7. IMPORTANCE OF TURBIDITY

7.1 Overview

Section 2 of this guidance manual is included to present an overview on the definition and sources of turbidity. Understanding turbidity, its causes and sources, and the significance to human health will provide the background on which the new turbidity standards are based.

7.2 Turbidity: Definition, Causes, and History as a Water Quality Parameter

Turbidity is a principal physical characteristic of water and is an expression of the optical property that causes light to be scattered and absorbed by particles and molecules rather than transmitted in straight lines through a water sample. It is caused by suspended matter or impurities that interfere with the clarity of the water. These impurities may include clay, silt, finely divided inorganic and organic matter, soluble colored organic compounds, and plankton and other microscopic organisms. Typical sources of turbidity in drinking water include the following (see Figure 7-1):

- Waste discharges;
- Runoff from watersheds, especially those that are disturbed or eroding;
- Algae or aquatic weeds and products of their breakdown in water reservoirs, rivers, or lakes;
- Humic acids and other organic compounds resulting from decay of plants, leaves, etc. in water sources; and
- High iron concentrations which give waters a rust-red coloration (mainly in ground water and ground water under the direct influence of surface water).
- Air bubbles and particles from the treatment process (e.g., hydroxides, lime softening)

Simply stated, turbidity is the measure of relative clarity of a liquid. Clarity is important when producing drinking water for human consumption and in many manufacturing uses. Once considered as a mostly aesthetic characteristic of drinking water, significant evidence exists that controlling turbidity is a competent safeguard against pathogens in drinking water.

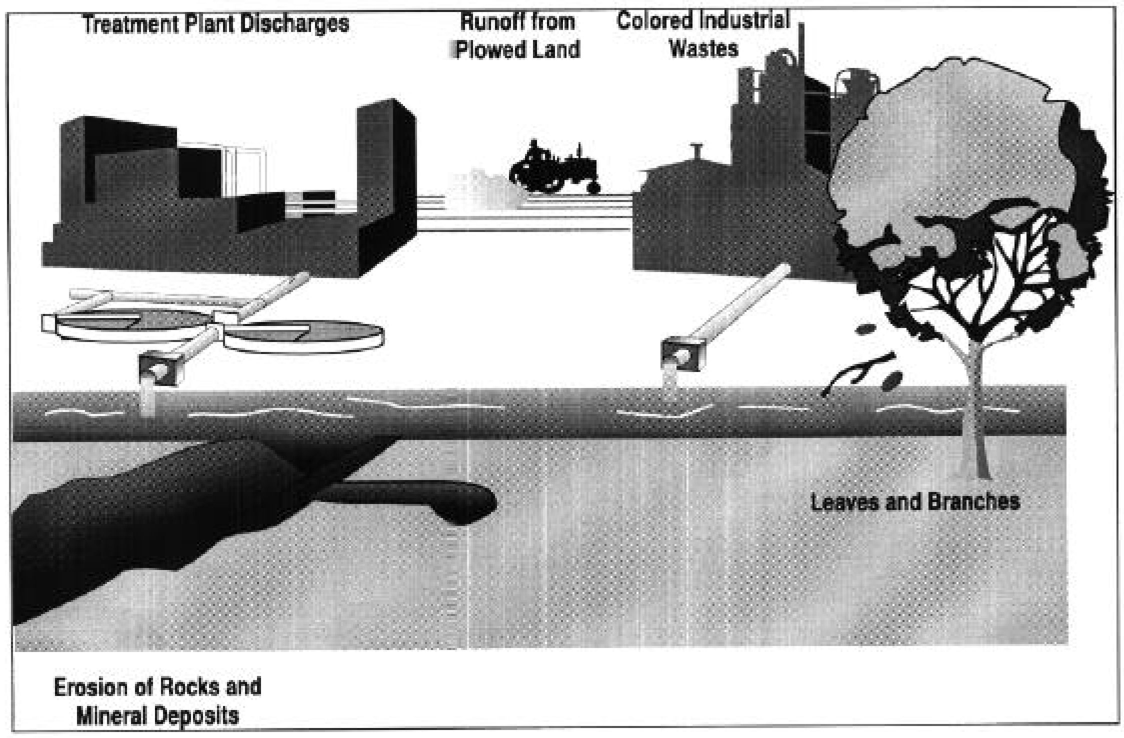
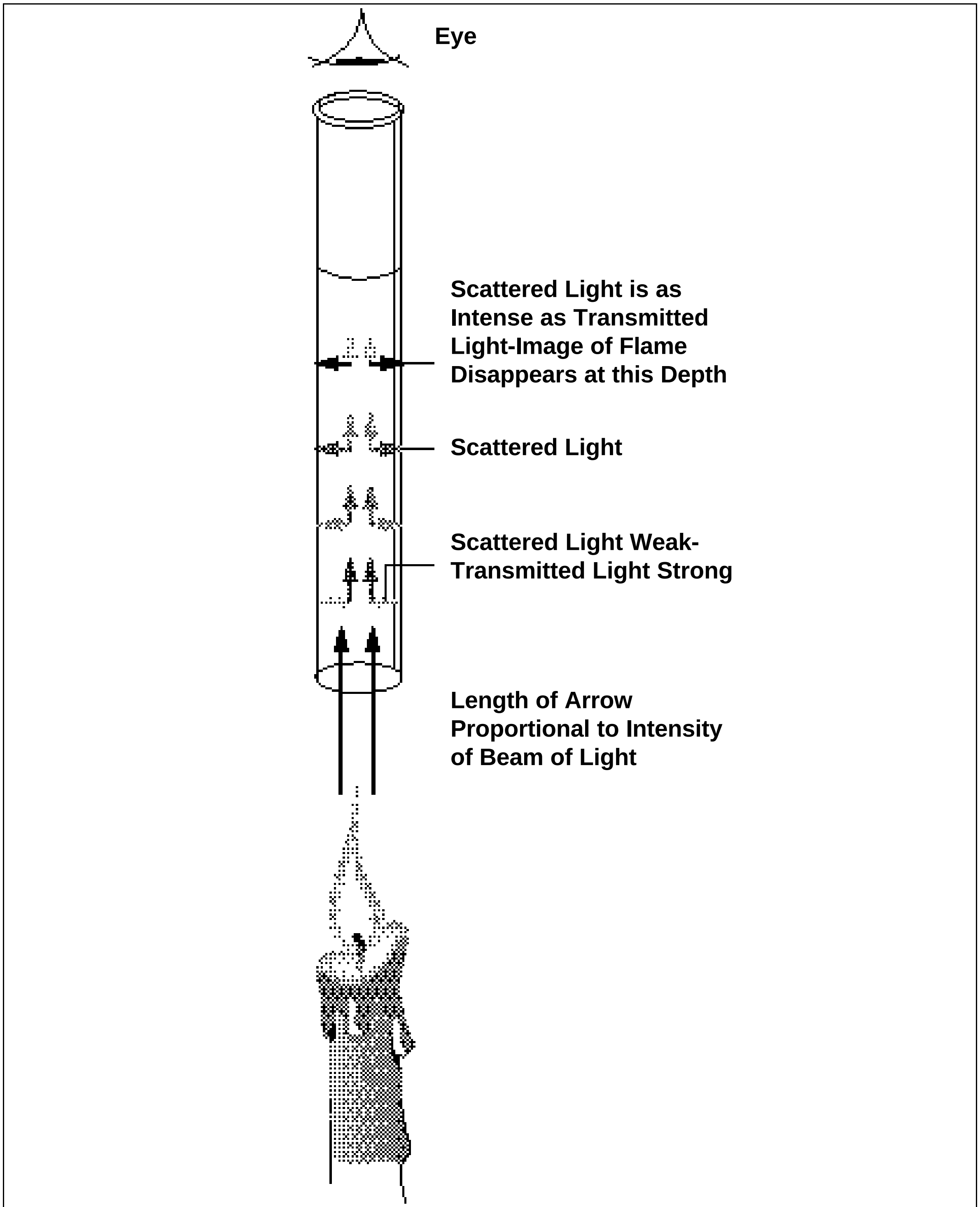


Figure 7-1. Typical Sources of Turbidity in Drinking Water

The first practical attempts to quantify turbidity date to 1900 when Whipple and Jackson developed a standard suspension fluid using 1,000 parts per million (ppm) of diatomaceous earth in distilled water (Sadar, 1996). Dilution of this reference suspension resulted in a series of standard suspensions, which were then used to derive a ppm-silica scale for calibrating turbidimeters.

The standard method for determination of turbidity is based on the Jackson candle turbidimeter, an application of Whipple and Jackson's ppm-silica scale (Sadar, 1996). The Jackson candle turbidimeter consists of a special candle and a flat-bottomed glass tube (Figure 7-2), and was calibrated by Jackson in graduations equivalent to ppm of suspended silica turbidity. A water sample is poured into the tube until the visual image of the candle flame, as viewed from the top of the tube, is diffused to a uniform glow. When the intensity of the scattered light equals that of the transmitted light, the image disappears; the depth of the sample in the tube is read against the ppm-silica scale, and turbidity was measured in Jackson turbidity units (JTU). Standards were prepared from materials found in nature, such as Fuller's earth, kaolin, and bed sediment, making consistency in formulation difficult to achieve.



Source: Sadar, 1996.

Figure 7-2. Jackson Candle Turbidimeter

In 1926, Kingsbury and Clark discovered formazin, which is formulated completely of traceable raw materials and drastically improved the consistency in standards formulation. Formazin is a suitable suspension for turbidity standards when prepared accurately by weighing and dissolving 5.00 grams of hydrazine sulfate and 50.0 grams of hexamethylenetetramine in one liter of distilled water. The solution develops a white hue after standing at 25°C for 48 hours. A new unit of turbidity measurement was adopted called formazin turbidity units (FTU).

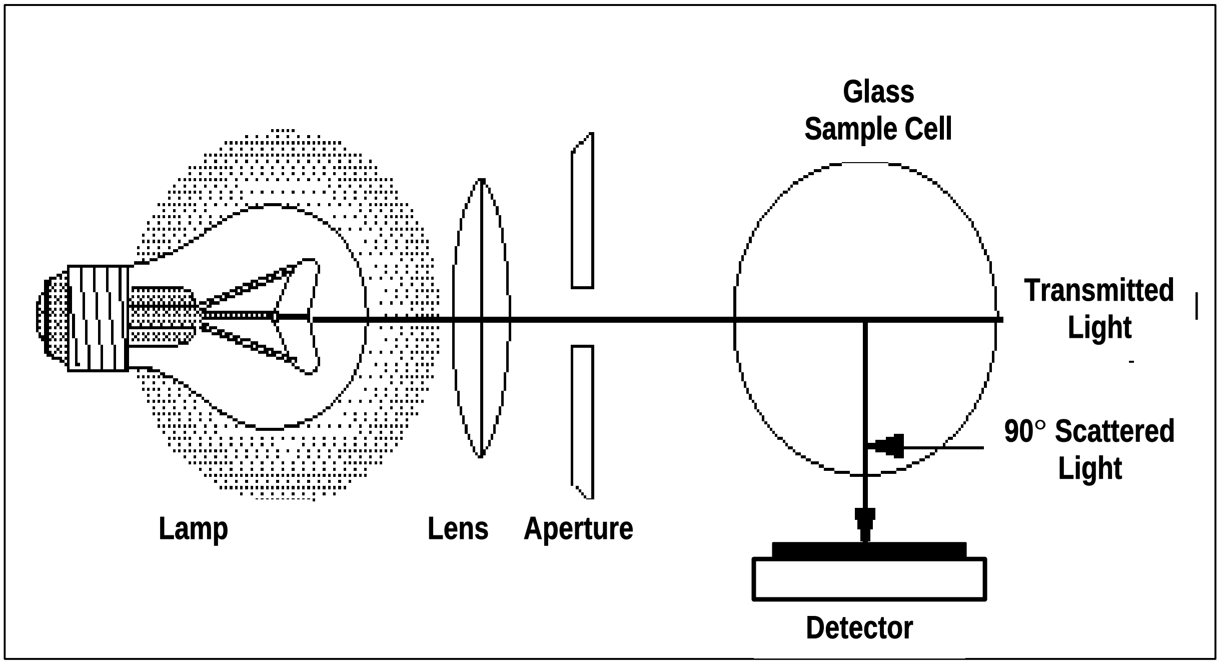
Even though the consistency of formazin improved the accuracy of the Jackson Candle Turbidimeter, it was still limited in its ability to measure extremely high or low turbidity. More precise measurements of very low turbidity were needed to define turbidity in samples containing fine solids. The Jackson Candle Turbidimeter is impractical for this because the lowest turbidity value on this instrument is 25 JTU. The method is also cumbersome and too dependent on human judgement to determine the exact extinction point.

Indirect secondary methods were developed to estimate turbidity. Several visual extinction turbidimeters were developed with improved light sources and comparison techniques, but all were still dependent of human judgement. Photoelectric detectors became popular since they are sensitive to very small changes in light intensity. These methods provided much better precision under certain conditions, but were still limited in ability to measure extremely high or low turbidities.

Finally, turbidity measurement standards changed in the 1970's when the nephelometric turbidimeter, or nephelometer, was developed which determines turbidity by the light scattered at an angle of 90° from the incident beam (Figure 7-3). A 90° detection angle is considered to be the least sensitive to variations in particle size. Nephelometry has been adopted by *Standard Methods* as the preferred means for measuring turbidity because of the method's sensitivity, precision, and applicability over a wide range of particle size and concentration. The nephelometric method is calibrated using suspensions of formazin polymer such that a value of 40 nephelometric units (NTU) is approximately equal to 40 JTU (AWWARF, 1998). The preferred expression of turbidity is NTU.

7.3 Turbidity's Significance to Human Health

Excessive turbidity, or cloudiness, in drinking water is aesthetically unappealing, and may also represent a health concern. Turbidity can provide food and shelter for pathogens. If not removed, turbidity can promote regrowth of pathogens in the distribution system, leading to waterborne disease outbreaks, which have caused significant cases of gastroenteritis throughout the United States and the world. Although turbidity is not a direct indicator of health risk, numerous studies show a strong relationship between removal of turbidity and removal of protozoa.



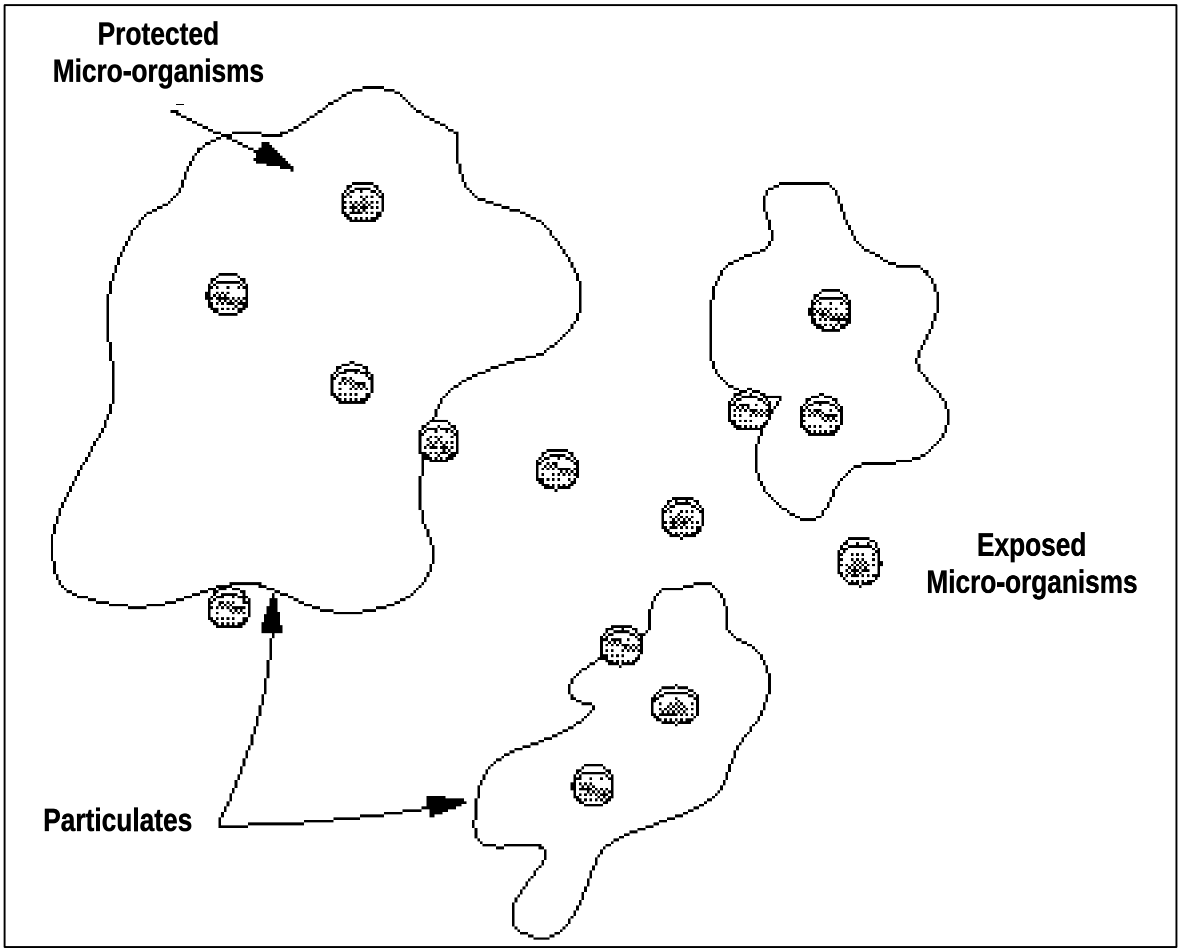
Source: Sadar, 1996; photo revised by SAIC, 1998.

Figure 7-3. Nephelometric Turbidimeter

The particles of turbidity provide "shelter" for microbes by reducing their exposure to attack by disinfectants (Figure 7-4). Microbial attachment to particulate material or inert substances in water systems has been documented by several investigators (Marshall, 1976; Olson et al., 1981; Herson et al., 1984) and has been considered to aid in microbe survival (NAS, 1980). Fortunately, traditional water treatment processes have the ability to effectively remove turbidity when operated properly.

7.3.1 Waterborne Disease Outbreaks

Notwithstanding the advances made in water treatment technology, waterborne pathogens have caused significant disease outbreaks in the United States and continue to pose a significant problem. Even in developed countries, protozoa have been identified as the cause of half of the recognized waterborne outbreaks (Rose et al., 1991). The most frequently reported waterborne disease in the United States is acute gastrointestinal illness, or gastroenteritis (Huben, 1991). The symptoms for this disease include fever, headache, gastrointestinal discomfort, vomiting, and diarrhea. Gastroenteritis is usually self-limiting, with symptoms lasting one to two weeks in most cases. However, if the immune system is suppressed, as with the young, elderly and those suffering from HIV or AIDS, the condition can be very serious and even life threatening. The causes are usually difficult to identify but can be traced to various viruses, bacteria, or protozoa.



Source: LeChevallier and Norton, 1991.

Figure 7-4. Particles of Turbidity May Provide Protection for Microorganisms

Giardia and *Cryptosporidium* are the two most studied organisms known to cause waterborne illnesses. These two protozoa are believed to be ubiquitous in source water, are known to occur in drinking water systems, have been responsible for the majority of waterborne outbreaks, and treatments to remove and/or inactivate them are known to be effective for a wide range of waterborne parasites (LeChevallier and Norton, in Craun, 1993). *Giardia* and *Cryptosporidium* have caused over 400,000 persons in the United States to become ill since 1991, mostly due to a 1993 outbreak in Milwaukee, Wisconsin.

Giardia and viruses are addressed under the 1989 SWTR. Systems using surface water must provide adequate treatment to remove and/or inactivate at least 3-log (99.9%) of the *Giardia lamblia* cysts and at least 4-log (99.99%) of the enteric viruses. However, *Cryptosporidium* was not addressed in the SWTR due to lack of occurrence and health effects data. In the mid-1980's, the United States experienced its first recognized waterborne disease outbreak of cryptosporidiosis (D'Antonio et al., 1985). It was soon discovered that the presence of *Cryptosporidium* in drinking water, even in very low concentrations, could be a significant health hazard (Gregory, 1994). In 1993, a major outbreak of cryptosporidiosis occurred even though the system was in full compliance with the SWTR. Several outbreaks caused by this pathogen have been reported (Smith et al., 1988; Hayes at al., 1989; Levine and Craun, 1990; Moore et al., 1993; Craun, 1993). The ESWTR's primary focus is to establish treatment requirements to further address public health risks from pathogen occurrence, and in particular, *Cryptosporidium*.

Table 7-1 displays several instances of past outbreaks of cryptosporidiosis in systems using surface water as a source, along with general information about the plant and turbidity monitoring. In three out of four of the cases displayed in the table (Milwaukee, Jackson County, and Carrollton), turbidity over 1.0 NTU was occurring in finished water during the outbreaks.

Table 7-1. Cryptosporidium Outbreaks vs. Finished Water Turbidity

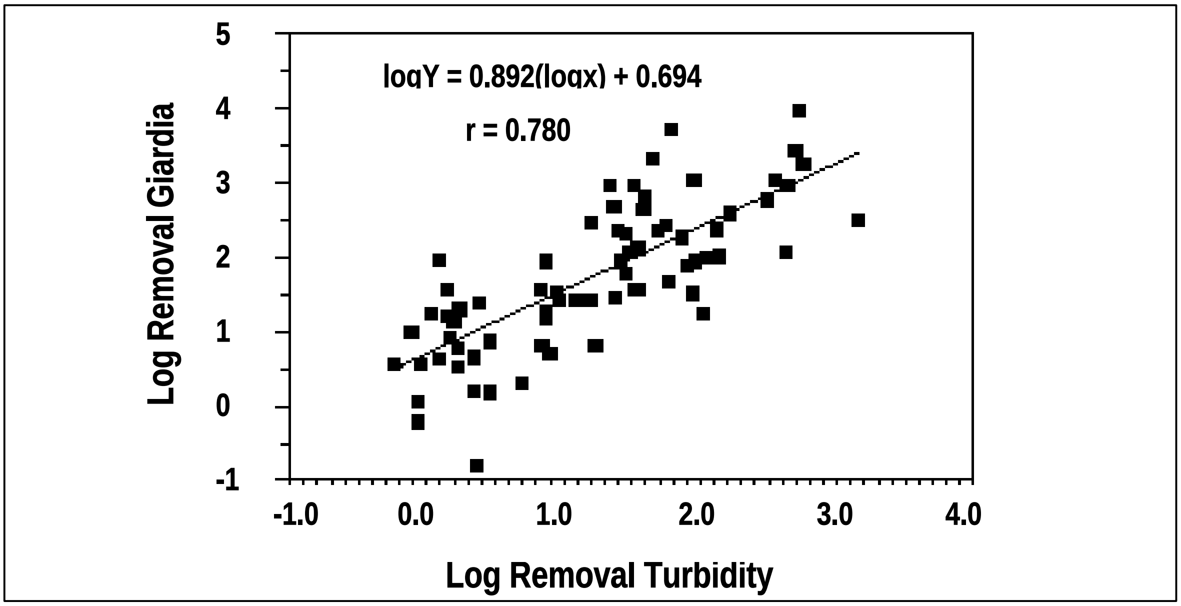
Location of Outbreak	Year	General Plant Information	Turbidity Information
Las Vegas, Nevada (CDC, 1996)	1993-1994	No apparent deficiencies or problems with this community system; SWTR compliant; system performed pre-chlorination, filtration (sand and carbon), and filtration of lake water; outbreak affected mostly persons infected with the human immunodeficiency virus (HIV)	The raw water averaged 0.14 NTU between January 1993 and June 1995, with a high of 0.3 NTU; the maximum turbidity of finished water during this time was 0.17 NTU.
Milwaukee, Wisconsin (CDC, 1996, Logsdon, 1996)	1993	Community system; SWTR compliant; however, deterioration in source (lake) raw-water quality and decreased effectiveness of the coagulation-filtration process	Dramatic temporary increase in finished water turbidity levels; reported values were as high as 2.7 NTU. (Turbidity had never exceeded 0.4 NTU in the previous 10 years.)
Jackson County, Oregon (USEPA, 1997)	1992	Poor plant performance (excessive levels of algae and debris); no pre-chlorination before filtration	Earlier in the year when outbreak occurred, filtered water had averaged 1 NTU or greater.
Carrollton, Georgia (USEPA, 1997, Logsdon, 1996)	1987	Conventional filtration plant; sewage overflowed into water treatment intake, followed by operational irregularities in treatment; filters were placed back into service without being backwashed.	Filtered water turbidity from one filter reached 3 NTU about three hours after it was returned to service without being washed.

7.3.2 The Relationship Between Turbidity Removal and Pathogen Removal

Low filtered water turbidity can be correlated with low bacterial counts and low incidences of viral disease. Positive correlations between removal (the difference between raw and plant effluent water samples) of pathogens and turbidity have also been observed in several studies. In fact, in every study to date where pathogens and turbidity occur in the source water, pathogen removal coincides with turbidity/particle removal (Fox, 1995).

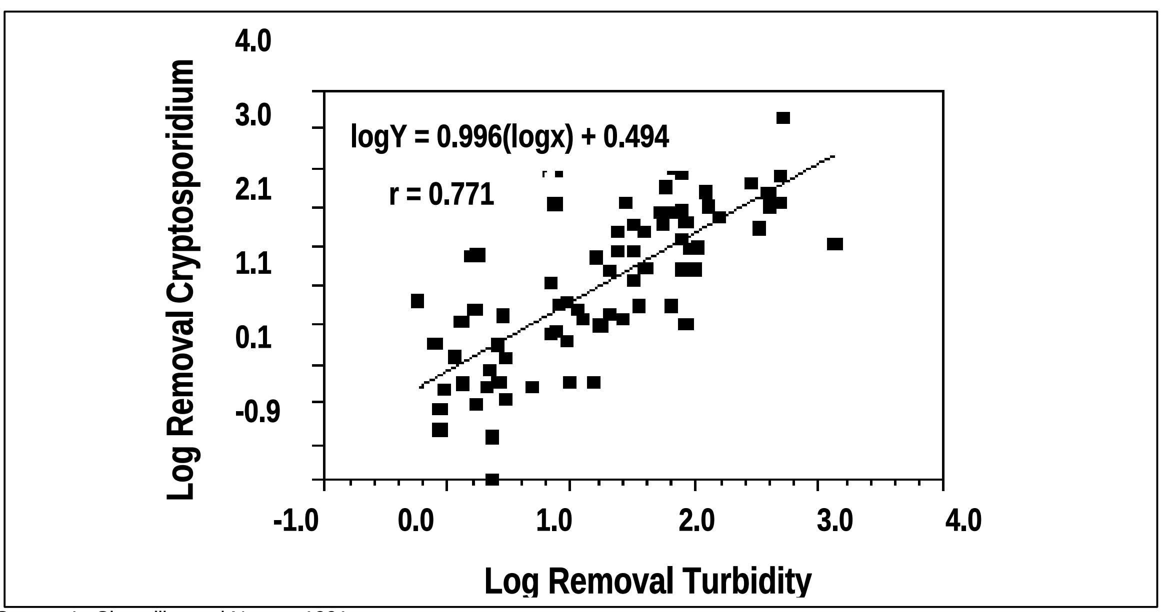
As an example, data gathered by LeChevallier and Norton (in Craun, 1993) from three drinking water treatment plants using different watersheds indicated that for every log removal of turbidity, 0.89 log removal was achieved for the parasites *Cryptosporidium* and *Giardia* (Figures 7-5 and 7-6). Of course, this exact relationship does not hold for all treatment plants. Table 7-2 lists several other studies in addition to LeChevallier and Norton's, and their conclusions on the relationship of turbidity to protozoan removal.

All studies in Table 7-2 show turbidity as a useful predictor of parasite removal efficiency. This evidence suggests that although a very low turbidity value does not completely ensure that particles are absent, it is an excellent measure of plant optimization to ensure maximum public health protection.



Source: LeChevallier and Norton, 1991.

Figure 7-5. Relationship Between Removal of *Giardia* and Turbidity



Source: LeChevallier and Norton, 1991.

Figure 7-6. Relationship Between Removal of *Cryptosporidium* and Turbidity

Table 7-2. Studies on the Relationship between Turbidity Removal and Protozoa Removal

Reference/Study	Discovery/Conclusion on Turbidity
Patania et al., 1995*	Four systems using rapid granular filtration, when treatment conditions were optimized for turbidity and particle removal, achieved a median turbidity removal of 1.4 log and median particle removal of 2 log. The median cyst and oocyst removal was 4.2 log. A filter effluent turbidity of less than 0.1 NTU or less resulted in the most effective cyst removal, by up to 1.0 log greater than when filter effluent turbidities were greater than 0.1 NTU (within the 0.1 to 0.3 NTU range).
Nieminski and Ongerth, 1995*	Pilot plant study: Source water turbidity averaged 4 NTU (maximum = 23 NTU), achieving filtered water turbidities of 0.1-0.2 NTU. *Cryptosporidium* removals averaged 3.0 log for conventional treatment and 3.0 log for direct filtration, while *Giardia* removals averaged 3.4 log for conventional treatment and 3.3 log for direct filtration. Full scale plant study: Source water had turbidities typically between 2.5 and 11 NTU (with a peak level of 28 NTU), achieving filtered water turbidities of 0.1-0.2 NTU. *Cryptosporidium* removals averaged 2.25 log for conventional treatment and 2.8 log for direct filtration, while *Giardia* removals averaged 3.3 log for conventional treatment and 3.9 log for direct filtration.
Ongerth and Pecoraro, 1995*	Using very low-turbidity source waters (0.35 to 0.58 NTU), 3 log removal for both cysts were obtained, with optimal coagulation. (With intentionally suboptimal coagulation, the removals were only 1.5 log for *Cryptosporidium* and 1.3 log for *Giardia*.)
LeChavallier and Norton (in Craun, 1993)	Data gathered from three drinking water treatment plants using different watersheds indicated that for every log removal of turbidity, 0.89 log removal was achieved for *Cryptosporidium* and *Giardia*.
Nieminski, 1992	A high correlation (r^2=0.91) exists between overall turbidity removal and both *Giardia* and *Cryptosporidium* removal through conventional water treatment.
Ongerth, 1990	*Giardia* cyst removal by filtration of well-conditioned water results in 90% or better turbidity reduction, which produces effective cyst removal of 2-log (99%) or more.
LeChavallier et al., 1991*	In a study of 66 surface water treatment plants using conventional treatment, most of the utilities achieved between 2 and 2.5 log removals for both *Cryptosporidium* and *Giardia*, and a significant correlation (p=0.01) between removal of turbidity and *Cryptosporidium* existed.
LeChavallier and Norton, 1992*	In source water turbidities ranging from 1 to 120 NTU, removal achieved a median of 2.5 log for *Cryptosporidium* and *Giardia* at varying stages of treatment optimization. The probability of detecting cysts and oocysts in finished water supplies depended on the number of organisms in the raw water; turbidity was a useful predictor of *Giardia* and *Cryptosporidium* removal.
Foundation for Water Research, 1994*	Raw water turbidity ranged from 1 to 30 NTU, and *Cryptosporidium* removal was between 2 and 3 log. Investigators concluded that any measure which reduces filter effluent turbidity should reduce risk from *Cryptosporidium*.
Hall et al., 1994	Any measure which reduces filtrate turbidity will reduce the risk from *Cryptosporidium*; a sudden increase in the clarified water turbidity may indicate the onset of operational problems with a consequent risk from cryptosporidiosis.
Gregory, 1994	Maintaining the overall level of particulate impurities (turbidity) in a treated water as low as possible may be an effective safeguard against the presence of oocysts and pathogens.
Anderson et al., 1996	In a pilot plant study, the removal of particles > 2 m was significantly related to turbidity reduction r=0.97 (p<0.0001); the removal of *Cryptosporidium* oocysts may be related to the removal of *Giardia*, r=0.79 (p<0.14); the reduction of turbidity may be related to the removal of *Giardia* cysts, r=0.67 (p<0.13) and *Cryptosporidium* oocysts (p<0.08)

- as discussed in EPA's Notice of Data Availability (USEPA, 1997)

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