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Turbidity

Guideline

The maximum acceptable concentration (MAC) for turbidity in water entering a distribution system is 1 nephelometric turbidity unit (NTU), established on the basis of health considerations. A less stringent value for turbidity in water entering a distribution system may be permitted if it is demonstrated that the system has a history of acceptable microbiological quality and that a higher turbidity value will not compromise disinfection. An aesthetic objective of 5 NTU has been set for water at the point of consumption.

Definition and Measurement

Turbidity in water is caused by suspended matter, such as clay, silt, finely divided organic and inorganic matter, soluble coloured organic compounds, plankton and other microscopic organisms.[1] Turbidity measurements relate to the optical property of a water that causes light to be scattered and absorbed rather than transmitted in straight lines through the sample. It is a parameter whose significance is to a large extent dependent on the measurement technique. The total intensity and angular distribution of light scattered from turbid waters represent the overall effects of intraparticle and interparticle interactions and depend, in a complex manner, on such factors as the number, size, shape and refractive index of the foreign particles and the wavelength of the incident light. Complex though the factors are, a number of generalizations can be made.[2,3]

Large particles, with diameters greater than about 10 times the wavelength of the incident light, show predominantly forward scattering of the incident light. The angular distribution of the scattered light becomes more symmetrical as the particle size decreases, until, at diameters less than about 5% of the incident wavelength, the distribution is essentially spherically symmetrical. The degree of symmetry of scattered light is also a function of particle shape, particle size and the refractive index change across the particle/liquid interface. The shorter the wavelength of the incident light, the greater the scattering observed; indeed, for the smaller particles, there is an approximately 15-fold change of turbidity within the wavelength range of visible light. For a given light source and a given sample of suspended material, the measured turbidity will depend on the detector geometry. At high particle concentrations, scattered light can itself be rescattered before reaching the detector or observer. A point can therefore be reached at which the measured scatter decreases with further increases of particle concentration. Not only is it possible to measure the same scattered light intensity from two different concentrations of the same particles, but samples containing different particulate matter can give the same turbidity reading with widely different particle concentrations.

Several methods may be used in the measurement of water turbidity, but only two of these, nephelometry and turbidimetry, form the basis for present standard methods.[4–7] Historically, turbidity has been measured in wastewater and drinking water using the Jackson candle turbidimeter.[8] A Jackson turbidity unit (JTU) is an empirical measure of turbidity based on the depth of a sample water column that is just sufficient to extinguish the image of a burning standard candle observed vertically through the sample. A depth of 21.5 cm corresponds to 100 JTU.[6,7] As an alternative to JTU, turbidimeters can be calibrated in terms of the concentration (in mg/L) of suspended solids giving rise to a certain turbidity (a gravimetric definition). Diatomaceous earths are commonly used as materials to form the standard suspensions. This type of definition (sometimes called the Fuller’s earth scale) is arbitrary and specific for the type and particle size of the clay used.[9] The Jackson candle turbidimeter is applicable only to turbidities greater than 25 JTU and, as such, has limited applicability to the monitoring of drinking water. Improved instruments that use electrical light sources and mirror optics, such as the Patterson turbidimeter,[4] can measure lower values.

The current method of choice for turbidity measurement, in both Canada and the United States, is the nephelometric method.[7,10–12] Nephelometric turbidimeters measure the intensity of light scattered at

90° to the path of the incident light. Differences in the physical design of such turbidimeters will cause differences in measured turbidity values. To minimize such differences, the light source, sample geometry and detector geometry are specifically defined, as is the calibration method.[7,10] Suspensions of formazin polymer have generally been adopted as the primary turbidity reference standard, although commercially prepared suspensions of styrene divinylbenzene beads are also available for use in standardization.[1,8] A suspension of formazin formed by the reaction of hydrazine sulphate (50 mg/L) with hexamethylenetetramine (500 mg/L) under carefully specified conditions has a defined turbidity of 40 NTU.[7,11] When measured on a candle turbidimeter, this standard suspension has a turbidity of about 40 JTU.[7] Note, however, that as there is no direct relationship between the intensity of light scattered at 90° and JTU, there is no basis for calibrating a nephelometer in terms of candle units.[7] Below 40 NTU, the turbidity of a sample, measured by the standard method, can be calculated directly (i.e., there is a linear response):[6,7]

$$\text{turbidity} = (\text{instrument reading of scattered light})\,(\text{NTU per unit of instrument reading})$$

It is difficult to relate turbidity, as defined, to the weight concentration of suspended matter in natural water samples, because the size, shape and refractive index of the particulates also affect the light-scattering properties of the suspension.[1] Instrumental response depends on, among other factors, the whiteness or lustre of the particulate matter: white particles (e.g., formazin) give a more sensitive response than darker substances (e.g., Fuller's earth), and suspensions of finely divided carbon show essentially no response.[13]

Using special experimental methods, the nephelometric response of exhaustively filtered deionized water has been shown to be 0.022 ± 0.003 NTU, with a quartz–iodine light source.[14] Standard nephelometers, however, are able to respond to changes of only about 0.02 NTU at turbidities below 1 NTU.[7] The practical lower limit of the standard nephelometric method, therefore, is about 0.1 NTU; measurements of turbidities below this value are likely to be irreproducible and unreliable.[15] Reproducibilities of ±9.22, ±3.96 and ±1.68% at turbidity levels of 1, 10 and 40 NTU, respectively, have been reported from single-laboratory comparisons.[12] Air bubbles and dirty sample tubes can cause false high readings for turbidity; very turbid samples or samples with colour due to dissolved substances will give low readings.[7,12]

Turbidity as defined by the above methods is a non-specific measure of suspended solids concentration. Electronic particle counters are now available that are capable of accurately counting and recording the number of suspended particles as a function of size (often in the 1- to 150-µm range). Although there is a general relationship between particle counts and turbidity (below 1 NTU), a firm correlation does not exist.[16,17] Examples of findings from a surface water plant that demonstrate the sensitivity of particle counts are as follows:[17]

Turbidity (NTU)	**Approximate particle counts/10 mL**
5	200 000
1	60 000
0.5	10 000
0.1	200

The concentration of asbestos fibres, a possible component of suspended material in potable water, is generally measured using electron microscopy techniques.[18,19]

Occurrence

The particles that cause turbidity in water range in size from colloidal dimensions (approximately 10 nm) to diameters of the order of 0.1 mm and can be divided into three general classes: clays; organic particles resulting from decomposition of plant and animal debris; and fibrous particles from asbestos minerals.[20] Clay particles generally have an upper diameter limit of about 0.002 mm.

The major part of suspended material in most natural waters is made up of soil particles derived from the land surface by erosion. The coarser sand and silt fractions are at least partially coated with organic material. Clay particles have varied proportions of clay mineral components, usually the phyllosilicates, as well as non-clay material, such as iron and aluminum oxides and hydroxides, quartz, amorphous silica, carbonates and feldspar.[20] Clays and organic particles are often found together as a "clay–organic complex."[20] It is, to a certain extent, artificial to treat the organic (humic) component in isolation from the inorganic component when considering the behaviour of suspended matter. However, humic substances do have a much higher adsorptive capacity than inorganic clays (870 meq/100 g and 80–100 meq/100 g, respectively[21]), and it is likely that in many instances the effect of humic components predominates.

Asbestos, a group of naturally occurring hydrated silicate minerals possessing a fibrous morphology, is also an identified component of suspended material in drinking water supplies. Other sources of turbidity in raw water include inorganic precipitates, such as metal (iron or manganese) oxides and hydroxides, and biological organisms, such as algae, zooplankton and filamentous or macro bacterial growths.[22–24]

Levels of turbidity in raw water can range from <1 to >1000 NTU. Removal of turbidity is achieved by filtration and, especially to low levels, by a combination of coagulation, sedimentation and filtration. Coagulation is effected by cationic species (e.g., hydrated aluminum and ferric oxides) and cationic organic polyelectrolytes. The positive electrical charge destabilizes the negatively charged colloidal particles, which allows aggregation to occur via chemical and van der Waals interactions.[25,26] Filtration is carried out through sand beds or other single-, dual- or mixed-media granular filters. This treatment process is capable of producing water with a turbidity of 1 NTU or less.[27,28] Continuous monitoring of turbidity throughout the treatment stages is a valuable aid in attaining such a performance.[8]

Following filtration, turbidity in a waterworks may be detrimentally affected by a number of mechanisms, such as post-flocculation of escaped dissolved coagulants, oxidation of dissolved metals, bacterial and other microflora growths, chemical additions for stability or corrosion control, resuspension of deposited materials (especially in low-flow parts of the system), pipe corrosion or line breaks.[29–32] Uncovered distribution system reservoirs may also result in increased turbidities, mainly through biological production.[33,34]

The U.S. Public Health Service's survey of community water supply systems, published in 1970, found that 3% of the 969 systems surveyed supplied water with a turbidity in excess of 5 JTU.[35] An analysis of the public water supplies of the 100 largest cities in the United States in 1962 showed that the maximum turbidity encountered in finished water was 15 JTU, with minimum and median values of zero;[36] the zero values probably correspond to a turbidity level of less than about 1 or 2 JTU.[37] Since the 1975 promulgation of the U.S. National Interim Primary Drinking Water Regulations, which have a 1 NTU maximum contaminant level (MCL) (monthly average) for turbidity from surface water treatment (unless specially approved to a 5 NTU MCL), turbidity control has received more attention.[10,38] A more recent survey of U.S. utilities indicated a median maximum of 0.85 NTU.[39] Specific plant operational studies have indicated that low turbidities in plant effluent are readily achievable, although it is recognized that competent operations are required.[40–42]

No nation-wide survey has been published on turbidities in Canadian water supplies. Reported performances of surface water treatment from three areas in Canada suggested that turbidities of less than 0.5 NTU in plant effluent were generally maintained.[17,24,28]

Relationship with Other Water Quality Parameters

Turbidity can affect or be affected by the physical, microbiological, chemical and radiological characteristics of water. In general, the relationships between turbidity and other water quality parameters are due to the turbidity itself; the adsorptive and complexing capacity of the many types of particulates that contribute to turbidity; and the fact that particulate matter is a source of nutrients and protection for some microorganisms.

Physical Characteristics

There is a considerable body of evidence that a large part of colour in water arises from colloidal particles. Black and co-workers used electrophoretic studies to demonstrate the predominantly colloidal nature of colour in water,[43,44] and it has been claimed that about 50% of colour is due to a "colloidal fraction" of humic substances.[45] True colour is therefore defined as the colour of water from which the turbidity has been removed.[46]

The relationship between high turbidity, in both raw and filtered water, and taste and odour has long been recognized.[47] Algal growths, actinomycetes and their debris contribute to taste and odour problems.[22] The increase in turbidity in the raw water supply during an epidemic of infectious hepatitis in Delhi, India, was also accompanied by objectionable taste and odour in the finished water.[48]

Microbiological Characteristics

The presence of turbidity can have significant effects on both the microbiological quality of drinking water and the detection of bacteria and viruses in the water. Microbial growth in water is most extensive on the surfaces of particles and inside loose flocs (both naturally occurring and of the kind formed during coagulation treatment). This occurs because nutrients adsorb to surfaces, and adsorbed bacteria are thus able to grow more efficiently than when in free suspension.[49,50] Similarly, it has been shown that river silt readily adsorbs viruses.[51] Historically, filtration has been demonstrated to provide a substantial barrier to disease-causing organisms.[52] During water treatment by coagulation, bacteria and viruses become trapped in the floc and are removed along with turbidity.[53,54] However, break-through of the floc in filter beds has been shown to be accompanied by an increase in virus penetration, even though the turbidity of the finished water remained below 0.5 JTU.[55] Studies have been reported that indicate bacteriological count reductions with decreasing filtrate turbidity and practically complete removal of algae and coliform bacteria with a 0.1 NTU effluent.[52] Turbidity increases in filter effluent can signal the potential for increasing passage of unwanted organisms, even if the turbidity in the effluent is less than 1 NTU. For example, increasing concentrations of *Giardia* cysts can occur with turbidity increases of only 0.2 to 0.3 NTU.[56,57]

Particulate matter (e.g., organic, inorganic, higher micro-organisms) can protect bacteria and viruses from the effects of disinfection or act as a source or vector for organisms. Distribution system studies have shown some conflicting findings with respect to turbidity. Haas *et al*. noted that increasing values of pH, temperature and turbidity were associated with increasing concentrations of micro-organisms.[58] Standard plate count increases with increasing turbidity have also been found at turbidity levels less than 2 NTU.[59] Work by Goshko *et al*. also found positive correlations between standard plate counts and turbidities in the 0.83 to 8.89 NTU range.[60] On the other hand, a study reported by Reilly and Kippin suggested that turbidity above or below 1 NTU did not affect the frequency of occurrence of either coliforms or standard plate count organisms.[61] Sanderson and Kelly reported coliform organisms in water having turbidities ranging between 3.8 and 84 NTU even after treatment with chlorine (free chlorine residuals between 0.1 and 0.5 mg/L and a minimum contact time of 30 minutes).[62] A study by Neefe and co-workers showed that chlorination alone would not protect human volunteers from infectious hepatitis when water deliberately contaminated with faecal matter was ingested.[63] Only by treating the water samples by coagulation and filtration prior to chlorination could the water be rendered safe to drink.

LeChevallier *et al*. studied chlorination efficiencies on coliforms in unfiltered surface water supplies and found a negative correlation with turbidity.[64] A derived model predicted that an increase in turbidity from 1 to 10 NTU would result in an eightfold decrease in the disinfection efficiency at a constant chlorine dose. A study by Hoff, which examined the disinfection efficiencies related to turbidities of 1 and 5 NTU on poliovirus and sewage effluent coliforms, found that cell-associated viruses and coliforms were more resistant to disinfection, whereas the effects of turbidities induced by clay and aluminum phosphate were negligible.[65] The type of turbidity had the major impact. For organic particulates, a reduction of turbidity from 5 to 1 NTU reduced the concentrations of disinfectant-resistant organisms approximately fivefold.

Hoff and Geldreich reiterated the importance of particulate characteristics for protection effects.[66] Studies with ozone by Sproul *et al*. also confirmed that alum and bentonite afforded little protection to a variety of test organisms at 1 and 5 NTU, whereas faecal material, and particularly human epithelial carcinoma cells, did provide protection.[67] Chlorine dioxide studies by Scarpino *et al*. suggested that temperature and turbidity affected the rate of inactivation of bentonite-adsorbed poliovirus.[68] At 25°C, turbidities in excess of 2.29 NTU reduced inactivation rates.

Nagy and Olson reported an apparent correlation between turbidity and filamentous fungal colony forming units in chlorinated distribution systems.[30] The occurrence of free-living nematodes in municipal water supplies has been found to be relatively common in North America. Nematodes of the Rhabditidae family are known to ingest pathogenic bacteria and viruses and hence are able to protect them against the action of chlorine.[69] Studies on nematodes indicate a higher incidence in raw and treated waters when high raw water turbidities were encountered.[70,71] In a study of the San Francisco water supply, coliform organisms were detected in the presence of chlorine levels of 0.35 mg/L or greater. Crustaceans apparently harboured the coliforms; on passing through a spigot, the crustaceans were ruptured and viable coliforms were released.[72] In laboratory tests, the presence of various clays and humic acid was shown to protect *Klebsiella aerogenes* from disinfection by ultraviolet light.[73]

Chlorine (as hypochlorous acid) reacts readily with organic matter containing unsaturated linkages, phenolic groups and nitrogen groups, giving rise to taste- and odour-producing compounds[74] as well as trihalomethanes.[75] Hence, waters with high organic turbidity will give rise to a substantial chlorine demand, which could lead to a reduction in the free chlorine residual maintained in distribution systems as protection against possible recontamination. For Ottawa River plants, Otson *et al*. noted that turbidity increases had a strong correlation with increased pre-chlorination dosage requirements.[28] In Oregon surface waters, chlorine demand had a positive correlation with both turbidity and total organic carbon levels.[64] The resultant model suggested a 180% increase in chlorine demand for a turbidity increase from 1 to 5 NTU.

The presence of turbidity may also interfere with the quantitation of bacteria and viruses. Bacteria are enumerated by incubating bacterial cells on nutritive media for a fixed period of time and counting the number of visible colonies that form during the incubation period. It is assumed that each colony represents one cell; however, a single colony could result from a particle containing many bacterial cells adsorbed on its surface. Fewer cells than were actually present would then be recorded. This phenomenon would also lead to an underestimation of bacterial numbers with the most probable number technique. Geldreich *et al*. noted that turbidity in a potable water sample may preclude use of the membrane filter procedure because of the filterable volume, the character of the suspended material and the surficial deposit thickness on the membrane.[76] Although crystalline or siliceous materials may not be a problem, other substances may clog filter pores or cause a confluent growth to develop during incubation. Coliform masking using the membrane filter technique has been observed, with the incidence of false-negative results being 17, 45 and over 80% for turbidities of ≤1, 5 and >10 NTU, respectively.[64,77] Additional studies suggested that turbidity *per se* up to values of approximately 10 NTU did not greatly affect coliform determinations, although associated non-coliform bacteria seriously inhibited detections.[78] Viruses can also be adsorbed on or within particulate matter and may be very difficult to elute; 1% recovery is not unusual.[55] In a recent review of virus detection methods, the authors concluded that there was no simple and accurate system available for enumerating viruses in highly turbid waters.[79]

Chemical Characteristics

The adsorption capacity of suspended particulates can lead to the entrapment of undesirable compounds (both inorganic and organic); as such, turbidity can bear an indirect relationship to the water quality parameters aimed at monitoring such compounds. Most important in this respect is the organic or humic component of turbidity.

Humic substances are able to bind substantial amounts of metals and hydrous oxides. Schnitzer and Kahn gave an excellent review of metal–humate complexes, the mechanism of their formation and their properties.[80] The ability of a number of natural waters in Ontario to complex copper has been demonstrated, with complexing capacities of up to 2.35 μmol Cu/L (0.149 mg/L) being reported.[81] A wide variety of heavy metal ions was found to be complexed in sediments of the Ottawa and Rideau rivers. A positive correlation between the unit surface area of the sediment and the concentration of adsorbed metal ions was observed.[82] In a study of mercury sorption and desorption characteristics of Ottawa River sediments, it was found that sorption rates are higher for organic-rich sands. Desorption of mercury was difficult, with less than 1% of the mercury being leached during a seven-hour contact period.[83] The strength of some metal–humate complexes may lead to negative errors in the analytical measurement of trace metals in natural water samples if turbidity exists.[84] One method that is used to remove undesirable metal ions during water treatment is adsorption with activated carbon. This process is aided by the presence of organic matter.[85]

Organic molecules are also adsorbed by natural organic matter. DDT, for example, is solubilized in 0.5% sodium humate solution by a factor of at least 20 over its solubility in pure water.[86] Herbicides such as 2,4-D, paraquat and diquat can be adsorbed onto clay–humic acid particulates, the adsorption being greatly influenced by metal cations present in the humic material.[87] The presence of turbidity, therefore, might also interfere with the detection of biocides in water samples.

Chlorination of water containing organic matter such as humic acids can produce trihalomethanes. Morris and Johnson observed a relationship between raw water turbidity and trihalomethane concentration in finished Iowa City water.[88] Stevens and co-workers found, in laboratory tests, that trihalomethane production was reduced if the water was filtered prior to chlorination.[89] Harms also reported that raw water turbidity was positively correlated with chloroform concentration in a South Dakota supply.[90] Potential trihalomethane control strategies, including alternative disinfectants, disinfectant application points and dosages and use of activated carbon, have implications related to turbidity concerns and effects.[91]

At the asbestos levels commonly found in drinking water (of the order of 10^4 to 10^6 fibres/L),[18] very little, if any, correlation has been observed between turbidity and asbestos concentration.[7,92,93] However, at high asbestos levels (10^9 to 10^{11} fibres/L), a general but non-linear relationship was reported.[94] Further studies on treatment efficiencies for asbestos removal have resulted in a recommendation by Logsdon and co-workers that plants designed for asbestos removal should produce filtered waters with turbidities 0.1 NTU or lower.[95,96] McGuire *et al*. suggested that this objective would help but not necessarily guarantee low asbestos counts ($<10^6$ fibres/L).[97] Boatman reported that turbidity could impede asbestos analyses because of restricted filter volumes.[19] Asbestos-cement pipes are used in some localities to transport drinking water, and it has been demonstrated that water with an aggressivity index of less than 10 can cause the release of asbestos fibres into the drinking water.[98]

Radiological Characteristics

There are several sources of radioactive contamination in potable water sources. They include dissolution of radioisotopes from natural formations, effluents from radioisotope manufacturing operations and nuclear generating stations and fallout from atomic detonations. In general, radioactivity in raw water sources is divided about equally between suspended solids and dissolved matter.[99,100] Fallout from atomic explosions, potentially the most hazardous to biological systems,[101] appears in surface waters predominantly as particulates.[99] Certain micro-organisms (e.g., plankton) have been shown to concentrate a variety of radionuclides.[101] Conventional water treatment, using coagulation, flocculation and filtration, removes essentially all suspended radioactive particles and some of the dissolved radioactivity.[100] Softening or precipitation processes are effective for the removal of radium-226.[102]

Health Considerations

The most important health-related effect of turbidity is probably its ability to protect bacteria and viruses from the effects of disinfection. Hudson, using 1953 data on infectious hepatitis and raw water turbidity for 12 U.S. cities, observed that infectious hepatitis incidence was greater with higher turbidity.[103] A similar relationship appeared to exist between turbidity and cases of poliomyelitis, although this finding was based on a smaller sample.[103] However, Shaffer *et al*. reported detection of poliovirus in waters with chlorine concentrations greater than 1 mg/L and turbidities less than 1 NTU.[104] Although a study of 16 U.S. cities in 1961 failed to reveal a clearly defined relationship between hepatitis incidence and finished water turbidity, the authors stated that, because of the many factors involved, it should not be inferred that there is none.[105] The infectious hepatitis epidemic in Delhi, India, occasioned by the massive contamination by sewage of the raw water source of a treatment plant, was also accompanied by a significant increase in raw water turbidity. Even though chlorination was practised, it was apparently insufficient to inactivate the infectious hepatitis virus.[48] The protection offered by organic or cellular material in particular has been reported in other studies.[65–67]

An outbreak of giardiasis in Rome, New York, where an unfiltered but chlorinated water supply was used, has been cited as illustrating the problem of particulates possibly protecting pathogens and interfering with marginal disinfection.[93] In another incident, high turbidities (>4 NTU), due to poor plant operation coupled with a malfunctioning chlorinator, were considered as causal factors in an outbreak.[52] In most water treatment plants, *Giardia* removal is a physical process involving coagulation, flocculation and filtration, because chlorine contact times are insufficient to result in complete disinfection.[106] In this case, monitoring of turbidity can be a useful indicator of plant performance, including cyst removal. Studies have shown that small increases in turbidity (about 0.2 NTU) can result in significant passage of *Giardia* cysts.[56] It has been suggested that 0.1 NTU should be set as a goal or objective for treated water.[52,56,106,107] However, giardiasis problems have occurred where turbidity limits have been met, and it cannot be assumed that a turbidity limit by itself will prevent water-borne disease.[57,108]

Particulate materials in water are usually not in themselves potential hazards, but they may have indirect effects.[20] The concentrations of heavy metal ions and biocides are usually much higher in suspended solids than in water. The possibility exists, therefore, that when such contaminated particles enter a different environment, for example, the stomach, release of the pollutants could occur, with possibly deleterious effects.

The metal–ligand binding in humate complexes can be represented by the equation:[80]

$$M^{n+} + H_mA \leftrightarrow MA^{n-m} + mH$$

where:

- M^{n+} = the metal ion
- H_mA = humic acid
- MA = the metal complex.

If the hydrogen ion concentration is increased, as, for example, by stomach acid, the equilibrium will be displaced in favour of the free ion and the undissociated humic acid. Similarly, it has been demonstrated that the absorption of some herbicides, in particular s-triazine compounds, by soil organic matter is pH dependent. Maximum absorption occurs at pH levels in the vicinity of the respective pK values of the herbicides—pH levels of about 4 to 6. Lowering or raising the pH decreases absorption and hence may lead to the release of free herbicides.[109]

Other Considerations

In *Canadian Drinking Water Standards and Objectives 1968*,[110] the turbidity limit was based predominantly on aesthetic grounds. It is generally accepted that turbidity above 5 JTU is objectionable to consumers.[111]

Because of the nature of the measurement, turbidity does not indicate the type, number or mass of particles. However, because of the ease of analysis and relative inexpensiveness of the equipment, it is a very useful tool to assess the performance of water treatment processes—especially for conventional surface water systems. Moreover, turbidity can serve to signal potential contamination problems or difficulties within a distribution system.

Rationale

1. Control of turbidity in public drinking water supplies is important for both health and aesthetic reasons. Excessive turbidity detracts from the appearance of treated water and can interfere with disinfection processes and the maintenance of a chlorine residual. It can serve as a source of nutrients for micro-organisms as well as interfering with their enumeration. The adsorptive properties of suspended particles can lead to a concentration of heavy metal ions and biocides in turbid waters. Turbidity has also been related to trihalomethane formation in chlorinated water. In addition, turbidity has often been associated with unacceptable tastes and odours.

2. Viable coliform bacteria have been detected in waters with turbidities higher than 3 NTU even in the presence of free chlorine residuals of up to 0.5 mg/L and after a contact time in excess of 30 minutes. Positive coliform tests have also been reported in water supplies where chlorination is the only treatment provided. Outbreaks of disease traced to chlorinated water supplies have been associated with high turbidity. The occurrence and persistence of micro-organisms within distribution systems have been correlated with turbidity and other factors.

3. The effect of turbidity on disinfection efficiency may be frequently related to the type and nature of the particulates. Surface water sources in particular may be susceptible to organic substances and undesired organisms that can impede disinfection or otherwise cause drinking water quality problems. Appropriate technology is available to treat and monitor turbidity to low levels. Therefore, the maximum acceptable concentration (MAC) for turbidity in water entering distribution systems has been set at 1 NTU. Provision of treated water at or below this limit will minimize the introduction of unfavourable particulate and biological matter into the distribution system and thereby render better disinfection opportunity, effectiveness and maintenance. Special site-specific problems may require more rigorous attention for the production of low-turbidity water.

4. Certain water supplies, such as groundwater, may contain non-organic–based turbidity, which may not seriously hinder disinfection. Therefore, a value greater than the MAC (1 NTU) for turbidity in water entering the distribution system may be permitted if the water system demonstrates a history of acceptable microbiological quality and that the less stringent value will not compromise disinfection.

5. Turbidity in excess of 5 NTU becomes apparent and may be objected to by a majority of consumers. Therefore, an aesthetic objective of 5 NTU has been set for water at the point of consumption.

References

1. American Public Health Association/American Water Works Association/Water Pollution Control Federation. Standard methods for the examination of water and wastewater. 17th edition. Washington, DC. p. 2-12 (1989).

2. Black, A.P. and Hannah, S.A. Measurement of low turbidities. J. Am. Water Works Assoc., 57: 901 (1965).

3. McCluney, W.R. Radiometry of water turbidity measurements. J. Water Pollut. Control Fed., 47: 252 (1975).

4. Eden, G.E. The measurement of turbidity in water. Proc. Soc. Water Treat. Exam., 14: 27 (1965).

5. American Water Works Association Task Group Report. Progress toward a filtrability index test. J. Am. Water Works Assoc., 51: 1539 (1959).

6. American Society for Testing and Materials. Standard test methods for turbidity of water, D1889-81. 1982 annual book of ASTM standards. Part 31. Water. p. 250. Philadelphia, PA (1977).

7. American Public Health Association/American Water Works Association/Water Pollution Control Federation. Standard methods for the examination of water and wastewater. 14th edition. p. 131. Washington, DC (1976).

8. Hach, C.C. Understanding turbidity measurement. Ind. Water Eng., 9(2): 18 (1972).

9. Packman, R.F. The preparation of turbidity standards. Proc. Soc. Water Treat. Exam., 11: 64 (1962).

10. U.S. Environmental Protection Agency. National interim primary drinking water regulations. EPA-570/9-76-003, Office of Water Supply, Washington, DC. p. 12 (1976).

11. U.S. Environmental Protection Agency. Turbidity. In: Methods for chemical analysis of water and wastes. EPA-625-6-74-003a. p. 295 (1976).

12. Traversy, W.J. Turbidity. In: Methods for chemical analysis of waters and wastewaters. Water Quality Division, Inland Waters Branch, Department of Fisheries and Forestry, Ottawa. p. 167 (1971).

13. Roberts, K.J. Turbidity—A relationship between the types of particulate matter and measured turbidity. In: Proceedings of the 95th Annual Conference of the American Water Works Association, June, Minneapolis, MN. Paper 28-b (1975).

14. Eichner, D.W. and Hach, C.C. How clear is clear water. Water Sewage Works, 118: 299 (1971).

15. Roberts, K.J. Personal communication. Water Technology Section, Pollution Control Planning Branch, Ontario Ministry of the Environment, Toronto, April (1978).

16. Beard, J.D. and Tanaka, T.S. A comparison of particle counting and nephelometry. J. Am. Water Works Assoc., 59: 533 (1977).

17. Gammie, L. Particle counting and turbidity in water treatment. In: Proceedings of the 36th Annual Convention, Western Canada Water and Sewage Conference, September 19–21 (1984).

18. Department of National Health and Welfare. A national survey for asbestos fibres in Canadian drinking water supplies. 79-EHD-4, Environmental Health Directorate (1979).

19. Boatman, E.S. Analyzing asbestos fibers in water by means of transmission electron microscopy. J. Am. Water Works Assoc., 74: 533 (1982).

20. National Academy of Sciences. Drinking water and health. Chap. IV. U.S. National Research Council, Washington, DC (1977).

21. Narkis, N. and Rebhun, M. The mechanism of flocculation processes in the presence of humic substances. J. Am. Water Works Assoc., 67: 101 (1975).

22. Mackenthun, K.M. and Keup, L.E. Biological problems encountered in water supplies. J. Am. Water Works Assoc., 62: 520 (1970).

23. Kay, G.P., Sykora, J.L. and Burgess, R.A. Algal concentration as a quality parameter of finished drinking waters in and around Pittsburgh, Pa. J. Am. Water Works Assoc., 72: 162 (1980).

24. Foley, P.D. Experience with direct filtration at Ontario's Lake Huron treatment plant. J. Am. Water Works Assoc., 72: 162 (1980).

25. Stumm, W. and O'Melia, C.R. Stoichiometry of coagulation. J. Am. Water Works Assoc., 60: 514 (1968).

26. Stumm, W. and Morgan, J.J. Chemical aspects of coagulation. J. Am. Water Works Assoc., 54: 971 (1962).

27. Logsdon, G.S. Treatment techniques for the removal of turbidity from drinking water. In: Manual of treatment techniques for meeting the interim primary drinking water regulations. EPA-600/8-77-005, revised April 1978, U.S. Environmental Protection Agency. p. 37 (1978).

28. Otson, R., Williams, D.T. and Bothwell, P.D. Comparison of trihalomethane levels and other water quality parameters for three treatment plants on the Ottawa River. Environ. Sci. Technol., 15: 1075 (1981).

29. Stinson, K.B. Treated water forever pure? Water Eng. Manage., 129: 34 (1982).

30. Nagy, L.A. and Olson, B.H. The occurrence of filamentous fungi in drinking water distribution systems. Can. J. Microbiol., 28: 667 (1982).

31. Curry, M.D. Is your water stable and what difference does it make. J. Am. Water Works Assoc., 70: 506 (1978).

32. Johnson, M.L. and Doe, P.W. Designing and constructing the Trap Falls water treatment plant. J. Am. Water Works Assoc., 75: 124 (1983).

33. Committee Report. Deterioration of water quality in large distribution reservoirs (open reservoirs). J. Am. Water Works Assoc., 75: 313 (1983).

34. Silverman, G.S., Nagy, L.A. and Olson, B.H. Variations in particulate matter, algae, and bacteria in an uncovered, finished-drinking-water reservoir. J. Am. Water Works Assoc., 75: 191 (1983).

35. McCabe, L.J., Symons, J.M., Lee, R.D. and Robeck, G.G. Survey of community water supply systems. J. Am. Water Works Assoc., 62: 670 (1970).

36. Dufor, C.N. and Becker, E. Selected data on public supplies of the 100 largest cities in the United States, 1962. J. Am. Water Works Assoc., 56: 237 (1964).

37. Baylis, J.R. Operator’s viewpoint. J. Am. Water Works Assoc., 52: 1169 (1960).

38. Stacha, J.H. and Pontius, F.W. An overview of water treatment practices in the United States. J. Am. Water Works Assoc., 76: 73 (1984).

39. Hoehn, R.C. and Johnson, J.D. Disinfection, water quality control, and safety practices of the water quality industry in 1978 in the United States. J. Am. Water Works Assoc., 75: 51 (1983).

40. Atherton, T. and Goss, J. Low turbidity water from fast processes. Water Eng. Manage., 128: 40 (1981).

41. Burnham, R.A. and Trinka, W.C. Packaged plant treats turbidity. Water Eng. Manage., 129: 56 (1982).

42. Morand, J.M. and Young, M.J. Performance of package water treatment plants for small communities. In: Proceedings of the American Water Works Association Seminar on Innovative Filtration Techniques, Las Vegas, NV. p. 129 (1983).

43. Black, A.P. and Willems, D.G. Electrophoretic studies of coagulation for removal of organic color. J. Am. Water Works Assoc., 53: 589 (1961).

44. Black, A.P. and Christman, R.F. Characteristics of colored surface waters. J. Am. Water Works Assoc., 55: 753 (1963).

45. Pennanen, V. Humus fractions and their distribution in some lakes in Finland. In: Humic substances, their structure and function in the biosphere. D. Povoledo and H.L. Golterman (eds.). Pudoc, Wageningen, The Netherlands. p. 207 (1975).

46. American Public Health Association/American Water Works Association/Water Pollution Control Federation. Standard methods for the examination of water and wastewater. 14th edition. Washington, DC. p. 64 (1976).

47. Atkins, P.F. and Tomlinson, H.D. Evaluation of daily carbon chloroform extracts with CAM. Water Sewage Works, 110: 281 (1963).

48. Dennis, J.M. 1955–56 infectious hepatitis epidemic in Delhi, India. J. Am. Water Works Assoc., 51: 1288 (1959).

49. Brock, T.D. Principles of microbial ecology. Prentice-Hall, NJ. p. 72 (1966).

50. Stotzky, G. Influence of clay minerals on microorganisms. III. Effect of particle size, cation exchange capacity, and surface area on bacteria. Can. J. Microbiol., 12: 1235 (1966).

51. Berg, G. Removal of viruses from sewage, effluents, and waters. 2. Present and future trends. Bull. W.H.O., 49: 461 (1973).

52. Logsdon, G.S. and Lippy, E.C. The role of filtration in preventing waterborne disease. J. Am. Water Works Assoc., 74: 649 (1982).

53. Clarke, N.A., Berg, G., Kabler, P.W. and Chang, S.L. Human enteric viruses in water: source, survival and removability. Adv. Water Pollut. Res., 2: 523 (1964).

54. Foliguet, J.M. and Doncoeur, F. Élimination des enterovirus au cours du traitement des eaux d’alimentation par coagulation–floculation–filtration. Water Res., 9: 953 (1975).

55. Robeck, G.G., Clarke, N.A. and Dostal, K.A. Effectiveness of water treatment processes in virus removal. J. Am. Water Works Assoc., 54: 1275 (1962).

56. Logsdon, G.S., Thurman, V.C., Frinot, E.S. and Stoecker, J.G. Evaluating sedimentation and various filter media for removal of *Giardia* cysts. J. Am. Water Works Assoc., 77: 61 (1985).

57. Cleasby, J.L. Slow sand filtration and direct in-line filtration of a surface water. In: Proceedings of the American Water Works Association Seminar on Innovative Filtration Techniques, Las Vegas, NV. p. 1 (1983).

58. Haas, C.N., Meyer, M.A. and Paller, M.S. Microbial alterations in water distribution systems and their relationship to physical-chemical characteristics. J. Am. Water Works Assoc., 75: 475 (1983).

59. Snead, M.C., Olivieri, V.P., Kruse, C.W. and Kawata, K. Benefits of maintaining a chlorine residual in water supply systems. EPA-600/2-80-010, U.S. Environmental Protection Agency, June (1980).

60. Goshko, M.S., Minnigh, H.A., Pipes, W.O. and Christian, R.R. Relationships between standard plate counts and other parameters in water distribution systems. J. Am. Water Works Assoc., 75: 568 (1983).

61. Reilly, J.K. and Kippin, J.S. Relationship of bacterial counts with turbidity and free chlorine in two distribution systems. J. Am. Water Works Assoc., 75: 309 (1983).

62. Sanderson, W.W. and Kelly, S. Comments following a paper by N.A. Clarke *et al.*, reference 53.

63. Neefe, J.R., Baty, J.B., Reinhold, J.G. and Stokes, J., Jr. Inactivation of the virus of infectious hepatitis in drinking water. Am. J. Public Health, 37: 365 (1947).

64. LeChevallier, M.W., Evans, T.M. and Seidler, R.J. Effect of turbidity on chlorination efficiency and bacterial persistence in drinking water. Appl. Environ. Microbiol., 42: 159 (1981).

65. Hoff, J.C. The relationship of turbidity to disinfection of potable water. Evaluation of the microbiology standards for drinking water. EPA-570/9-78-OOC, U.S. Environmental Protection Agency. p. 103 (1978).

66. Hoff, J.C. and Geldreich, E.E. Comparison of the biocidal efficiency of alternative disinfectants. J. Am. Water Works Assoc., 73: 40 (1981).

67. Sproul, O.J., Buck, C.E., Emerson, M.A., Boyce, D., Walsh, D. and Howser, D. Effect of particulates on ozone disinfection of bacteria and viruses in water. EPA-600/2-79-089, U.S. Environmental Protection Agency, August (1979).

68. Scarpino, P.V., Brigano, F.A.O., Cronier, S. and Zink, M.L. Effect of particulates on disinfection of enteroviruses in water by chlorine dioxide. EPA-600/2-79-054, U.S. Environmental Protection Agency, July (1979).

69. Chang, S.L., Woodward, R.L. and Kabler, P.W. Survey of free-living nematodes and amebas in municipal supplies. J. Am. Water Works Assoc., 52: 613 (1960).

70. Mott, J.B., Mulamoottil, G. and Harrison, A.D. A 13-month survey of nematodes at three water treatment plants in Southern Ontario, Canada. Water Res., 15: 729 (1981).

71. Tombes, A.S., Abernathy, A.R., Welch, D.M. and Lewis, S.A. The relationship between rainfall and nematode density in drinking water. Water Res., 13: 619 (1979).

72. Tracy, H.W., Camarena, V.M. and Wing, F. Coliform persistence in highly chlorinated waters. J. Am. Water Works Assoc., 58: 1151 (1966).

73. Bitton, G., Henis, Y. and Lahav, N. Effect of several clay minerals and humic acid on the survival of *Klebsiella aerogenes* exposed to ultraviolet irradiation. Appl. Microbiol., 23: 870 (1972).

74. Sawyer, C.N. and McCarty, P.L. Residual chlorine and chlorine demand. In: Chemistry for sanitary engineers. 2nd edition. Chap. 21. McGraw-Hill, Toronto (1967).

75. Rook, J.J. Chlorination reactions of fulvic acids in natural waters. Environ. Sci. Technol., 11: 478 (1977).

76. Geldreich, E.E., Allen, M.J. and Taylor, R.H. Interferences to coliform detection in potable water supplies. In: Evaluation of the microbiology standards for drinking water. EPA-570/9-78-OOC, U.S. Environmental Protection Agency. p. 13 (1978).

77. Seidler, R.J. and Evans, T.M. Project summary—Persistence and detection of coliforms in turbid finished drinking water. EPA-600/S2-82-054, U.S. Environmental Protection Agency, August (1982).

78. Herson, D.S. and Victoreen, H.T. Hindrance of coliform recovery by turbidity and non-coliforms. EPA-600/2-80-097, U.S. Environmental Protection Agency, August (1980).

79. Fenters, J.D. and Reed, J.M. Viruses in water supply. J. Am. Water Works Assoc., 69: 328 (1977).

80. Schnitzer, M. and Kahn, S.U. Humic substances in the environment. Marcel Dekker, New York, NY. p. 204 (1972).

81. Chau, Y.K. and Lum-She-Chan, K. Measurement of complexing capacity of lake waters. In: Humic substances, their structure and function in the biosphere. D. Povoledo and H.L. Golterman (eds.). Pudoc, Wageningen, The Netherlands. p. 11 (1975).

82. Oliver, B.G. Heavy metal levels of Ottawa and Rideau river sediments. Environ. Sci. Technol., 7: 135 (1973).

83. Ramamoorthy, S. and Rust, R.R. Mercury sorption and desorption characteristics of some Ottawa River sediments. Can. J. Earth Sci., 13: 530 (1976).

84. Gardiner, J. The chemistry of cadmium in natural water—1. A study of cadmium complex formation using the cadmium specific-ion electrode. Water Res., 8: 23 (1974).

85. Culp, G.L. and Culp, R.L. New concepts in water purification. Van Nostrand Reinhold, Toronto. p. 221 (1974).

86. Wershaw, R.L., Burcar, P.J. and Goldberg, M.C. Interaction of pesticides with natural organic material. Environ. Sci. Technol., 3: 271 (1969).

87. Kahn, S.U. Adsorption of 2,4-D from aqueous solution by fulvic acid–clay complex. Environ. Sci. Technol., 4: 236 (1974).

88. Morris, R.L. and Johnson, L.G. Agricultural runoff as a source of halomethanes in drinking water. J. Am. Water Works Assoc., 68: 492 (1976).

89. Stevens, A.A., Slocum, C.J., Seeger, D.R. and Robeck, G.G. Chlorination of organics in drinking water. J. Am. Water Works Assoc., 68: 615 (1976).

90. Harms, L.L. and Looyenga, R.W. Preventing haloform formation in drinking water. EPA-600/2-80-091, U.S. Environmental Protection Agency, August (1980).

91. American Water Works Association. Treatment techniques for controlling trihalomethanes in drinking water (1982).

92. Logsdon, G.S. and Symons, J.M. Removal of asbestiform fibers by water filtration. J. Am. Water Works Assoc., 69: 499 (1977).

93. Symons, J.M. and Hoff, J.C. Rationale for turbidity maximum contaminant level. Presented at 3rd Water Quality Technology Conference, American Water Works Association, Atlanta, GA, December 8–10 (1975).

94. Lawrence, J. and Zimmerman, H.W. Asbestos in water: mining and processing effluent treatment. J. Water Pollut. Control Fed., 49: 156 (1977).

95. Logsdon, G.S., Evavold, G.L., Patton, J.L. and Watkins, J. Filter plant design for asbestos fiber removal. Am. Soc. Civ. Eng. J. Environ. Eng. Div., 109: 900 (1983).

96. Logsdon, G.S., Symons, J.M. and Sorg, T.J. Monitoring water filters for asbestos removal. Am. Soc. Civ. Eng. J. Environ. Eng. Div., 107: 1297 (1981).

97. McGuire, M.J., Bowers, A.E. and Bowers, D.A. Optimizing large-scale water treatment plants for asbestos-fiber removal. J. Am. Water Works Assoc., 75: 364 (1983).

98. Farren, E.F., Buelow, R.W., Thurnau, R.C., Gardels, M., Sorrell, R.K., Snyder, P. and Dressman, R.C. Water quality deterioration in the distribution system. Presented at 5th Water Quality Technology Conference, American Water Works Association, Kansas City, MO, December (1977).

99. Setter, L.R., Regnier, J.E. and Diephaus, E.A. Radioactivity of surface waters in the United States. J. Am. Water Works Assoc., 51: 1377 (1959).

100. Straub, C.P. Significance of radioactivity data. J. Am. Water Works Assoc., 53: 704 (1961).

101. Davis, J.J. Dispersion of radioactive materials by streams. J. Am. Water Works Assoc., 50: 1505 (1958).

102. Sorg, T.J. and Logsdon, G.S. Treatment technology to meet the interim primary drinking water regulations for inorganics: part 5. J. Am. Water Works Assoc., 72: 411 (1980).

103. Hudson, H.E. High-quality water production and viral disease. J. Am. Water Works Assoc., 54: 1265 (1962).

104. Shaffer, P.T.B., Metcalf, T.G. and Sproul, O.J. Chlorine resistance of poliovirus isolants recovered from drinking water. Appl. Environ. Microbiol., 40: 1115 (1980).

105. Taylor, F.B., Eagen, J.H., Smith, H.F.A., Jr., and Coene, R.F. The case for water-borne infectious hepatitis. Am. J. Public Health, 56: 2093 (1966).

106. Lin, S.D. *Giardia lamblia* and water supply. J. Am. Water Works Assoc., 77: 40 (1985).

107. American Water Works Association. AWWA statement of policy: quality goals for potable water. J. Am. Water Works Assoc., 60: 1317 (1968).

108. Committee Report. Waterborne disease in the United States and Canada. J. Am. Water Works Assoc., 73: 528 (1981).

109. Schnitzer, M. and Kahn, S.U. Humic substances in the environment. Marcel Dekker, New York, NY. p. 286 (1972).

110. Department of National Health and Welfare. Canadian drinking water standards and objectives 1968. p. 19 (1968).

111. U.S. Department of Health, Education and Welfare. Public Health Service drinking water standards, revised 1962. Environmental Control Administration, Rockville, MD. p. 21 (1962).