How Waterborne Disease Outbreaks Relate to Treatment Failures

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Summary

Persons working in jobs related to drinking water treatment need to be aware of the circumstances that can lead to waterborne outbreaks in the general population consuming tap water. Often such outbreaks are associated with not just one event but with the coincidence of a combination of problems, a single one of which might not have caused a disease outbreak. This case study reviews a number of outbreaks, demonstrating how the occurrence of two or more events or problems in the same time frame could have led to the persistence of pathogens through the treatment process and into the drinking water and thus caused the outbreak in question. Because treatment-related outbreaks tend to be associated with multiple causes, water treatment plant operation needs to be optimized at all times, especially during times of changing source water quality. In addition, those responsible for managing and operating water treatment plants need to be aware of conditions within the watershed or the recharge area of the aquifer serving as the source of water for the plant.

Keywords: Drinking water, disease outbreaks, source protection, treatment optimization

Context and Logistics

Learning Objectives

This case study will allow students to:

- gain an understanding of the interrelationships of source water quality, water treatment efficacy, and risks of transmission of waterborne pathogens; and
- understand that occurrence of multiple unfavorable changes in a matter of hours or days can result in failures in complex treatment systems for drinking water or wastewater.

Accommodating Course(s) and Level

- This case study is appropriate for students in environmental systems courses that present information on biological treatment and physical-chemical treatment concepts. It is appropriate for seniors who have studied water treatment processes or M.S. students.

Prerequisite Course(s)

- A course in hydrology would be useful, but perhaps not required. Knowledge of water treatment processes, in a prior course or earlier in the course in which this case study is presented, is required.

Type of Activity

- This would be appropriate for small groups.

Level of Effort by Instructor

- Perhaps one hour, plus time to grade papers if written assignments are given.

Level of Effort by Individual Student

- About two hours

Suggested Assessment Methods

- Review of answers to questions presented in case study.

Introduction

Among those who manage and oversee the production of drinking water using surface water sources, an important concept for provision of safe drinking water has been the use of multiple barriers including watershed protection to provide high quality source water, filtration to remove particulate contaminants, and disinfection to kill microorganisms. When watershed protection is difficult or not possible because of the size and ownership of the watershed, greater challenges may confront the filtration and disinfection barriers. For systems using groundwater, aquifer protection or wellhead protection, or both, are important factors in preventing outbreaks, along with effective treatment, which may be disinfection only.

For all water sources, monitoring raw and treated water quality is also an aspect of outbreak prevention, as monitoring provides feedback on the efficacy of treatment. In all disease outbreaks in which pathogens passed through treatment, the treatment being used, whether filtration and disinfection of surface waters, or disinfection of a groundwater, was inadequate to prevent the outbreak. Understanding the causes of treatment inadequacies is a necessary step to designing and operating water treatment facilities successfully.

Over the years, in spite of provision of treatment, waterborne disease outbreaks have taken place. This case study draws on literature in which outbreak events related to water treatment failures are analyzed, reviews a number of outbreaks and suggests factors believed to have contributed to those outbreaks, and presents guidance for avoiding outbreaks. Discussion of distribution systems is not included in the scope of this case study. Geldreich (1996) devoted one chapter to invasion of pathogens into water distribution systems in *Microbial Quality of Water Supply in Distribution Systems*. This and other information sources should be used to gain a greater understanding of outbreaks related to water distribution system problems.

Case Study

Effect of Source Water Quality Changes on Treatment

The concept that multiple circumstances contribute to disease outbreaks has been suggested by various authors (Logsdon, Budd, and Long 1996; Rose et al, 2000; Craun et al, 2001; Hrudey et al, 2002). Information on outbreaks in eight systems served by surface water treatment plants and one system using chlorinated well water was reviewed by Logsdon, Schneider, and Budd (2004).

Rose et al (2000) reviewed waterborne disease outbreaks from 1971 through 1994, and looked for an association with high total monthly precipitation. Rose et al reported that for systems using surface water sources, during all four seasons, the percentages of outbreaks that happened during the months in the highest 10 percent of precipitation totals were the following: Winter, 25%; Spring, 40%; Summer, 31%; and Fall 40%. Rose et al noted that high amounts of precipitation can affect source water quality and can lead to outbreaks. Curriero et al (2001) found a statistically significant association between outbreaks and precipitation events. They reported that 51% of outbreaks were associated with precipitation events above the 90^{th} percentile ($P = 0.002$) and 68% were associated with outbreaks above the 80th percentile (P = 0.001). For surface water supplies the association was for precipitation during the month of the outbreak.

High amounts of precipitation are likely to cause large runoff events unless the precipitation is stored as snow mass. As it travels to water bodies, runoff can mobilize contaminants, causing deterioration of the quality of rivers and reservoirs, making them more difficult to treat.

Following the May, 2000 Walkerton outbreak in Ontario (discussed later in this document) in which seven persons died and over 2300 cases of illness occurred, several persons who served in expert advisory positions for the public inquiry on the outbreak prepared a paper that discussed the lessons learned from Walkerton and other outbreaks (Hrudey et al 2002). Three of their five key observations are:

- Any sudden or extreme change in water quality, flow or environmental conditions (extreme precipitation, snowmelt, runoff or flooding) should arouse suspicion of adverse conditions that might cause drinking water contamination;
- The drinking water system must have and continuously maintain robust and resilient, multiple barriers appropriate to the level of contamination challenge to the raw water supply; and
- System operators must have an effective, continuing capacity to learn from past problems, failures and near failures so as to respond quickly and effectively to adverse monitoring signals."

In the review of outbreaks presented below, the multiple factors that may have contributed to the outbreaks are suggested.

Giardiasis Outbreaks

Information on waterborne disease outbreaks is presented in Table A and in the text below. In addition to the factors discussed below, additional factors might have been involved but were not discussed in the literature. In some cases, reviews of outbreaks did not specify if the source water was generally degraded or if it degraded just before the outbreak.

Camas, Washington was the site of a giardiasis outbreak in the spring of 1976. Quality of the surface water source was described as generally excellent by Kirner et al. (1978) who discussed a number of treatment deficiencies, including poor control of alum feed, inadequate coagulation, inadequate chlorination, and loss of some filter media in two pressure filters. Inspection of the condition of media in pressure filters is difficult, and may be neglected at some facilities. They noted that the time interval between chlorination failures and the occurrence of a majority of the giardiasis cases corresponded with the incubation period for the disease.

Kirner et al. reported that the Camas treatment plant utilized injection of pretreatment chemicals just ahead of pressure filters. Neither flocculation nor sedimentation was provided. Detention time after chemical addition was only six minutes, and occurred in the water over the media in the filter vessel. Raw water alkalinity was low (4 mg/L during the outbreak investigation), and a chemical feed point for addition of soda ash before the filters had been provided to supplement alkalinity after prechlorination and alum feed, but soda ash was applied only to finished water for pH control at the time of the investigation. The authors stated that adding soda ash to the low-alkalinity raw water was necessary for attaining effective coagulation.

An outbreak of waterborne giardiasis at Berlin, New Hampshire in 1977 involved two filtration plants; an old pressure filtration plant that employed no coagulants and a new plant employing coagulation, upflow clarification, and rapid sand filtration. Each plant was implicated in the outbreak (Lippy, 1978).

The older treatment plant was a pressure filtration plant built in 1940. It had eight filters piped in parallel without rate controllers, so clogged filters had lower rates of flow, while clean filters carried more of the flow. No provision was made for measuring flows in individual filters, so operators could not determine filtration rates for each filter. No chemical coagulants were used. Upon inspection, some of the filter beds were found to be severely disrupted, which would have resulted in localized zones of very high flows and filtration rates. Again, failure to inspect the condition of media in pressure filters seems likely to have occurred. A sampling tap was provided for only one filter, so the quality of effluent from the seven other filters could not be determined.

At this plant the combination of disrupted filter beds, no chemical coagulation, and no filtration rate measurement or rate control for individual filters, prevented effective removal of *Giardia* cysts. Failures in disinfection also were a contributing factor.

A newly constructed treatment plant treating water on the Androscoggin River was also implicated in the outbreak at Berlin. Investigation of the plant revealed presence of a construction change in a joint between the filter box wall and the concrete slab that formed the floor for the filter gullet, which served as both a collector channel for spent washwater and a filter influent water channel, and which was directly over the filter effluent channel. The original plan called for use of a sealer gasket in the joint, but this was changed to a butt joint that allowed up to 3 percent of the influent settled water from the upflow clarifiers to bypass filtration (Lippy, 1978). Lippy stated that the plant did have a number of good design features, but it was new, and some difficulties had been experienced in maintaining an acceptable sludge blanket. The plant staff had attempted to pace water production at the new treatment plant with water demand occurring in the system, causing daily increases and decreases in flow through the upflow clarifiers, which would tend to wash out some of the floc blanket during flow increases. Failure to properly develop the floc blanket could have reduced the efficiency for removal of cysts in sedimentation, causing the settled water to contain more cysts than would be found in water treated by effective sedimentation. In addition, filter backwash water was returned directly to the canal that carried plant influent from the Androscoggin River.

The combination of bypassing a small fraction of settled water, impaired sedimentation efficacy, and recycling of untreated backwash water are considered to be important contributors to the passage of *Giardia* cysts at this plant.

Waterborne outbreaks that occurred in Colorado in the early 1980's were reviewed by Karlin and Hopkins (1988). In one case, referred to as Water and Sanitation District 3, a treatment train consisting of prechlorination, sedimentation, and dual media filtration was used . Two serious problems were the failure to use any coagulant chemical and upset filter beds. The usual long detention time available in a storage tank apparently provided protection from *Giardia* cysts because the watershed had heavy human use and contained beaver dams, both potential sources of *Giardia* cysts. Problems began when a treated water pump failed and the storage tank was emptied. This reduced the chlorine contact time to the residence time for water in the plant and in distribution mains, and disinfection efficacy decreased. After the pump failure, an outbreak of giardiasis occurred. In this situation, the inadvertent reduction of chlorine contact time made the disinfection barrier inadequate, while the filtration barrier routinely had been inadequate.

McKeesport, Pennsylvania experienced a giardiasis outbreak early in 1984 at a conventional filtration plant that employed chemical coagulation, flocculation, sedimentation, and filtration (Logsdon et al, 1985). The rapid sand filtration plant was old, having been built in 1907 and 1908 (Trax, 1916), so by inference the design of this plant would have been strongly influenced by George Fuller's conventional treatment plant design with rapid sand filters operated at 2 gpm/sf. Also, filtration plants designed at the beginning of the 20th century did not have surface wash, but relied solely on backwashing to clean the media, and this plant lacked auxiliary scour for more effective media cleaning. Chemical mixing and flocculation had not been updated even though much more effective approaches to mixing and flocculation had been developed in the time since construction of the plant. Baffled hydraulic flocculation with a detention time of 20 to 30 minutes was used, and no mechanical mixer was used for rapid mix (Allegheny County Health Department, 1984). The original sand medium (probably about 0.5 mm effective size) had been replaced with 30 inches of anthracite monomedium with an effective size of 0.9 mm (Logsdon et al. 1985) even though that plant had not been designed for that kind of filter medium.

Late in December, 1983, main breaks caused water demand so high that the plant staff could not effectively backwash the filters. Filters were run for several days without backwashing, and filtered water turbidity increased to 5 nephelometric turbidity units (ntu) on December 29. An outbreak of waterborne giardiasis took place in January and early February. After the outbreak, a monitoring program (Sykora, et al. 1986) revealed presence of *Giardia* cysts in the Youghiogheny River (the source water) and in wastewater effluents in upstream communities, so routine contamination of the source water is a likely factor in this outbreak.

The combination of factors involved in this case included excessive demand for water, which put pressure on the plant to produce at maximum capacity without adequate filter washing, coupled with old facilities that did not provide for optimum chemical mixing and flocculation. Whereas the plant had been effective during normal operating conditions, the crisis situation during Christmas season of 1983 was beyond the plant's capability.

This plant was essentially obsolete, but to provide safe drinking water to the public until a new facility could be built, a number of improvements were made for the short-term (Baker, undated). These included:

- adding 6 inches of 0.45 mm effective filter sand to the filters, thus changing the anthracite filters to dual media filters;
- baffling of filter influent to reduce velocity of the influent water within the filter box and control washing out of media at the end of the filter box across the filter from the point where influent water was introduced;
- periodic supplemental agitation of fluidized media to prevent mudball formation; and
- reduced rates of filtration, because even though the plant had been designed for 2 gpm/sf, the rates could no longer be controlled (Lukas, 1988)

After a number of physical and operational improvements had been made, Baker (undated) indicated that in 1985 the filtered water turbidity had been over 0.2 ntu in 84.1% of samples with none under 0.1 ntu. In contrast, in 1987, 95.5% of samples were under 0.1 ntu and 98.8% of samples were under 0.2 ntu. By making some physical improvements and by careful operation, even a very old plant was capable of producing low filtered water turbidity, for the period of time until a new plant could be placed on line.

Cryptosporidiosis Outbreaks

Carrollton, Georgia experienced an outbreak of cryptosporidiosis in January and February, 1987, when an estimated 13,000 persons in western Georgia suffered from gastroenteritis (Hayes et al, 1989). The community was served by a conventional 8-MGD water filtration plant employing two treatment trains with alum coagulation, mechanical rapid mix (backmix), flocculation, sedimentation, and rapid sand filtration at 2 gpm/sf through a total of 10 filters having 20 inches of sand capped with 12 inches of anthracite (Logsdon et al., 1990). A review of the plant (Logsdon et al., 1990) indicated that flocculation was poor because of repairs being made to equipment at the plant. Filter headloss instrumentation was not working, so operators had no data on filter headloss. In addition, filters were removed from service and returned to use without being backwashed in numerous instances in late December and January. During the plant inspection this practice caused filtered water turbidity from one filter to reach 3 ntu about three hours after it was returned to service without being washed. The practice of placing filters back into service without backwashing was believed to have been a cause for the outbreak. Monitoring of filtered water turbidity from individual filters was possible, but it had to be done manually. Lack of on-line turbidimeters for each filter resulted in plant staff being unaware of the high turbidity caused by restarting filters without prior backwash.

In this case, the presence of *Cryptosporidium* in the source water is thought to have caused problems when weak floc resulting from inadequate pretreatment associated with process equipment changes coincided with the practice of restarting dirty filters. *Cryptosporidium* oocysts captured in the filter beds during earlier portions of the filter run could then be sloughed off the filter media and washed out of the filter into the treated water, upon restart of the filter. Such a scenario could have resulted in the delivery of concentrated slugs of the pathogen from time to time in the month of January. This concept was supported by research of Logsdon et al (1981) in which *Giardia* cysts that were previously removed in a filter run were discharged from a filter during turbidity breakthrough even though no cysts were present in the filter influent. At Carrollton, lack of monitoring data kept operators from understanding the true nature of filter performance.

During the spring of 1992, an outbreak of cryptosporidiosis occurred in the vicinity of Talent, Oregon (Leland et al, 1993). This community, with a population of about 3000, was served by a small water system having two treatment plants. One was a 1 MGD (3.8 ML/d) package plant that employed a treatment train of mechanical rapid mixing (not working), flocculation for 12 minutes, sedimentation in tube settlers at an overflow rate of 2.5 gpm/sf, and dual media filtration at 2 gpm/sf (but some rate control valves were inoperable) to treat water from Bear Creek. During the time of the outbreak the plant was using a polymer as the sole coagulant (no inorganic coagulant such as alum or ferric chloride was used) along with a filter aid polymer. Inspection by the Oregon Health Division staff revealed poor coagulation, flocculation and sedimentation. Cationic polymers can serve as primary coagulants, but in this case, metal coagulant was needed, as demonstrated when use of alum improved plant performance. Leland et al. noted that when alum and polymers were used for coagulation, the filtered water turbidity dropped to 0.15 ntu from the 0.4 ntu that had been attained by coagulation with polymer alone.

In addition to the inadequate pretreatment, Leland et al noted that on May 2, wastewater flow from a wastewater treatment plant about 5 miles upstream constituted nearly 30 percent of the flow of Bear Creek at the treatment plant. Thus at a time when pretreatment was less than adequate, the plant was challenged by very poor water quality. Also noted was a small rainstorm on April 29-30 which might have contributed contaminated runoff to the creek. This outbreak, though, does present the possibility of source water contamination during times of sustained low flow.

An outbreak of cryptosporidiosis in Milwaukee in April, 1993, was the largest waterborne disease outbreak documented in the United States since the beginning of record keeping in 1920. It has been estimated that 403,000 persons became ill (MacKenzie et al 1994). The estimated number of illnesses in this outbreak is similar to the total of estimated cases (over 466,000) for all documented waterborne outbreaks for the 73 years from 1920 through 1992 (Craun, 1986a; Craun, 1986b; Center for Disease Control, 1985; St. Louis, 1988; Levine et al, 1990; Harwaldt et al, 1992; Moore et al, 1994). Milwaukee's Howard Avenue filtration plant, implicated in the outbreak, was a 100 MGD conventional treatment plant with coagulation, 2 minutes of rapid mix, 1 hour of flocculation, 4.3 hours of sedimentation at the 100 MGD rate, and rapid sand filtration at 3 gpm/sf (Fox and Lytle, 1996). This plant had been in service for about 41 years at the time of the outbreak.

A number of factors converged to bring about problems in Milwaukee. Runoff in late March was unusually heavy. The report on the outbreak by MacKenzie et al. (1994) stated, "Rivers that were swelled by spring rains and snow runoff may have transported oocysts into Lake Michigan and from there to the intake of the MWW southern plant." Raw water turbidity was as high as 44 ntu, whereas raw water turbidity for previous months was 3 to 4 ntu (Fox and Lytle, 1996). Results for treated water also deviated from the norm. Filtered water turbidity did not exceed 0.4 ntu between January 1983 and January 1993 (MacKenzie et al, 1994), and according to Fox and Lytle (1996) filtered water typically was less than 0.1 ntu in the time frame immediately preceding March 1993. When the heavy runoff event of late March affected the source water quality at the intake in Lake Michigan, turbidity of filtered water at the plant was variable and rose to as high as 2.7 ntu, according to Fox and Lytle. These authors also noted that although filter effluent turbidimeters had been installed, they were not used, and filtered water turbidity was monitored only once per eight hours. Monitoring filtered water turbidity only three times per day does not provide operators with timely information needed to manage pretreatment and filter operation adequately, especially during times of challenging source water quality.

After many years of successfully using alum as the coagulant, the utility had switched to using polyaluminum chloride in September, 1992. The plant staff did not have extensive experience with this coagulant when the source water quality rapidly deteriorated in March, 1993. Poor quality raw water, use of a coagulant for which plant staff lacked experience in treating turbid water, and filtered water turbidities several-fold higher than normal were followed by a massive outbreak.

North Battleford, Saskatchewan was the site of an outbreak of cryptosporidiosis that affected an estimated 5,800 to 7,100 persons in the Battlefords area in March and April, 2001. This outbreak was the subject of a Commission of Inquiry in Saskatchewan (Laing, 2002). North Battleford, with a population of about 15,000, uses the North Saskatchewan River as the source of water for a surface water treatment plant (originally built about 1950) located 3.5 km (2.2 miles) downstream of the community's wastewater treatment plant , which was built subsequently in 1957. Production from this water treatment plant is supplemented by ground water from another plant.

The 10.4 ML/d (2.7 mgd) surface water treatment plant at North Battleford employed a solids contact unit with 1.6 hours of retention time at design flow, in which chemicals are added and mixed, a floc blanket forms, and settling occurs. The plant had four dual media filters, which were not equipped with effluent turbidimeters. During times of low demand, such as in the late winter and spring of 2001, the plant had been operated for as little as 6 to 8 hours per day.

On March 20 the solids contact unit was drained, and sludge was removed so the floor of the unit could be inspected. Cleaning and repair were completed that day, and the unit was returned to service that evening. Operation was for 6 to 8 hours per day from March 21 to April 25. On some days, when the plant was started, filters that had been stopped the previous day were returned to service without having been backwashed (Stanley, 2003). Based on plant records it was determined that almost no settling occurred in the solids contact unit until April 24. During this time treated water (final) turbidity exceeded 0.5 ntu on nine days.

Attempting to operate a solids contact unit in an on-off mode is inadvisable. Maintaining a floc blanket requires continuous operation. When settling is not effective, a conventional treatment train really is operating in a mode more like direct filtration, with filtration being the only effective physical barrier to passage of microbes. Restarting dirty filters is a risky operating procedure and can lead to turbidity breakthrough at the start of a run. The combination of ineffective treatment plus a wastewater treatment plant discharge only 3.5 km (2.2 miles) upstream on the same side of the river led to serious problems. Siting a wastewater treatment plant outfall a relatively short distance upstream of an existing water treatment plant intake is poor environmental engineering practice.

Acute Gastrointestinal Illness Outbreaks

In May, 2000 seven persons died and over 2300 became ill in a waterborne outbreak in Walkerton, Ontario, which was caused by *E. coli* O157:H7 and *Campylobacter jejuni* (O'Connor, 2002). Walkerton used ground water from three wells with one, Well 5, under the influence of surface water. Chlorination was insufficient to maintain a residual when contamination occurred, and monitoring was not done frequently enough to reveal a problem with the well water. In addition, operators did not correctly report chlorine residuals or locations where residual measurements were made in some instances.

This outbreak occurred after cattle manure had been spread in late April at a farm near Well 5, following agricultural best management practices for manure handling. On April 22-23, 70 tons of manure (the Walkerton report does not specify metric or U.S. units) was spread on farm land at a rate of 12 to 13 tons/ha (9,700 to 10,700 pounds/acre or 0.22 to 0.25 pound/sf). The manure was disked in to a depth of about 7 cm (3 inches).

Rainfall at Walkerton was heavy from May 8 through 12, when 13.4 cm (5.3 inches) fell in five days. The casing for Well 5 extended only 5 m (16 feet) below the surface of the ground, and highly fractured bedrock was under the soil. Water withdrawn from the well came from a zone between 5.4 and 7.7 m below the surface. The design of the well did not prevent surface water from entering the well, and with an inadequate chlorine residual, the bacteria penetrated into the distribution system.

O'Connor (2002) concluded that if continuous chlorine residual monitors had been in place, corrective action could have been taken before severe contamination of the distribution system occurred. This system had a history of using inadequate chlorination, but the absence of highly contaminated runoff in the well water must have helped Walkerton avoid an outbreak before May, 2000. Inadequate chlorination, inadequate monitoring of chlorine residuals, and construction of the well were factors contributing to the outbreak.

A number of factors contributed to the delay in ascertaining the cause of the outbreak at Walkerton. On two successive days in May the operating staff falsely assured the Bruce-Grey-Owen Sound Health Unit that the water was safe (O'Connor, 2002). In addition, the Province of Ontario did not have a legal requirement for prompt reporting of adverse drinking water sample results to health authorities and regulatory authorities. If the Health Unit had been in possession of those adverse sample results, they would not have been misled by the false assurances that no problems were occurring with the community water supply.

Conclusion

Increased care in plant operations can make a major contribution to reducing the occurrence of waterborne outbreaks. By recognizing that changes in raw water quality, treated water quality, and operating modes that depart from the norm can signal the potential for occurrence of serious problems, and by striving to maintain consistent treated water quality at all times, water treatment plant managers and operators can maximize the protection against waterborne outbreaks. Water systems that use ground water need to clearly understand the nature of their source water and the extent to which it is protected from contamination by surface water. Design engineers can enhance the ability of plant operators to cope with difficult treatment situations by providing for operational flexibility and comprehensive plant performance monitoring capability at water treatment plants.

Supporting Information

Reports of waterborne outbreaks that have occurred in the United States are typically brief journal papers or other documents of limited length. In contrast the Canadian reports of inquiries in Walkerton and North Saskatchewan (listed in the references) are hundreds of pages long and very detailed, and are recommended for those who seek in-depth information on waterborne outbreaks.

Answers to questions in the next section are provided to instructors as supporting information.

Questions

1. What is the multiple barrier approach to providing safe drinking water?

2. Why are multiple barriers recommended for drinking water acquisition and treatment?

3. List the bacterial, viral and protozoan pathogens that may cause gastrointestinal illness in humans.

4. What are some factors that can lead to ineffective water treatment and disease outbreaks?

5. How can the following changes in source water quality affect water treatment efficacy?
    a. Increased turbidity
    b. Change of alkalinity or pH or both
    c. Increase of dissolved organic carbon
    d. Decreased temperature

6. What water quality parameters and plant performance monitoring data can be obtained to help operators understand the need for treatment and the efficacy of treatment?

7. Explain the merits of designing water treatment facilities for extra operational flexibility.

8. Explain the merits of designing water treatment facilities with comprehensive performance monitoring capabilities.

9. How might the concept of multiple adverse changes in the quality of treatment plant influent and in process operations lead to failure in a wastewater treatment plant?

Analysis

Circumstances surrounding numerous waterborne outbreaks caused by problems related to water treatment indicate that in order for an outbreak to happen, more than one problem or change of circumstances may be occurring in a given time frame. Factors increasing the risks of outbreak include:

- Degraded source water quality
    - Quality is always poor
    - A good quality source water degrades due to runoff or contamination
- Filtered water quality degrades
    - Excessive filter ripening or initial improvement time
    - Turbidity too high after ripening
    - Turbidity breakthrough event occurs
- Disinfection is inadequate
- On-off operation of water treatment processes
    - Floc in sludge blanket clarifiers may settle to bottom and fail to resuspend on restart
    - Restarting dirty filters instead of backwashing before restart can result in discharge of floc stored in filter bed during prior filter run

Combinations of the above factors can lead to outbreaks. For example, if raw water quality is always poor, then a failure of treatment can bring about an outbreak. If raw water quality is normally very good, a water system may employ ineffective treatment without a resulting outbreak, but if quality deteriorates, then an outbreak could follow.

This suggests that to maximize public health protection, water systems should monitor source water quality diligently. Water system staff needs to be aware of sources of contamination in the watershed. Examples include wastewater treatment plant outfalls, combined sewer overflow points, sanitary sewer overflows, and farm animal waste sources.

Plant operators must diligently monitor source water quality, pretreatment chemistry, treated water quality, and filter performance; and should optimize treatment at all times. This is especially crucial when raw water quality worsens. Runoff events caused by heavy rainfall or snowmelt can raise not only the turbidity but also the concentration of natural organic matter in source water. Runoff events also have the potential to alter pH and alkalinity in source water. Increases in natural organic matter and changes in pH and alkalinity can necessitate changes in coagulation practice. Bench-scale or pilot plant testing may be needed to identify appropriate pretreatment chemistry. Failure to ensure that coagulation chemistry is appropriate after changes in source water quality occur may lead to inadequate coagulation and increased risk of passage of pathogens into finished water, especially if disinfection is inadequate.

Because of the heightened risk involved in times of changing source water or changing treated water quality, treatment plant operators should be particularly diligent to detect deviations from normal operating conditions. A deterioration of source water quality should signal the need for special care in treatment plant operations. Treatment plant problems should not be allowed to continue after they have been detected. A deterioration of treated water quality at the treatment plant should be cause for immediate, careful, and informed remedial measures.

Filtered water turbidity is one measure of the adequacy of coagulation and filtration. A goal of 0.1 ntu for filtered water turbidity has been advocated by the Partnership for Safe water. While a turbidity goal of 0.1 ntu or less has already been used by numerous utilities and is reasonably attainable, such a goal may require refinements in operation and possible upgrade of facilities at some locations. Physical improvements may be required to upgrade some facilities, but optimization of chemical coagulation will be critical for almost all locations. The availability of new coagulants and coagulant aids may offer opportunity for improvement in some cases, while optimization of chemical dose and pH conditions for the existing coagulant may be appropriate in other cases.

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