residual, turbidity, water temperature, and pH.

Changes in distribution system water quality were not observed immediately on the day of the treatment change. Approximately 15 days passed before some decrease in free chlorine residual concentrations, turbidity, and pH occurred. Before the change in the point of disinfection application, increased chlorine residuals were inconsistent in limiting some coliform occurrences, probably because of sediment accumulations that resulted in an average turbidity of 20.7 NTU in these dead-end sections. The most extreme example occurred during one week in December 1974, when the total coliform density averaged 138 organisms per 100 mL in the eight samples collected from selected dead-end flushings. Once the turbidity decreased to an average of 10.1 NTU, this interference with disinfection was not apparent. Why the turbidity in the dead-ends was reduced following the treatment change is not known; the protocol and frequency of main flushing remained unchanged. Perhaps this reduction in turbidity was a result of more water flow with increased tap-ins from residential developments or it may have been a result of more stable scale formation on the pipe walls (pH shifted from 8.0 to 7.8) following treatment modifications.

After the point of chlorination was moved, a free chlorine residual concentration of at least 0.2 mg/L was effective in controlling coliform occurrences in the dead-end sections of the distribution network. When free chlorine residual concentrations declined to 0.1 mg/L or less during warm water periods, however, viable coliforms in these protected pipe habitats were detected in densities as great as 30 organisms per 100 mL. Water temperatures during these periods of low free chlorine residual concentrations fluctuated from 20 to 25°C (68 to 77°F). Sudden increases in standard plate count densities often occurred a few days to a week in advance of the appearance of coliforms in these waters. Thus, increased standard plate counts could serve as an early signal of a loss of disinfection effectiveness or other undesirable quality changes occurring in water distribution systems.

The effects that GAC or BAC treatment have on distribution water quality are largely undocumented. Several coliform species (Klebsiella, Enterobacter, and Citrobacter) have been found to colonize GAC filters, regrow during warm water periods, and discharge into the process

effluent. Carbon particles have also been detected in finished water from several water plants using powdered carbon or GAC treatment. Over 17 percent of finished water samples examined from nine water treatment facilities contained carbon particles colonized with coliform bacteria (28). These findings confirm that carbon fines provide a mechanism by which microorganisms penetrate treatment barriers and reach the distribution system. Other mechanisms that could be involved in protected transport of bacteria include aggregates or clumps of organisms from colonization sites in GAC or sand filtration and by the protected nature of particulates in water.

Case History: Another important finding was that full-scale GAC treatment (Manchester, New Hampshire) resulted in a statistically significant increase in heterotrophic bacterial densities in distribution water as compared to a similar water treatment operation (Concord, NH) that does not employ GAC (29). Furthermore, water temperature, pH, and turbidity had a positive influence on heterotrophic bacterial densities (30). These physical-chemical conditions of water are key factors that also impact disinfection effectiveness. Stability of disinfectant residuals during water distribution is important for a number of purposes; particularly to prevent colonization of surviving organisms and to disinfect contaminants that intrude into the pipe network. Microbial colonization may lead to corrosive effects in the distribution system and aesthetic changes in taste, odor, and appearance. Regrowth of potential health-related opportunistic organisms and their impact on coliform detection should not be dismissed as a trivial problem. Further, the maintenance of a disinfectant residual to the consumer's tap keeps the system clean and protects against some cross-connection contamination. The sudden disappearance of disinfectant residuals is a sensitive indication of distribution system problems. Although the maintenance of a disinfectant residual in the distribution system will not combat massive levels of external gross contamination that are detectable through odors, color and milky turbidity changes, the residual may quickly inactivate pathogens in situations that are involved with contaminants seeping into large volumes of high quality potable water (31).

Distribution system problems associated with the use of combined chlorine residual or no residual have been documented in several instances (32-34). In these cases, the use of combined chlorine is characterized by an initial satisfactory phase in which chloramine residuals are easily maintained throughout the system and bacterial counts are very low. Over a period of years, however, problems may develop including increased densities of heterotrophic bacteria, loss of chloramine residuals in the pipe network extremities, increased taste and odor complaints necessitating more frequent flushing of the system.

Where treatment modifications are highly effective in reducing the concentrations of dissolved organic compounds in water, there will be less trihalomethane production and also less bacterial regrowth because of the reduction of assimilable organic carbon in the distribution system. The reduced potential for bacterial regrowth may, however be slow to appear in many systems because of the untold years of organic accumulations in pipe sediments and tubercle material.

SUMMARY

Microbial quality in the distribution system is a reflection of raw source water characteristics, treatment process configurations and their

modifications and the physical conditions within the distribution system itself. Based on case history experiences there may at times be a microbial breakthrough that is caused by fluctuations in raw surface water turbidity, chlorine demand and water pH. These situations call for appropriate changes in operational practices to compensate for water quality degradations.

In the effort to reduce THM production, operational practices should not abandon the concept of multiple barriers nor the necessity to produce a high quality process water that can be effectively disinfected. A growing data base from many systems suggests there may be some microbial migration deeper into the treatment train while achieving better organic contaminant reductions. This situation makes disinfectant concentration and contact time values of critical importance.

Changes in water supply treatment practices to reduce the formation of disinfectant by-products must be carefully monitored for microbial breakthrough. Increases in microbial populations in finished water may lead to biofilm development in distribution pipe networks and the potential for more frequent coliform occurrences.

None of these issues are beyond control using reasonable treatment precautions by water plant operations. Due to the complex interaction of many significant variables within the treatment train, it can be reasoned that there will always be at least some biological activity in the final effluent from any treatment system, assuming traditional disinfection procedures and doses. What is required is a revised monitoring program for water treatment processes that will provide more useful microbiological information by which to fine-tune treatment effectiveness and provide better quality waters entering the distribution system.

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Table 1. # CHLORINE APPLICATION POINT STUDY
CINCINNATI, OHIO WATER WORKS

	BEFORE TREATMENT MODIFICATION SAMPLE POINT (MEAN VALUES)					AFTER TREATMENT MODIFICATION SAMPLE POINT (MEAN VALUES)				
PARAMETER	SOURCE	STORED SOURCE	COAGULATED & SETTLED	FILTERED	FINISHED	SOURCE	STORED SOURCE	COAGULATED & SETTLED	FILTERED	FINISHED
FLOW TIME, HRS.	0	48	52	52.5	55.5	0	48	52	52.5	55.5
TURBIDITY, NTU	32	1.0	1.2	0.1	0.1	14	0.80	1.1	0.07	0.06
TOTAL COLIFORM PER 100 mL	9600	200	< 1	< 1	< 1	84000	2400	1400	< 1	< 1
SPC PER mL	NR	NR	500	< 1	5	NR	NR	5500	15	< 1
pH	7.3	7.1	8.5	8.3	8.7	7.6	7.2	8.1	8.1	8.2
FREE Cl_2 RESIDUAL, mg/L	NR	NR	1.8	1.6	1.5	NR	NR	0	1.8	1.4
TOTAL Cl_2 RESIDUAL, mg/L	NR	NR	2.0	1.8	1.6	NR	NR	0	2.0	1.5

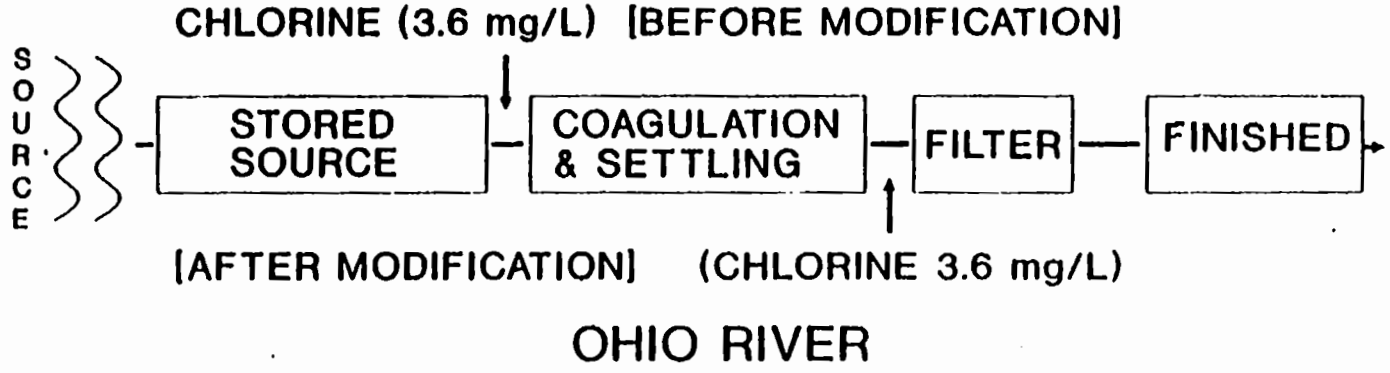


Table 2. Microbial Quality of GAC Filter Adsorber Influent and Effluent Receiving Clarified and Chlorinated Process Water*

Water Treatment Process	Year/ /Season**	Water Temp. °C	pH	Turbidity NTU	SPC per mL	Total Coliform per 100 mL	Total Chlorine Residual mg/L
Clarified & Chlorinated Processed Water (Influent to GAC filter adsorber)	1978						
	Winter	4.8	8.7	2.5	--	--	1.64
	Spring	16.1	8.5	2.0	--	--	1.62
	Summer	30.0	8.4	2.8	1,300	60.0	1.57
	Autumn	18.3	7.7	3.9	530	9.6	1.57
	1979						
	Winter	7.1	7.6	2.9	440	15.3	1.90
	Spring	20.9	7.3	2.7	120	8.3	1.45
	Summer	28.7	7.5	2.8	210	22.1	1.29
	Autumn	24.0	7.5	2.7	140	< 0.1	2.13
Filter Adsorber Effluent							
	1978						
	Winter	--	8.7	0.5	24	0.4	0.83
	Spring	--	8.4	0.3	62	2.7	0.63
	Summer	--	8.0	0.3	2,800	5.8	0.00
	Autumn	--	7.5	0.8	750	1.5	0.00
	1979						
	Winter	--	7.3	0.9	425	< 0.1	0.00
	Spring	--	7.1	0.4	2,850	6.0	0.00
	Summer	--	7.2	0.3	98	12.7	0.00
	Autumn	--	7.1	0.4	110	11.8	0.00

*Data from full scale operation, Jefferson Parish, LA.
**Seasonal geometric means based on 46 samples per season.

Table 3. Microbial Quality of GAC Filter Adsorber Influent and Effluent Receiving Sand Filter Process Water*

Water Treatment Process	Year/ /Season**	Water Temp. °C	pH	Turbidity NTU	SPC per mL	Total Coliform per 100 mL	Total Chlorine Residual mg/L
Sand Filter Process Water (Influent to Adsorber)	1977						
	Winter	10.0	10.0	0.4	10	< 0.1	1.60
	Spring	23.5	9.9	0.2	1.7	< 0.1	1.63
	Summer	30.5	9.9	0.2	10	< 0.1	1.57
	Autumn	13.0	8.7	0.9	34	< 0.1	1.70
	1978						
	Winter	4.0	8.6	0.4	10	< 0.1	1.67
	Spring	16.1	8.5	0.3	10	< 0.1	1.62
	Summer	30.0	8.4	0.4	17	< 0.1	1.53
	Autumn	18.3	7.7	0.9	33	< 0.1	1.83
	1979						
	Winter	7.1	7.5	1.1	73	< 0.1	1.90
	Spring	20.9	7.3	0.5	27	< 0.1	1.40
	Summer	28.7	7.5	0.3	26	< 0.1	1.27
	Autumn	24.0	7.4	0.5	23	< 0.1	2.17
Adsorber Effluent							
	1977						
	Winter	--	9.9	0.3	16	< 0.1	0.00
	Spring	--	9.6	0.2	96	< 0.1	0.00
	Summer	--	9.6	0.2	605	< 0.1	0.00
	Autumn	--	8.5	0.8	138	< 0.1	0.01
	1978						
	Winter	--	8.5	0.4	31	< 0.1	0.20
	Spring	--	8.1	0.3	40	< 0.1	0.00
	Summer	--	7.9	0.2	647	< 0.1	0.00
	Autumn	--	7.4	0.7	305	< 0.1	0.00
	1979						
	Winter	--	7.3	0.8	415	< 0.1	0.00
	Spring	--	7.1	0.4	2,500	< 0.1	0.00
	Summer	--	7.2	0.3	130	< 0.1	0.00
	Autumn	--	7.1	0.4	63	< 0.1	0.00

*Data from full scale operation, Jefferson Parish, LA

** Seasonal geometric means based on 46 samples per season.

Table 4.

Characterizing the *Pseudomonas* Population in GAC Contactor Effluents*

Process	Season	Maximum Density/mL SPC	Maximum Density/mL Pseudomonas	Yearly Occurrences Pseudomonas Species
Plant Influent	1986			
Chlorinated	Winter	52	22	*Ps. alcaligenes*
	Spring	100	--	*Ps. pseudoflava*
	Summer	44	>100	*Ps. pickittii*
	Autumn	53	44	*Ps. pseudoalcaligenes*
	1987			
	Winter	38	33	*Ps. maltophila*
	Spring	170	57	*Ps. paucimobilis*
	Summer	110	23	
	Autumn	23	--	
Contactor #1	1986			
Effluent	Winter	2,300	86	*Ps. pseudoflava*
	Spring	80,000	>100	*Ps. pickittii*
	Summer	53,000	>100	*Ps. pseudoalcaligenes*
	Autumn	55,000	>100	
	1987			
	Winter	130,000	>100	*Ps. mallei*
	Spring	85,000	--	*Ps. maltophilia*
	Summer	19,000	70	*Ps. paucimobilis*
	Autumn	--	--	
Contactor #2	1986			
Effluent	Winter	62,000	>100	*Ps. paucimobilis*
	Spring	27,000	>100	*Ps. pseudoflava*
	Summer	77,000	>100	*Ps. pickittii*
	Autumn	110,000	>100	
	1987			
	Winter	43,000	>100	*Ps. maltoshilia*
	Spring	22,000	73	*Ps. paucimobilis*
	Summer	--	90	
	Autumn	--	--	
Contactor #3	1986			
	Winter	64,000	>100	*Ps. maltophila*
	Spring	38,000	>100	*Ps. pickittii*
	Summer	11,000	>100	*Ps. pseudoalcaligenes*
	Autumn	95,000	>100	
	1987			
	Winter	85,000	>100	*Ps. maltophila*
	Spring	55,000	>100	
	Summer	61,000	71	
	Autumn	4,400	--	

*Data from full scale operation, Jefferson Parish, LA.

Table 5. Bacterial Populations in Water Treatment Processes Using Standard Plate Count Medium or R-2A Medium with Extended Incubation Times*
(Organisms/mL)

Sampling day	Lime-softened water			Sand filter effluent			GAC adsorber effluent		
	SPC, 2 days	SPC, 6 days	R2A, 6 days	SPC, 2 days	SPC, 6 days	R2A, 6 days	SPC, 2 days	SPC, 6 days	R2A, 6 days
Initial	120	350	510	890	1,200	1,500	< 1	140	220
7	31	202	510	820	22,000	35,000	1	24,000	95,000
14	7	7	130	< 1	1,200	9,400	< 1	600	4,400
21	7	18	150	2,200	2,500	33,000	< 1	5,200	16,000
28	3	39	530	700	7,800	67,000	1	11,000	55,000
35	< 1	490	330	100	6,000	25,000	< 1	12,000	74,000
42	70	120	1,700	1,200	71,000	22,700	N.D.	56,000	52,000
49	9	1,200	23	5,000	41,000	3,000	80	4,200	100
56	< 1	10	< 1	< 1	700	12,000	N.D.	1,900	50,000
63	29	190	170	170	2,000	3,000	N.D.	5,000	48,000

*Data revised from Symons (15). All cultures incubated at 35°C.
SPC = Standard Plate Count
N.D. = Not Done

Table 6. Heterotrophic Plate Counts and Total Coliform Densities In Pilot Water Treatment Facility, Shreveport, LA

Date	Temp	Non-Ozonated Water				Ozonated Water			
		Influent ---> GAC ---> Effluent				Influent ---> GAC ---> Effluent			
(1980)	(C^{o})	HPC	T.C.	HPC	T.C.	HPC	T.C.	HPC	T.C.
July 8	32	3,300	< 1	4,100	4	290	< 1	13,000	1
Aug 12	31	2,500	1	550	8	30	< 1	1,100	< 1
Sept 15	29	400	9	1,600	7	78	1	3,400	2
Oct 6	21	130	4	750	2	9	< 1	550	1
Nov 12	14	1,700	9	300	1	240	5	1,500	< 1
Dec 8	14	1,900	N.D.	7,600	N.D.	2	< 1	1,300	< 1
(1981)									
Jan 13	10	82	2	67	2	3	< 1	3,600	< 1
Feb 10	9	110	4	70	5	5	< 1	1,700	15
Mar 24	19	660	1	150	1	55	5	2,900	1
Apr 15	23	170	< 1	240	1	230	7	2,200	N.D.
May 14	24	300	8	130	7	200	1	4,700	28
June 24	34	550	33	140	455	870	135	2,900	80
July 16	31	700	25	160	215	2,900	81	2,400	91

Raw Lake Water Quality: 10^2 - 10^4 Total Coliform per 100 mL
HPC = Heterotrophic Plate Count per mL using soil extract agar
T.C. = Total Coliform Density per 100 mL
N.D. = No Data

Table 7. CHLORINE APPLICATION POINT STUDY
WESTERN PENNSYLVANIA WATER COMPANY

	BEFORE TREATMENT MODIFICATION SAMPLE POINT (MEAN VALUES)						AFTER TREATMENT MODIFICATION SAMPLE POINT (MEAN VALUES)					
PARAMETER	SOURCE	PLANT INFLUENT	COAGU-LATION	SETTLED	GAC FILTERED	FINISHED	SOURCE	PLANT INFLUENT	COAGU-LATION	SETTLED	GAC FILTERED	FINISHED
FLOW TIME, HRS.	0	0.5	3.75	12.5	13.5	14.8	0	0.5	3.8	12.5	13.5	14.7
TURBIDITY, NTU	51	38	5.7	8.5	0.6	0.2	6.8	5.2	6.3	2.3	0.3	0.2
TOTAL COLIFORM PER 100 mL	21000	4	1	1	8	< 1	14000	4200	100	43	44	< 1
SPC PER mL	NR	490	200	50	150	3	NR	29000	4790	7100	850	1
pH	7.2	7.1	7.3	7.1	7.2	7.1	7.1	7.1	7.5	7.4	6.9	6.8
FREE Cl_2 RESIDUAL, mg/L	NR	0.4	< 0.1	< 0.1	< 0.2	0.6	NR	< 0.1	< 0.1	< 0.1	0.1	< 0.4
TOTAL Cl_2 (ClO_2) RESIDUAL, mg/L	NR	0.8	0.4	0.3	0.2	0.8	NR	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1

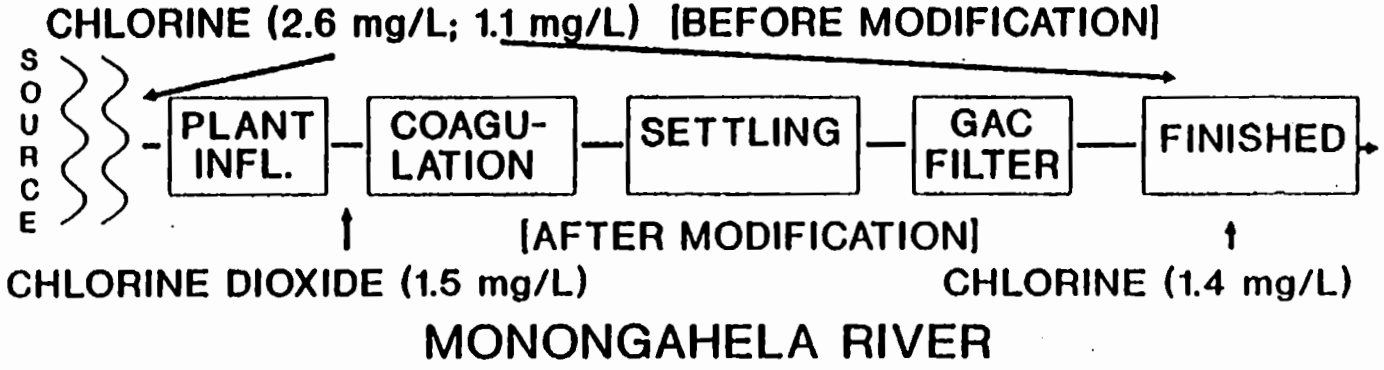


Table 8.

MONONGAHELA RIVER

Table 8.

Potassium Permanganate As A Pre-Oxidant

St. Joseph, MO Water Treatment Application*

	$KMnO_4$ 1.1 mg/L Applied			$KMnO_4$ Not Applied		
	Source**	Settling Basin #1	% Reduction	Source**	Settling Basin #1	% Reduction
Retention time (hrs)	-	8.5	-	-	10.8	-
Turbidity (NTU)	755	30	96.0	2,520	62	97.5
Total Coliform (per 100 mL)	52,000	88	99.9	87,000	35,700	59.0

Data from Blanck (23)

*Average of 4 runs (Aug. 5-10, 1982) Applied; one run (Aug. 15) as control.
**Missouri River

Table 9.

Potassium Permanganate As A Pre-Oxidant

Davenport, Iowa Water Treatment Application*

	Source**	Flocculator #2 Effluent	% Reduction
Retention time (hrs)	-	35.9	-
Turbidity (NTU)	11.8	1.9	93.9
Total Coliform (per 100 mL)	8,660	17	99.8
Standard Plate Count (per 1 mL)	7,960	1,030	99.9

Data from Blanck (23) $KMnO_4$ ↑ 0.61 mg/L Applied

*Average values for 10 months (1983)
**Mississippi River

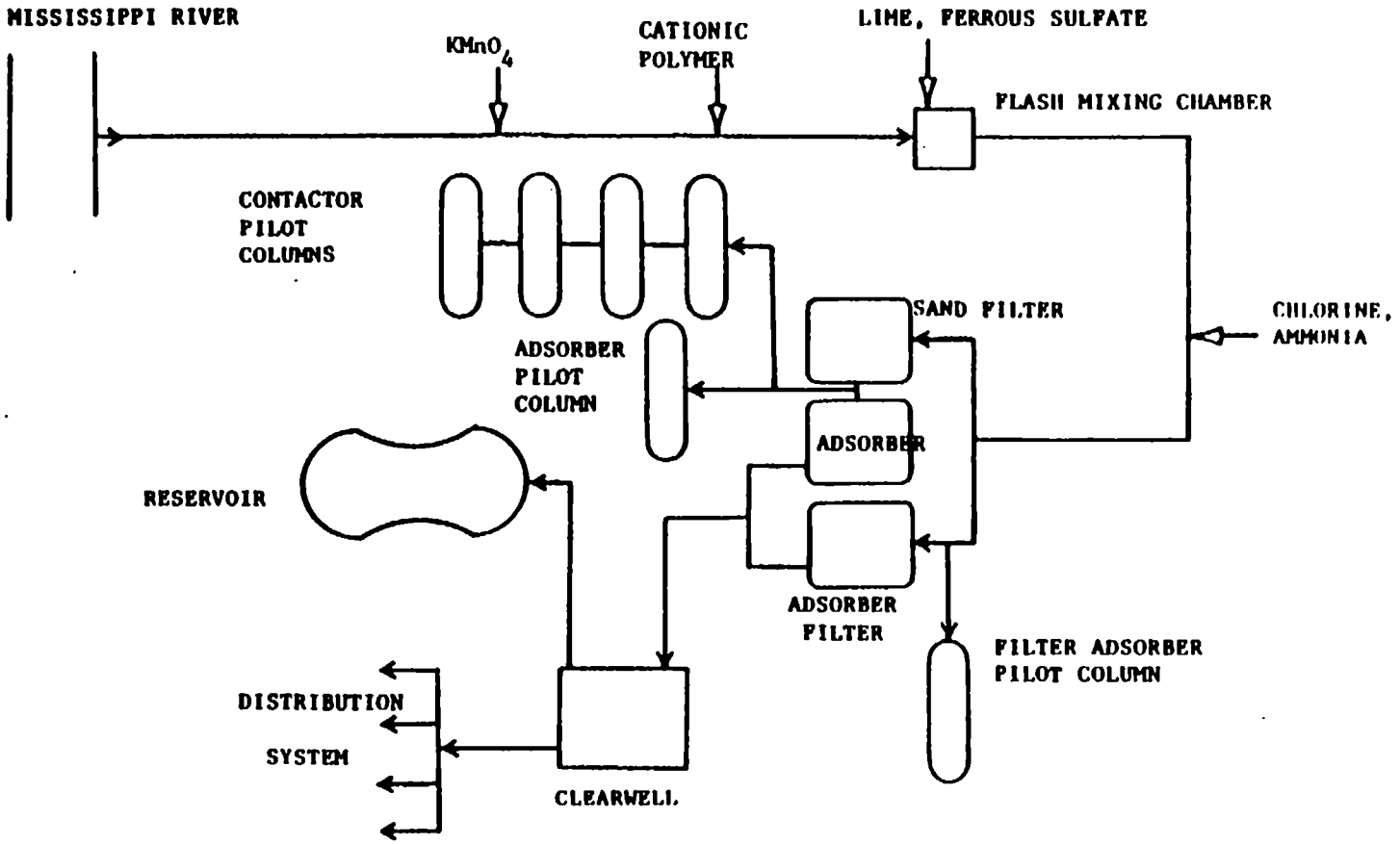


FIGURE 1. FULL-SCALE FILTER AND PILOT COLUMN FLOW CHART FOR JEFFERSON PARISH, LA.

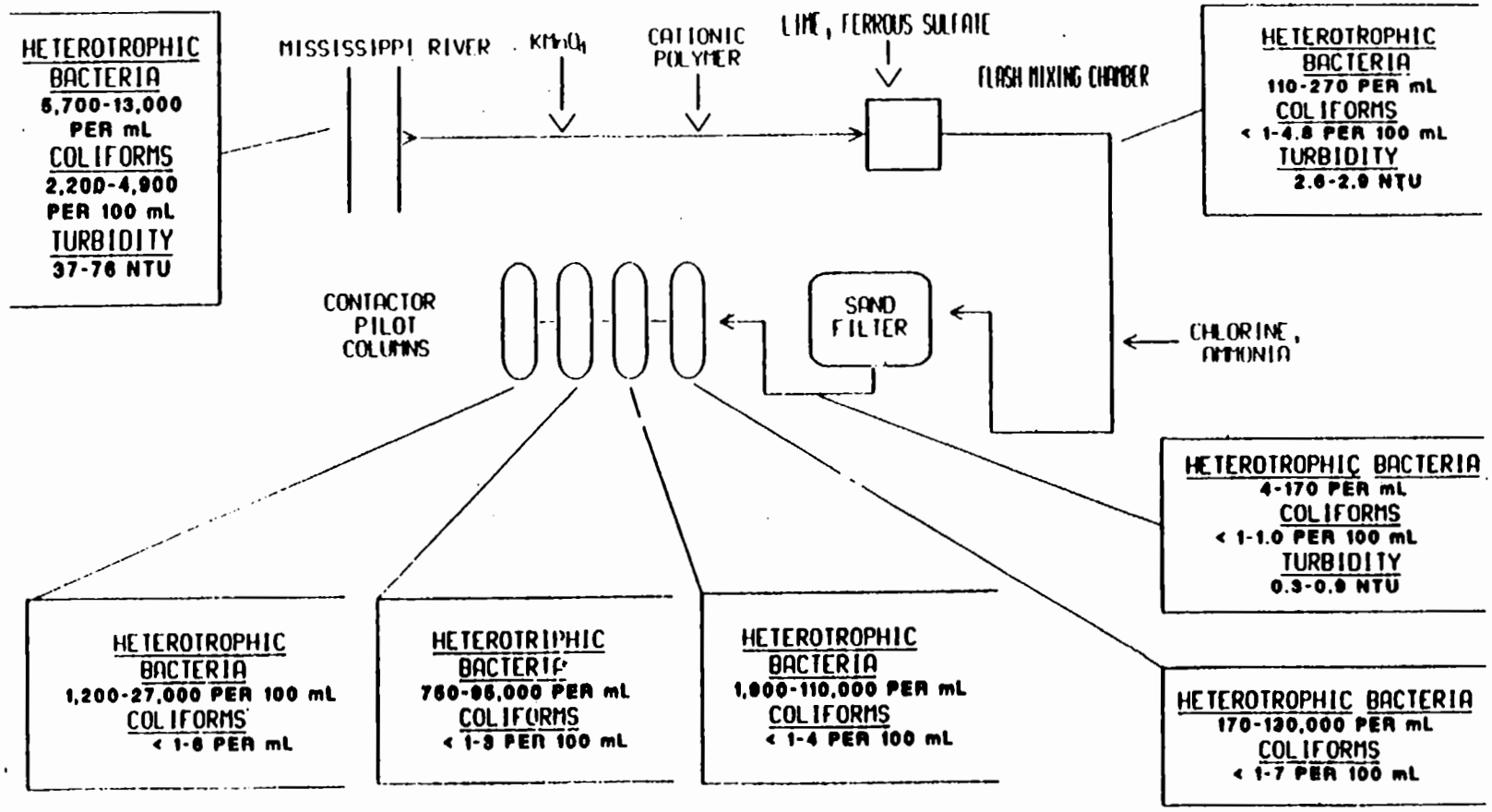


FIGURE 2. MICROBIAL QUALITY OF EFFLUENTS FROM CONTACTORS IN SERIES

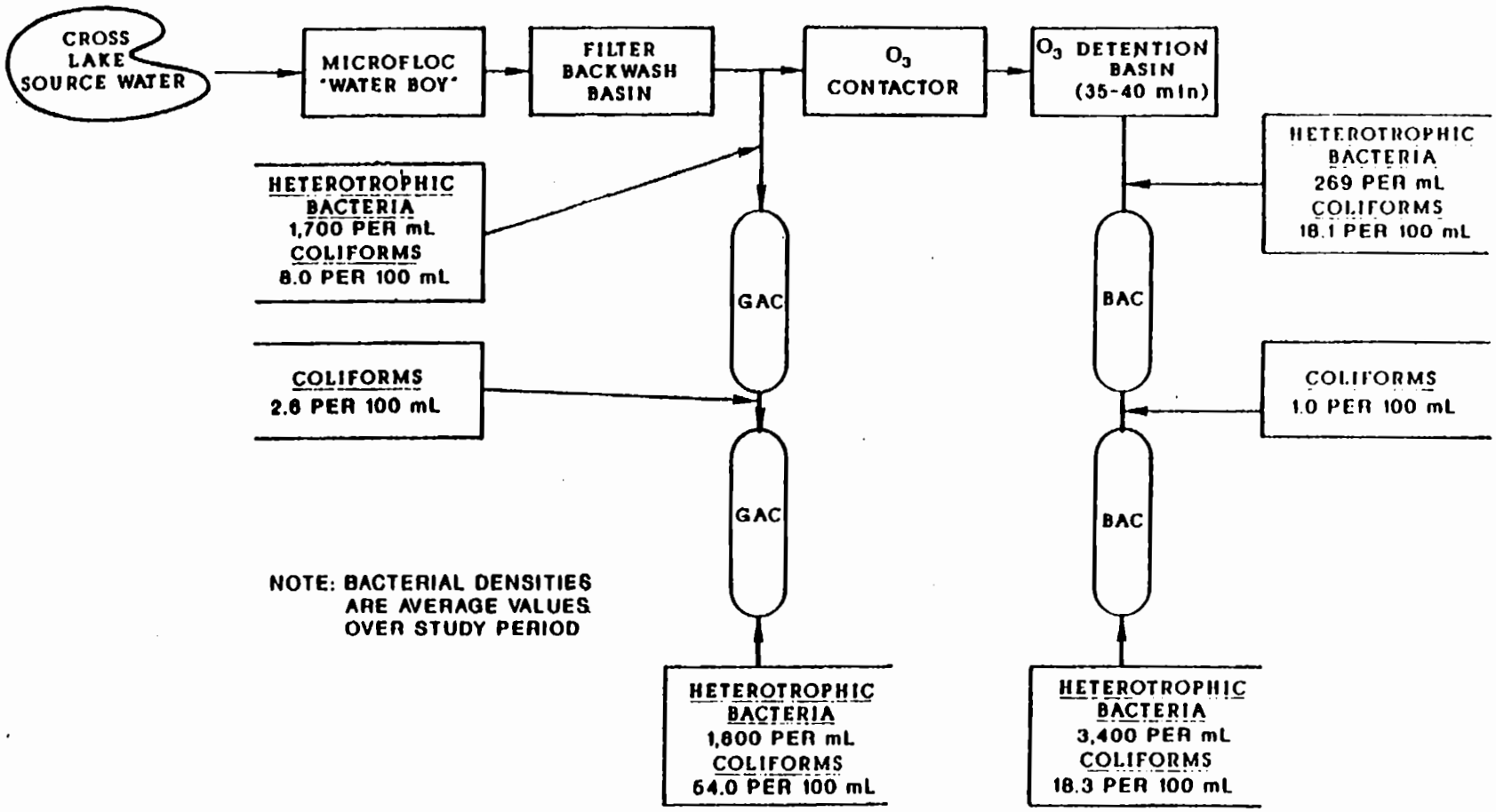


Figure 3. MICROBIAL QUALITY OF EFFLUENTS-GAC VS O_3 + GAC SHREVEPORT LA. PILOT TREATMENT FACILITY

Figure 4. ST. JOSEPH WATER COMPANY
PURIFICATION PLANT
FLOW DIAGRAM

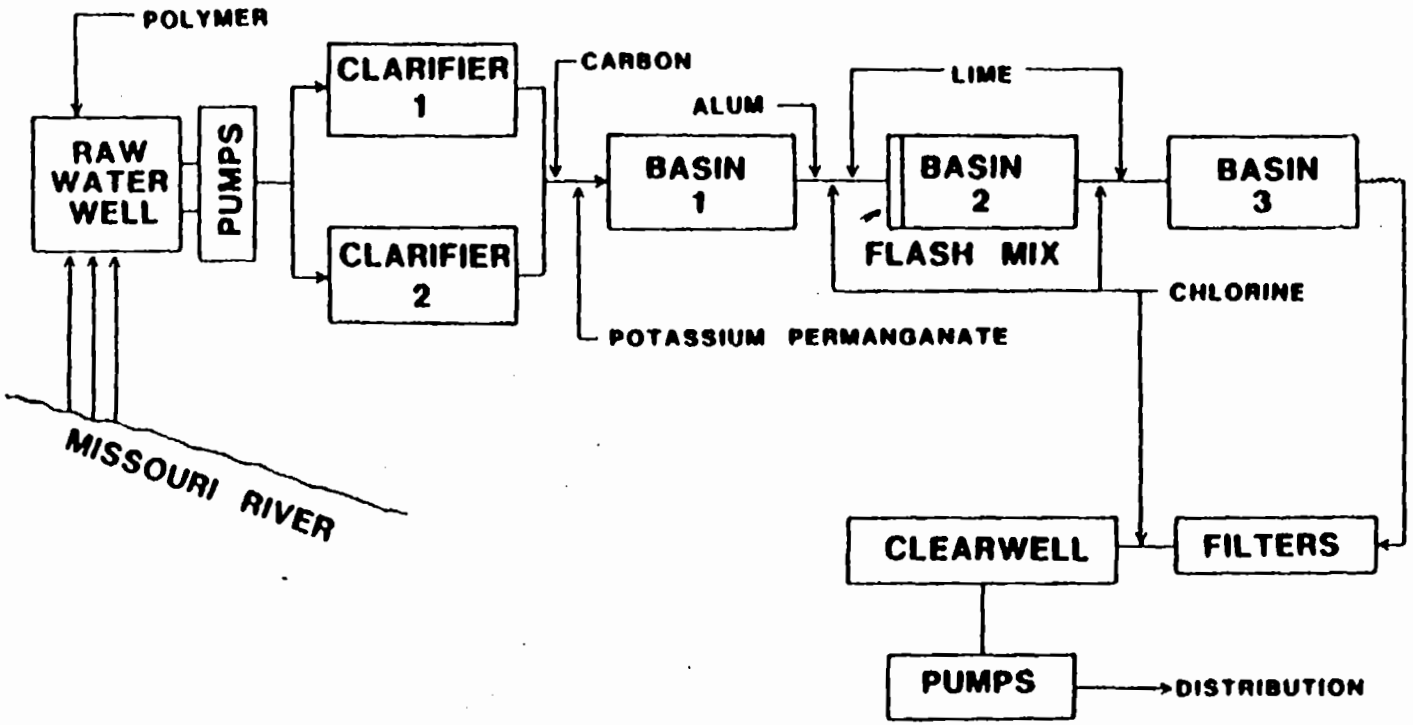
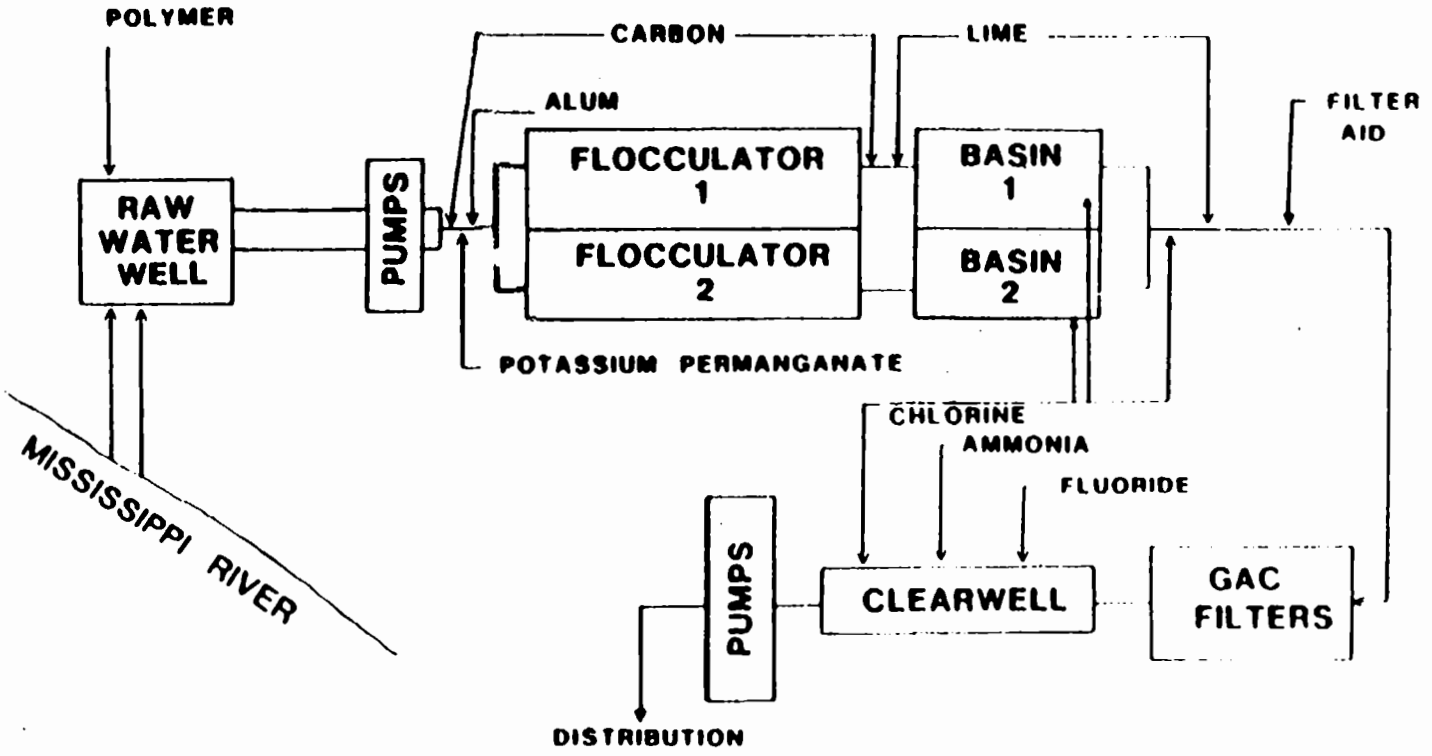


Figure 5.

DAVENPORT, IOWA FLOW DIAGRAM - EAST RIVER STATION



TECHNICAL REPORT DATA
(Please read Instructions on the reverse before complet

1. REPORT NO.	2.	3. PB92-217363
EPA/600/A-92/184		

4. TITLE AND SUBTITLE	5. REPORT DATE
Microbiological Changes in Source Water Treatment: Reflections in Distribution Water Quality	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Edwin E. Geldreich	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
U.S. Environmental Protection Agency Cincinnati, Ohio 45268	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Risk Reduction Engineering Laboratory-Cincinnati, OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, OH 45268	Published Paper 14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES Project Officer = Edwin E. Geldreich, (513)569-7232
Proceedings, Water Quality for the New Decade, Annual Conference, Philadelphia, PA, 6/23-27/91, p:107-137

16. ABSTRACT

Microbial quality in the distribution system is a reflection of raw source water characteristics, treatment process configurations and their modifications. Based on case history experiences there may at times be a microbial breakthrough that is caused by fluctuations in raw surface water turbidity, chlorine demand and water pH. These situations call for appropriate changes in operational practices to compensate for water quality degradations.

In the effort to reduce THM production, operational practices should not abandon the concept of multiple barriers nor the necessity to produce a high quality process water that can be effectively disinfected. A growing data base from many systems suggests there may be some microbial migration deeper into the treatment train while achieving better organic contaminant reductions. This situation makes disinfectant concentration and contact time (C•T) values of critical importance.

None of these issues are beyond control using reasonable treatment precautions by water plant operations. Due to the complex interaction of many significant variables within the treatment train, it can be reasoned that there will always be at least some biological activity in the final effluent from any treatment system, assuming traditional disinfection procedures and doses. What is required is a revised monitoring program for water treatment processes that will provide more useful microbiological information by which to fine-tune treatment effectiveness for better quality waters.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Microbial barriers Source water quality influence Case histories Treatment modifications Impact on water quality		

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
RELEASE TO PUBLIC	UNCLASSIFIED	33
	20. SECURITY CLASS (This page)	22. PRICE
	UNCLASSIFIED	