TECHNICAL BRIEF

WHO/FWC/WSH/17.01

WATER QUALITY AND HEALTH - REVIEW OF TURBIDITY: Information for regulators and water suppliers

1. Summary

This technical brief provides information on the uses and significance of turbidity in drinking-water and is intended for regulators and operators of drinking-water supplies.

Turbidity is an extremely useful indicator that can yield valuable information quickly, relatively cheaply and on an ongoing basis. Measurement of turbidity is applicable in a variety of settings, from low-resource small systems all the way through to large and sophisticated water treatment plants.

Turbidity, which is caused by suspended chemical and biological particles, can have both water safety and aesthetic implications for drinking-water supplies. Turbidity itself does not always represent a direct risk to public health; however, it can indicate the presence of pathogenic microorganisms and be an effective indicator of hazardous events throughout the water supply system, from catchment to point of use. For example, high turbidity in source waters can harbour microbial pathogens, which can be attached to particles and impair disinfection; high turbidity in filtered water can indicate poor removal of pathogens; and an increase in turbidity in distribution systems can indicate sloughing of biofilms and oxide scales or ingress of contaminants through faults such as mains breaks.

Turbidity can be easily, accurately and rapidly measured, and is commonly used for operational monitoring of control measures included in water safety plans (WSPs), the recommended approach to managing drinking-water quality in the WHO Guidelines for Drinking-water Quality (WHO, 2017). It can be used as a basis for choosing between alternative source waters and for assessing the performance of a number of control measures, including coagulation and clarification, filtration, disinfection and management of distribution systems.

Turbidity is also an important aesthetic parameter, with turbidities of 4 nephelometric turbidity units (NTU) and above being visible, and affecting the appearance and acceptability of drinking-water to consumers.

Although turbidity can be used in multiple ways within WSPs, this versatility can cause confusion and misinterpretation. Each of the relationships between turbidity and drinking-water quality is different and needs to be considered separately.

Table 1. Summary of turbidity targets

Location or process step	Turbidity targets or indicators of contamination	Notes	Monitoring frequency
Source water			
	Rapid changes in source water turbidity.	May be an indication of pollution triggered by environmental events (e.g. storms or fires) or anthropogenic activities (in both groundwater and surface-water catchments), or ingress of contamination through groundwater infrastructure. Appropriate responses and corrective actions should be identified in water safety plans (WSPs) for foreseeable events (e.g. adjust operation of treatment and disinfection processes, abstraction depth management, and diversion or avoidance of affected source waters). Unpredicted turbidity changes should be investigated to determine causes.	The frequency of turbidity monitoring depends on variability in source water quality and flow (e.g. more variable source water should be monitored more frequently). Increased monitoring is suggested in extreme events such as heavy rainfall, to inform appropriate corrective actions because turbidity can change very rapidly.
	Turbidity changes over longer time periods.	May indicate changes in the catchment which should be investigated to inform appropriate corrective actions.	
Water treatment: The turbidity targets for large well-run municipal supplies in the disinfection section apply irrespective of the type of treatment processes applied. Technology-specific targets apply where filtration is used to achieve defined pathogen reductions (see below).			
Filtration (see Table 4 for more details)	Direct and conventional filtration: 0.3 nephelometric turbidity units (NTU) in 95% of measurements taken each month from combined filter effluent, with none to exceed 1 NTU.	Consistent with: • 1–2 log removal of viruses • 2.5–3 log removal of *Cryptosporidium* and *Giardia*	In higher resource settings, the turbidity of filtered water should typically be monitored continuously online, and the performance of individual filters should be monitored to optimize filter performance. Where continuous monitoring is not practised (e.g. in lower resource settings), turbidity of filtered water should be monitored at a frequency that will allow filtrate quality issues to be detected in a timely fashion (e.g. minimum daily, but more frequent monitoring may be required depending on the specific conditions – for example, variability of source water quality and flow – and available resources). Periods of vulnerable operation (e.g. filter start-up, ripening after backwash and end-of-filter run) should be considered when developing monitoring plans.
	Diatomaceous earth and slow sand filtration: ≤1 NTU in 95% of measurements of filtered water taken each month.	Consistent with: • 1–2 log removal of viruses • 3 log removal of *Cryptosporidium* and *Giardia* Log$_{10}$ removal values based on meeting defined operational turbidity targets	
	Membrane filtration (microfiltration and ultrafiltration): <0.1 NTU.	Can achieve 4–7 log removal of *Cryptosporidium* and *Giardia*, and 1–6 log reductions of viruses, all depending on pore sizes. However, log reduction credits are limited by the sensitivity of turbidity monitoring.	Typically monitored continuously online.
Disinfection	Ideally below 1 NTU. Large well-run municipal supplies should be able to achieve turbidities of <0.5 NTU at all times, and should be able to average turbidities of ≤0.2 NTU. In lower resource settings including small supplies the aim should be to keep turbidities below 5 NTU.	At turbidities of >1 NTU, higher disinfection doses or contact times will be required to ensure that adequate Ct (i.e. product of disinfectant concentration and contact time) or ultraviolet (UV) light intensity is achieved.	In higher resource settings, the turbidity of water for disinfection should typically be monitored continuously online (particularly for surface water supplies). Where continuous monitoring is not practised (e.g. in lower resource settings), the turbidity of water for disinfection should be monitored at a frequency that will allow any turbidity issues that may impact the effectiveness of disinfection to be detected in a timely fashion (e.g. minimum daily monitoring, but more frequent monitoring may be required, depending on the specific situation and available resources).
Distribution systems and storage			
	Unexpected increases in turbidity.	Can be caused by a range of faults and events (e.g. mains breaks, resuspension of sediments, detachment of biofilms or oxide scales, backflow, cross connections). Increased turbidity should be immediately investigated and corrective actions implemented. Where "booster" chlorination is applied during storage or distribution, consider the guidance provided under 'disinfection' above. Distribution system monitoring should be undertaken at key points within the network including after treated water storages (and at consumer taps).	Turbidity should be measured in conjunction with measuring chlorine residuals (in disinfected supplies) and collecting samples for *Escherichia coli* testing. This could vary from daily to weekly samples, depending on multiple factors (e.g. resource availability, intermittency of supply, and variations in hydraulic conditions and population served). Increased monitoring is suggested in association with operational incidents such as mains breaks, to inform appropriate corrective action.

Table 1. Summary of turbidity targets (continued)

Location or process step	Turbidity targets or indicators of contamination	Notes	Monitoring frequency
Point of use			
Aesthetic aspects	Ideally <1 NTU.	"Crystal-clear" water has a turbidity of <1 NTU; at 4 NTU and above, water becomes visibly cloudy. Although turbidity may be caused by particles with little health significance, complaints about unexpected turbidity should always be investigated because they could reflect significant faults or breaches in distribution systems, or may result in consumers seeking out alternative, potentially less safe sources of water.	
Household water treatment and storage	Ideally <1 NTU, although this may be difficult in many supplies where household water treatment is necessary to ensure the safety of drinking-water. In such cases, the aim should be to keep turbidities below 5 NTU. Disinfection should still be practised even if 5 NTU cannot be achieved.	At turbidities of >1 NTU, higher disinfection doses or contact times will be required. Increases in turbidity of stored household water, such as harvested rainwater, can indicate water quality deterioration.	

2. General description

Turbidity describes the cloudiness of water caused by suspended particles such as clay and silts, chemical precipitates such as manganese and iron, and organic particles such as plant debris and organisms (APHA/AWWA/WEF, 2012; Health Canada, 2012). As turbidity increases, it reduces the clarity of water to transmitted light by causing light to be scattered and adsorbed. Typically expressed in NTU, turbidity is a practical parameter that can be measured using online devices, and benchtop and portable meters or turbidity tubes (e.g. in small communities where resources are limited). Turbidities below 4 NTU can only be detected by instruments; however, at 4 NTU and above, a milky-white,[1] muddy, red-brown or black suspension can be visible and can reduce the acceptability of drinking-water.

The sources of turbidity are diverse, and many of the constituent particles (e.g. clays, soils and natural organic matter) are harmless. However, turbidity can also indicate the presence of hazardous chemical and microbial contaminants, and have significant implications for water quality (Table 2). The implications will vary depending on the characteristics of the turbidity. In addition, as indicated in Table 2, the point of detection is important in considering potential impacts. Elevated turbidity in source waters can signal pollution events in the catchment (e.g. heavy rain, spills or contamination of groundwater), and can challenge the effectiveness of coagulation and clarification, filtration and disinfection. Failure to meet turbidity targets for filtered water can indicate the possible presence of pathogens in drinking-water, and increased turbidity in distribution systems can represent detachment of biofilms and oxide scales or entry of external sources of contamination. Each source needs to be considered in context because the treatment and management implications will vary (Table 2).

[1] Milky-white suspensions can also be caused by supersaturated air being released from water. Unlike turbidity, suspensions of air clear from the bottom of a glass upward. The air could have been introduced during pipe repair or could have been released following changes in water pressure.

Table 2. Sources of turbidity, and water quality and treatment implications

Location	Source of turbidity	Water quality implications	Treatment and management implications
Source water	Inorganic particles released by weathering of rocks, soils and clays	• Impacts on pH, alkalinity and hardness • Source of metals and metal oxides • Poor appearance and taste of water	• Need to adjust coagulation, flocculation and sedimentation • Increased demand on operational resources (e.g. filter backwashing and chemical usage) • Increased disinfectant demand and decreased penetration of ultraviolet (UV) light
	Human and livestock waste	• Source of pathogenic microorganisms	• Increased treatment requirements • Increased demand on operational resources (e.g. filter backwashing and chemical usage) • Increased disinfectant demand and decreased penetration of UV light
	Industrial waste	• Source of metals and metal oxides • Poor appearance and taste of water	• Increased or modified treatment requirements • Increased demand on operational resources (e.g. filter backwashing and chemical usage)
	Biological growth (e.g. algae, zooplankton and cyanobacteria) in source waters	• Cyanobacteria can be a source of toxins and tastes and odour compounds • Poor appearance of water	• Increased or modified treatment requirements • Increased demand on operational resources (e.g. filter backwashing and chemical usage) • Increased disinfectant demand and decreased penetration of UV light
	Natural organic matter including decomposing plant material	• Poor appearance of water • Nutrients supporting biological growth in distribution systems	• Increased disinfectant demand and decreased penetration of UV light • Increased demand on operational resources (e.g. filter backwashing and chemical usage) • Precursors of disinfection by-products
Treatment	Poor control of treatment chemical dosing (e.g. coagulants, settling aids and pH adjustment chemicals)	• Poor appearance of water • Increase dissolved chemicals (e.g. aluminium)	• Inefficient treatment • Increased operational costs (chemical usage) • Failure to meet treatment turbidity targets
	Precipitates from insoluble components of treatment chemicals, or formed during processes such as pH correction	• Poor appearance of water	• Inefficient treatment • Failure to meet treatment turbidity targets
	Oxidation products of natural chemicals such as arsenic, iron and manganese	• Source of metal oxides • Poor appearance (e.g. brown or black water) and taste of water	• Need for removal processes • Increased distribution system maintenance requirements
Distribution	Intrusion of soils and sewage through mains breaks	• Source of hazardous chemical and microbial contaminants • Source of silt and organic matter favouring regrowth • Poor appearance and taste of water	• Need for review and enhancement of standard repair procedures to minimize intrusion • Need for increased proactive replacement programme for ageing mains • Need to clean and flush mains with disinfectant • Need to maintain or boost residual disinfectant
	External contamination from backflow or cross connections	• Source of hazardous chemical and microbial contaminants	• Need for backflow or cross connection inspection programme
	Resuspension of accumulated silts and sediments, or detachment of corrosion chemicals and scales	• Source of metals and metal oxides • Poor appearance and taste of water	• Need for review of mains cleaning programme • Need for improved system operation to avoid rapid surges and reversals of flow • Increased disinfectant demand
	Detachment of biofilms	• Release of opportunistic pathogens (e.g. *Legionella*, *Naegleria* and *mycobacteria*) and embedded enteric pathogens • Poor appearance and taste of water	• Increased disinfectant demand • Need to maintain or boost residual disinfectant • Need for routine mains hygiene programme

Source: Adapted from Health Canada, 2012

3. Measurement of turbidity

One of the advantages of turbidity is that it can be measured easily using simple, low-cost manual comparators, and portable, benchtop and online automated meters. These devices measure scattering or attenuation of light from a range of sources (e.g. natural light, tungsten lamps or light-emitting diodes), with the results being expressed in units that reflect the method of measurement (Table 3). The nephelometric method is the most common, with turbidity being expressed as NTU. Other units include formazin nephelometric units,[1] formazin attenuation units, Jackson turbidity units and turbidity units. The various turbidity units are related, and often similar, but not always equivalent. This is particularly true for Jackson turbidity units and turbidity units which are based on visual assessments while the other units are meter readings. Standardized methods – including guidance on sample collection and calibration standards – have been established for various types of turbidity meters (APHA/AWWA/WEF, 2012; Health Canada, 2012; ISO, 2016). As turbidity measured in collected samples can change as a result of temperature variations, particle flocculation and sedimentation, samples should be analysed as soon as possible using online or onsite meters at treatment plants and portable meters in the field (APHA/AWWA/WEF, 2012; Health Canada, 2012; ISO, 2016).

Table 3. Relative comparison of technology options for turbidity measurement

Method	Units	Basis	Advantages	Disadvantages
Nephelometric or formazin method, Using portable, benchtop or online instruments	Nephelometric turbidity unit (NTU) or formazin nephelometric unit (FNU) NTU and FNU are considered to be equivalent	• Measures the intensity of scattered light at a detector typically positioned at 90 degrees to an incident light beam (white light in the case of NTU and infrared in the case of FNU) • Both are calibrated using formazin standards	• Accurate • Sensitive (0.01–5 NTU spectrum) • Suitable for field testing • Suitable for operational monitoring of water treatment plant performance	• Higher cost • More complex technology • Requires power source • Requires maintenance and calibration • Requires consumable materials (e.g. calibration standards) • Requires technical proficiency
Turbidimetric method	Formazin attenuation units (FAU)	• Measures the attenuation of light at a detector positioned in line with an incident light beam • Calibrated using formazin standards	• Accurate above 40 FAU • Suitable for use in highly turbid waters (typically in the range 40–4000 FAU)	• Not as sensitive as the nephelometric method • Other disadvantages as above
Jackson candle (original standard instrument)	Jackson turbidity unit (JTU)	• Turbidity present in a water sample obscures a lighted candle viewed through a specialized sample column	• Low cost • Low technology	• Not suitable for field testing • Result open to individual interpretation • Limited sensitivity (limit of detection 4 JTU)
Turbidity tube	Turbidity unit (TU)	• Water added to sample tube obscures a visual marker at the base of cylinder • Level of water in the tube corresponds to an approximate turbidly value	• Low cost • Low technology • Robust • Simple to use • Appropriate for field testing and use by community members • May measure up to 2000 TU	• Limited sensitivity (limit of detection 5 TU) • Result open to individual interpretation

Electronic meters are in common use; however, in smaller rural and remote communities, issues can include cost, sources of electricity, and availability of technical and servicing support and replacement parts. The whole-of-life costs – including cost of replacement parts as well as consumable items such as calibration standards and batteries – must be carefully considered when selecting an appropriate technology for turbidity measurement in low-resource settings. Turbidity tubes represent simpler, lower cost alternatives but sensitivity is a limitation, with a lower limit of 5 TU (WHO, 2008). This limits the effectiveness of turbidity tubes for operational monitoring of processes such as filtration; nevertheless, turbidity tubes remain among the most appropriate means of turbidity measurement in lower resource settings. Despite more recent developments in the application of smart-phone optical sensors for turbidity measurement, a significant technology gap remains with respect to durable, low-cost, low-technology turbidity meters that are sensitive below 1 NTU.

Accuracy and sensitivity are always important, but are usually more critical when measuring turbidities below 1 NTU; for example, when used to measure the operation of filtration technologies, where acceptable performance is determined by meeting targets of 0.3 NTU or below (USEPA, 2006; Health Canada, 2012). Online, benchtop or portable instruments are available that can reliably measure turbidities below 0.1 NTU. Although different instruments can produce some degree of variability, turbidity meters can deliver consistent and reliable results, provided that careful calibration and maintenance, standard operating procedures and analyst training are implemented (Health Canada, 2012).

[1] Formazin polymer is used as a standardized suspension to calibrate turbidity meters (USEPA, 2003; ISO, 2016).

The frequency of turbidity monitoring will depend on variability (e.g. in source water), and whether it is being used to measure performance of an essential control measure such as filtration or disinfection. In high-resource settings, turbidity is often monitored continuously online (particularly where filtration is practised), whereas in low-resource settings where continuous monitoring is not feasible, turbidity should be monitored at a frequency that will allow issues to be detected in a timely fashion (e.g. minimum daily, but more frequent monitoring may be required depending on the specific situation and available resources). In distribution systems, turbidity monitoring could vary from daily to weekly samples, depending on factors such as resource availability, intermittency of supply, variations in hydraulic conditions and population served. Increased monitoring is suggested during extreme events such as heavy rainfall or in association with incidents such as mains breaks, to inform appropriate corrective action.

4. Turbidity and drinking-water safety

4.1 Turbidity and disease

Achieving low turbidities in drinking-water is a proven indicator of pathogen removal and hence of drinking-water safety. Incidents of elevated turbidity have been associated with several outbreaks of disease (Hrudey and Hrudey, 2004; Mann et al., 2007). However, a direct proportional relationship between removal of turbidity and pathogens has not been demonstrated (Health Canada, 2012). Similarly, investigations of potential links between levels of turbidity in drinking-water and rates of endemic gastrointestinal disease in communities have produced mixed results. Some studies have reported a relationship between turbidity and endemic disease but others have not (Mann et al., 2007; Tinker et al., 2010; Beaudeau, 2014); thus, although correlations may exist in individual drinking-water supplies, a uniform relationship has not been established.

4.2 Operational monitoring

4.2.1 Source waters

Turbidity can be used to monitor source water quality. Rapid changes in turbidity can be an indication of substantial pollution events in surface water and groundwater catchments (e.g. triggered by storms, thaws, fires or spills, which may be coupled with anthropogenic activities such as clearing of forests), or ingress of contamination through groundwater infrastructure. Turbidity changes over intervals that are longer than historical results may indicate changes in the catchment that require attention. Changes in turbidity should be investigated to determine causes and to identify appropriate corrective actions.

Turbidity in surface waters tends to be more variable than in groundwater, and regular turbidity measurements of surface source waters can be used to adjust treatment and disinfection processes (e.g. adjustment of coagulant and disinfectant doses), intake depth management (e.g. in reservoirs and river intakes), and diversion or avoidance of particular raw water sources.

4.2.2 Filtration

Turbidity is a practical indicator of coagulation and flocculation, and of filter (individual and combined) performance. One of the strengths of turbidity is that it can be monitored continuously, with results linked to automatic alarm systems that allow rapid responses and, where necessary, remedial action if deviations from required performance are detected. Achieving specified turbidity targets at well-designed filtration plants that have been optimized to achieve particle removal is a critical component of demonstrating pathogen reductions (Table 4). Turbidity targets and associated pathogen reductions vary, depending on the type of treatment process (Emelko et al., 2005; USEPA, 2006; Health Canada, 2012).

The turbidity targets shown in Table 4 provide 95% and maximum targets, which allow short-term performance spikes of limited magnitude during normal operation. The occurrence of such spikes during activities such as plant start-up, filter ripening and end-of run operation should be minimized and ideally eliminated by applying recognized good practices (USEPA, 1999; USEPA, 2006; Health Canada, 2012). Significant incidents such as coagulation faults, pH changes, flow surges and rapid changes in source water quality can lead to exceedances of the turbidity targets and can decrease removal of pathogens such as *Cryptosporidium* and *Giardia* (Nieminski and Ongerth, 1995; Patania et al., 1995; Huck et al., 2001; Emelko et al., 2005). Immediate responses should be implemented to any exceedance of turbidity targets; for example, automatic plant shut down or discharging of filtered water to waste until compliance is restored.

Membrane filtration, including microfiltration and ultrafiltration, typically produces water with turbidities of below 0.1 NTU, and achieves from 4 to greater than 7 log reduction of *Cryptosporidium* and *Giardia*, and from 1 to greater than 6 log reduction of viruses, depending on membrane pore size (Health Canada, 2012). Online monitoring of turbidity can be used to detect losses of membrane integrity and reduced performance. However, turbidity can be relatively insensitive as a means of detecting minor

Table 4. Turbidity targets and associated *Cryptosporidium* and virus removals by media filtration

Treatment type	Turbidity target	Pathogen reduction (log_{10})	
		Cryptosporidium	Viruses
Conventional filtration Coagulation, flocculation and sedimentation followed by media filtration **Dissolved air flotation and filtration (DAFF)** Coagulation, flocculation and flotation followed by media filtration	≤0.3 nephelometric turbidity units (NTU) in 95% of measurements taken each month of combined filter effluent, with no measurements to exceed 1 NTU	3.0	2.0
Direct filtration Coagulation, flocculation without sedimentation followed by media filtration	≤0.3 NTU in 95% of measurements taken each month of combined filter effluent, with no measurements to exceed 1 NTU	2.5	1.0
Slow sand	≤1 NTU in 95% of measurements taken each month of filtered water, with no measurement to exceed 5 NTU	3.0	2.0
Diatomaceous earth	≤1 NTU in 95% of measurements taken each month of filtered water, with no measurements to exceed 5 NTU	3.0	1.0

Source: Values from USEPA (2003, 2006)

defects in membrane structure that may allow passage of pathogens. It has been suggested that laser turbidity meters, although more costly, are more sensitive and could detect smaller membrane breaches than conventional turbidity meters (USEPA, 2005; Health Canada, 2012). An alternative that can provide greater assurance about membrane integrity and performance is to augment turbidity monitoring with less frequent (e.g. daily) but more sensitive direct integrity monitoring, such as pressure decay testing (USEPA, 2005; 2006).

4.2.3 Disinfection

Turbidity can be used as an operational parameter to assess the likely effectiveness of disinfection, and as a basis for setting disinfectant doses and modifying contact times (where such modification is possible).

Turbidity above 1–2 NTU reduces the efficacy of chlorination by increasing chlorine demand and potentially shielding microorganisms from inactivation (LeChevallier et al., 1981; Keegan et al., 2012). While there is evidence that disinfection can be achieved at higher turbidities, chlorine doses or contact times need to be increased to ensure that adequate Cts[1] are achieved (Keegan et al., 2012). Similarly, turbidity can reduce the effectiveness of ultraviolet (UV) light disinfection by reducing UV light transmission or by shielding microorganisms from inactivation (Christensen and Linden, 2003; Batch et al., 2004; Passantino et al., 2004; Amoah et al., 2005; Templeton et al., 2007; Cantwell et al., 2008; Kollu and Ormeci, 2012).

Turbidity should ideally be kept below 1 NTU because of the recorded impacts on disinfection. This is achievable in large well-run municipal supplies, which should be able to achieve less than 0.5 NTU before disinfection at all times and an average of 0.2 NTU or less, irrespective of source water type and quality. However, keeping turbidity below 1 NTU is not always possible in low-resource settings including small supplies; in such cases, the aim should be to keep turbidities below 5 NTU. At turbidities above 1 NTU, higher disinfection doses or contact times will be required to ensure that adequate Ct or UV light intensity is achieved.

4.3 Distribution systems

Turbidity can be included in operational monitoring of water quality in distribution systems as an indicator of integrity, and of good operation and maintenance of the network (Health Canada, 2012; WHO, 2014). The level of turbidity in distribution systems will vary depending on the source of supply; the type of treatment; the operating conditions (e.g. pressure fluctuations, and continuous or intermittent supply); and the characteristics, condition, complexity and integrity of the distribution network. Turbidity targets can be identified by determining background levels throughout the system when water treatment is functioning effectively and there are no known faults in the distribution system. Any substantial and unexpected increases above background values should be immediately investigated to determine cause and significance. This should include investigating customer complaints of increased turbidity, which may provide an early indication of more serious and widespread public health issues.

[1] The effectiveness of a disinfectant is based on the combination of dose and contact time with target micro-organisms. Ct is the product of the concentration of a disinfectant in water (C in mg/L) and contact time (t in minutes) with water and entrained microorganisms.

Increased turbidity can be caused by a range of faults and events that may give rise to public health or aesthetic concerns (Table 2). Such faults and events can include elevated turbidity in water entering the system, loss of integrity (e.g. due to mains breaks), resuspension of sediments and scale, and detachment of biofilms or oxide scales. These events can lead to entry of external contamination, release of pathogens from biofilms, and impacts on appearance and taste of drinking-water (Table 2).

Water utilities should have standard operating procedures included in WSPs to (WHO, 2014):

- minimize ingress through mains breaks, and to flush and disinfect parts of systems potentially affected by faults and new installations;
- minimize resuspension of sediments, biofilms and oxide scales during normal operation and when undertaking planned activities such as mains cleaning, system maintenance and cleaning of water storage systems (impacts of cleaning and maintenance activities can be reduced by implementing targeted flushing strategies to remove turbidity generated by planned activities); and
- prevent cross connections.

Biofilms occur naturally in water systems, and their extent and thickness is influenced by factors such as flow, disinfectant residuals and nutrients in drinking-water. Opportunistic pathogens such as *Legionella, Pseudomonas* and mycobacteria can grow and survive in biofilms, but most biofilm organisms are not pathogenic. In addition, enteric pathogens that contaminate water systems through poor treatment, mains breaks and other faults may be deposited in biofilms and survive for longer periods (WHO, 2014). Although biofilms generally have limited public health significance, resuspension can cause increased turbidity and discolouration, and produce distinctive tastes and odours; also, biofilms will increase disinfectant demands.

When the source of elevated turbidity is unknown, immediate action should be taken to identify the cause and to institute appropriate corrective actions. This can include additional testing to determine the characteristics of turbidity (e.g. is it biological or does it represent the presence of manganese or iron oxides?) and the extent and persistence of the problem.

Further information on turbidity in distribution systems is available in Water Safety in Distribution Systems (WHO, 2014).

4.4 Household water treatment and storage

Turbidity can be used in operational monitoring of treatment processes and performance of clarification chemicals used in household and small drinking-water supplies (Elliott et al., 2008; Preston et al., 2008; Koltarz et al., 2009; WHO, 2011; Mwabi et al., 2012; WHO/UNICEF, 2012). Turbidity can also be used to measure the performance of some treatment processes in reducing chlorine demand or the performance of barriers designed to remove pathogens and microbial indicators (Elliott et al., 2008; Mwabi et al., 2012).

High levels of turbidity in source water may limit the effectiveness of household treatment methods; for example, by overloading and clogging filters, or reducing the effectiveness of chlorination or solar disinfection (WHO, 2011). While high turbidity is not desirable, chlorination can still provide benefits. Free chlorine residuals can be produced in the presence of turbidities ranging from above 1 NTU to above 100 NTU (Crump et al., 2005; Lantagne, 2008; Mohamed et al., 2015), resulting in inactivation of bacterial indicators and reductions in diarrhoeal disease (Crump et al., 2005; Elmaksoud et al., 2014). Based on the available evidence, while water should ideally be chlorinated at turbidities less than 1 NTU, if this cannot be achieved (e.g. through pre-treatment or settling), disinfection should still be practiced with higher disinfection doses or contact times (Table 1).

Increases in turbidity of stored household water, such as harvested rainwater, can indicate deterioration in water quality.

5. Turbidity and aesthetic quality of drinking-water

Visible turbidity reduces the aesthetic acceptability of drinking-water. Turbidity can vary in colour and appearance, ranging from milky-white clay-based particles to muddiness from sediments and soils, red-brown iron-based particles and black manganese-based particles. At high levels, turbidity can lead to staining of materials, fittings and clothes exposed during washing.

Many consumers equate turbidity with safety, and consider turbid water as being unsafe to drink. This response is exacerbated when consumers have been accustomed to receiving high-quality water. As a guide, "crystal-clear" water has a turbidity below 1 NTU, and water becomes visibly cloudy at 4 NTU and above. This is well above the levels expected in well-maintained and treated surface water supplies, and in most groundwater supplies. Although turbidity may be caused by particles with little health significance, complaints about unexpected turbidity should always be investigated because they could reflect significant faults or breaches in distribution systems.

Aesthetic impacts can lead to indirect health impacts if consumers lose confidence in a drinking-water supply and drink less water, or choose to use lower turbidity alternatives that may not be safe.

6. Conclusions

Turbidity is an important and versatile operational parameter that should be included in WSPs to support water quality management from catchment to consumer. It can be used to monitor source water quality, the effectiveness of coagulation and clarification, filtration and disinfection performance in a water treatment plant, and the effectiveness of distribution system management. At the household level, it can also be used to assess the appearance and acceptability of drinking-water supplied to consumers as well as the effectiveness of household water treatment and safe storage.

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