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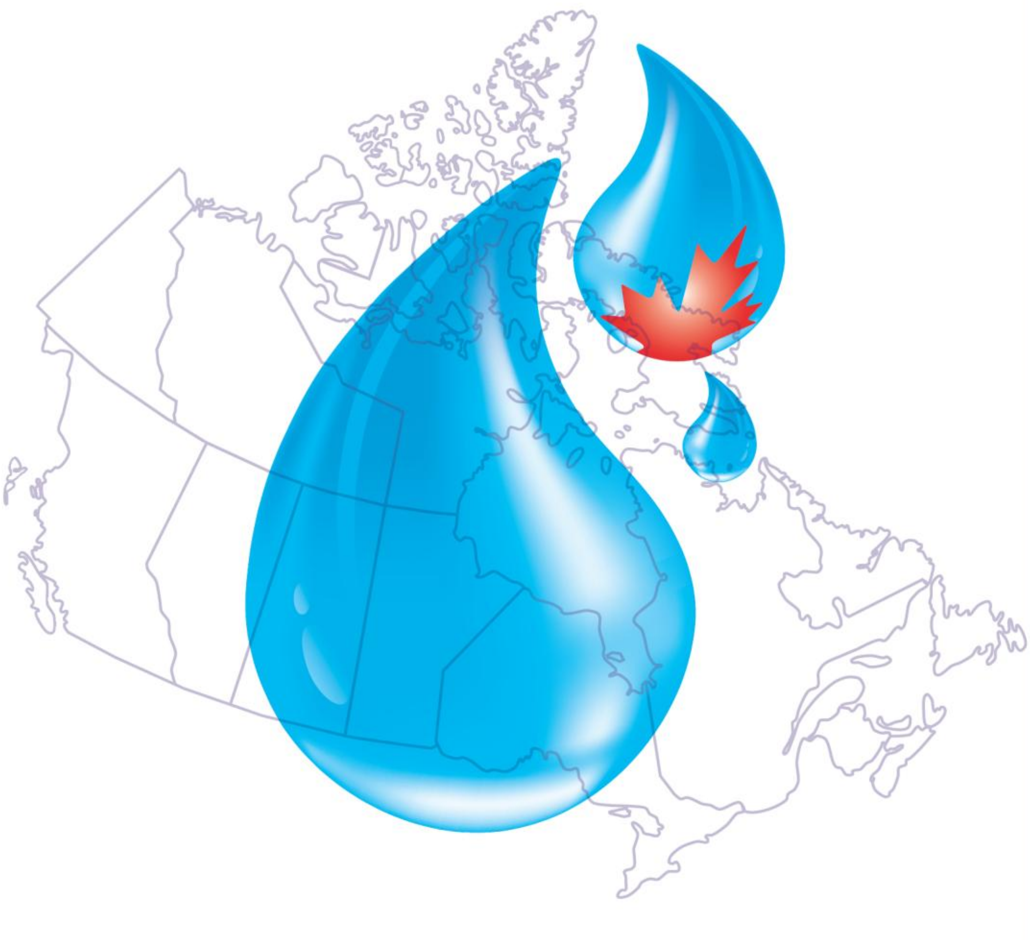
Guidelines for Canadian Drinking Water Quality

Guideline Technical Document

Turbidity



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Turbidity

**Prepared by the
Federal-Provincial-Territorial Committee on Drinking Water
of the
Federal-Provincial-Territorial Committee on Health and the Environment**

**Health Canada
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Turbidity

Part I: Overview and Application

1.0 Guideline

Turbidity levels are an important consideration for the effective design and operation of a variety of treatment processes and as an indicator of water quality changes in drinking water systems. For filtration systems that use conventional, direct, slow sand, diatomaceous earth or membrane technologies, the turbidity from individual filters or units should meet the following treatment limits in order to achieve health-based pathogen removal goals:

1. *For **conventional and direct filtration**, less than or equal to **0.3 nephelometric turbidity units (NTU)** in at least 95% of measurements either per filter cycle or per month and never to exceed 1.0 NTU ;*
2. *For **slow sand or diatomaceous earth filtration**, less than or equal to **1.0 NTU** in at least 95% of measurements either per filter cycle or per month and never to exceed 3.0 NTU ; and*
3. *For **membrane filtration**, less than or equal to **0.1 NTU** in at least 99% of measurements per operational filter period or per month. Measurements greater than 0.1 NTU for a period of greater than 15 minutes from an individual membrane unit should immediately trigger an investigation of the membrane unit integrity.*

Other considerations:

The aforementioned filtration systems should be designed and operated to reduce turbidity levels as low as reasonably achievable and strive to achieve a treated water turbidity target from individual filters of less than 0.1 NTU.

To ensure effectiveness of disinfection and for good operation of the distribution system, it is recommended that water entering the distribution system have turbidity levels of 1.0 NTU or less. For systems that are not required to filter by the appropriate authority, a higher turbidity level may be considered acceptable, provided that it does not hinder disinfection.

2.0 Executive summary

Turbidity is a measure of the relative clarity or cloudiness of water. It is not a direct measure of suspended particles, but rather a general measure of the scattering and absorbing effect that suspended particles have on light.

This guideline technical document reviews and assesses all identified health risks associated with turbidity in drinking water. It assesses new studies and approaches, and takes into consideration the availability of appropriate treatment technology. From this review, several guidelines for turbidity in drinking water are established, depending on the source water type and treatment processes used for filtration.

2.1 Health effects

The types of suspended particles that are most frequently encountered in natural water are not considered to be significant chemical hazards. The most important health-related function of turbidity is its use as an indicator of the effectiveness of drinking water treatment processes, particularly filtration, in the removal of potential microbial pathogens. There is no precise relationship between the magnitude of turbidity reduction and the removal of pathogens. Turbidity reduction, particle removal and pathogen removal are each largely dependent upon the source water quality and the selection and operation of the treatment technology.

Turbidity also has different implications for water quality and treatment depending on the nature of the particles involved and the location of the turbidity within the drinking water system. High turbidity measurements or measurement fluctuations can indicate a decline in source water quality, inadequate water treatment or disturbances in the distribution system.

2.2 Treatment and distribution

Generally, minimum treatment of supplies derived from surface water sources or groundwater under the direct influence of surface water (GUDI) should include adequate filtration (or technologies providing an equivalent log reduction credit) and disinfection. In the production of safe drinking water, filtration is an important barrier for removing particles that cause turbidity. Microorganisms, in addition to being particles themselves, can become attached to soil and waste particles in the environment and can aggregate or attach to inorganic or other particles during treatment. Effective removal of microbial pathogens is best achieved when water of low turbidity is produced and effective inactivation of microbial pathogens is best achieved when low-turbidity water is disinfected.

The most important consideration when dealing with turbidity is the need to reduce it to a level as low as reasonably achievable and to minimize fluctuation. Optimizing treatment performance for turbidity reduction and particle removal also generally optimizes pathogen removal and subsequent disinfection while reducing the potential formation of undesirable disinfection by-products. To maximize protection of public health from microbial contamination, filtration systems should strive to achieve the turbidity target of 0.1 NTU. Systems will have a higher risk for the passage of pathogens into the filtered water if they are not optimized to: (1) reduce filtered water turbidity levels to as low as possible; and (2) reduce the magnitude and likelihood of increases in turbidity levels.

The health-based treatment limits (HBTL) for the different filtration technologies have been established to help ensure that systems are meeting the minimum levels of pathogen removal (log removal credits) provided in the enteric protozoa guideline technical document. The HBTL are achievable by most filtration systems. However, filtration systems should be designed, operated and appropriately optimized to decrease turbidity levels as low as reasonably achievable and strive to achieve a treated water turbidity target from individual filters of less than 0.1 NTU at all times.

Where filtration is not required to meet pathogen removal goals, it is best practice to keep turbidity levels below 1.0 NTU to minimize the potential for interference with disinfection. In addition, to minimize particulate loading and effectively operate the distribution system, it is also good practice to ensure that water entering the distribution system has turbidity levels below 1.0 NTU.

3.0 Application of the guideline

Note: Specific guidance related to the implementation of drinking water guidelines should be obtained from the appropriate drinking water authority in the affected jurisdiction.

The turbidity limit that applies to a drinking water system depends on a variety of factors including requirements to meet pathogen removal goals, type of treatment technology used, and location in the drinking water system. The HBTL for individual filtration technologies were established so that the physical removal credits given for enteric viruses and protozoa combined with disinfection will achieve similar levels of public health protection for the various types of treatment systems. Generally, minimum treatment of supplies whose source is either surface water or GUDI should include adequate filtration (or technologies providing an equivalent log reduction credit) and disinfection. Surface water is defined as all waters open to the atmosphere and subject to surface runoff. GUDI is a groundwater supply that is vulnerable to surface water contamination or contamination by pathogens and, as such, should be treated as a surface water supply.

Turbidity has different implications for water quality and treatment depending on the nature of the particles involved and the location of the turbidity within the drinking water supply chain. An understanding of the type and source of the turbidity can be valuable when assessing the implications on the water quality or treatment. High turbidity measurements or measurement fluctuations can indicate inadequate water treatment, changes in source water quality, or disturbances in the distribution system.

As part of the multi-barrier approach to drinking water treatment, pathogen physical log removal credits should be used in conjunction with disinfection credits to meet or exceed overall treatment goals. Specific information pertaining to pathogen reduction requirements can be found in the guideline technical documents for enteric protozoa and enteric viruses. Because of the potential relationship between turbidity levels and microorganisms, this document should be read in conjunction with all guideline technical documents on microbiological parameters.

3.1 System-specific guidance

3.1.1 Pathogen removal

Where turbidity reduction is required as part of a strategy to meet pathogen removal goals, filtration systems should be designed and operated to reduce turbidity levels as low as reasonably achievable. At a minimum, these systems should meet the HBTL applicable to their specific treatment technologies. The filtration technologies discussed all employ monitoring of turbidity in the treated water as a tool for assessing the performance of the water treatment processes. Since the levels of turbidity achievable in filtered water and the associated potential pathogen removal vary depending on the pretreatment and the filtration technology used, different HBTL have been established to apply to each of the treatment technologies. It should be noted that the interpretation and implications of turbidity monitoring results may vary significantly between different filtration technologies and treatment scenarios.

For all filtration technologies, the HBTL for systems that are filtering to meet pathogen removal goals apply specifically to the turbidity of effluent water from individual filters. However, it is recommended that both the individual filter effluent turbidity and the combined filter (or clearwell or tank) effluent turbidity be continuously monitored. Continuous monitoring of the effluent turbidity from each individual filter is necessary to (1) ensure that each filter is functioning properly; (2) help determine when to end filter runs; and (3) detect any short-term or rapid increases in turbidity that represent a process failure and a potential health risk. Continuous monitoring of the combined filter effluent turbidity in the clearwell or tank will help ensure that the quality of the water entering the distribution system has not deteriorated following filtration.

3.1.1.1 Interpretation of the guideline

The HBTLs apply to turbidity that is measured in the effluent of individual filters during the period of filter operation when the effluent water is being disinfected and distributed to consumers. They are set based on meeting the values in the portion of measurements specified in Section 1.0 (95% or 99%) and also include ‘never to exceed values’.

Assessing whether a system’s performance satisfies the HBTL in at least 95% or 99% of turbidity measurements per filter cycle or per month, requires the collection of data over a period of time. The analysis of these data will then dictate whether further actions are needed to improve filter effluent turbidity. Action should be initiated if the applicable HBTL is exceeded. It is not the intent of the guideline to allow filters to operate above the HBTLs for reasons that can be foreseen, controlled or minimized. In many cases systems will be able to remain below these HBTLs 100% of the time. Any turbidity reading above the “never to exceed” value should be addressed immediately.

The actions initiated to address exceedances of the HBTL will be dependent on site-specific considerations and should be determined by the responsible authority on a case-by-case basis, taking into account local knowledge of the system’s capabilities and performance. Examples of possible actions may include conducting an investigation of filter performance or initiating corrective actions such as repairs, maintenance or removing the filter from service.

The turbidity target of 0.1 NTU provides the benchmark for assessing system optimization and for comparing improvements over time. Systems employing filtration for pathogen removal and meeting the applicable HBTL should strive to meet the treated water turbidity target of less than 0.1 NTU. Utilities should be aware that filters that meet the target of 0.1 NTU may achieve greater pathogen removal and improve overall public health protection. Developing and implementing a system optimization plan will improve filter performance and help ensure that systems are achieving the appropriate log removal credits.

3.1.1.2 Conventional and direct filtration

Conventional and direct filtration systems should strive to achieve a treated water turbidity target of less than 0.1 NTU at all times. Where this is not achievable or optimization has not yet been attained, it is considered acceptable for the treated water turbidity from individual filters to be less than or equal to 0.3 NTU. In general, all filters should be designed so that the filtered water produced immediately after filter backwashing is directed into a waste stream (“filter-to-waste”). Turbidity levels should be consistently kept below 0.3 NTU (with a target of less than 0.1 NTU) throughout the entire filter cycle, with the exception of the filter-to-waste period. However, it is recognized that some systems, such as those that are not filtering-to-waste, may not be able to achieve this value 100% of the time. Comparison of a system’s performance with the HBTL for 95% of turbidity measurements per filter cycle or per month allows utilities to establish operational procedures that are effective for each individual system. However, utilities should be aware that any turbidity measurement above 0.3 NTU may result in lower pathogen removal. Waterwork systems using conventional or direct filtration should investigate and minimize any occurrences of turbidity levels above 0.3 NTU.

The value of 1.0 NTU is identified as "never to exceed" because readings above this value suggest a significant problem with filter performance and subsequent disinfection efficacy may be impacted. Any turbidity values above 1.0 NTU should be investigated and addressed immediately.

3.1.1.3 Slow sand and diatomaceous earth filtration

Slow sand and diatomaceous earth filtration systems should also strive to achieve a treated water turbidity target of less than 0.1 NTU at all times. Although particulate removal using slow sand filtration may not achieve the same turbidity levels as conventional filtration, reducing turbidity as low as possible (goal of 0.1 NTU) remains an important goal and helps ensure that a slow sand filtration plant has been properly designed and is being well operated. Where this is not achievable or optimization has not yet been attained, it is considered acceptable for the treated water turbidity from individual filters to be less than or equal to 1.0 NTU. The value of 1.0 NTU is intended to apply throughout the entire filter cycle, with the exception of the filter-to-waste period. Slow sand filters should be operated to waste after starting or scraping until the filter effluent is consistently less than the standard required for the system. Waterworks systems using slow sand or diatomaceous earth filtration should investigate and minimize any occurrences of turbidity levels above 1.0 NTU.

Comparison of a system's performance with the HBTL for 95% of turbidity measurements per filter cycle or per month allows utilities to establish operational procedures that are effective for each individual system. Operators of slow sand and diatomaceous earth filtration systems should compare readings with operational monitoring records and flag any results above 1.0 NTU as exceedances of the HBTL. Utilities should be aware that any turbidity measurement above 1.0 NTU may result in lower pathogen removal and subsequent disinfection efficacy may be impacted.

The value of 3.0 NTU is stated as "never to exceed" because such significant exceedances suggest a major problem with performance. Any turbidity levels above 3.0 NTU should be investigated and addressed immediately.

3.1.1.4 Membrane filtration

Membrane filtration systems should reduce turbidity to as low as reasonably achievable. Turbidity measurements from membrane filter units should be below 0.1 NTU when membranes are intact and functioning properly. An individual membrane unit may be defined as a group of pressure vessels, cartridges or modules that are valved and isolated from the rest of the system for testing and maintenance. Any increase in turbidity above 0.1 NTU should be considered a potential breach in the integrity of either the membrane filtration unit or an individual filter cartridge. However, recognizing that the measurement of turbidity values below 0.1 NTU is more likely to be affected by the sensitivity of the turbidimeter to measurement error at lower turbidities, it may not be possible for 100% of measurements to be below this value. Therefore, comparison of a system's performance with the HBTL for 99% of turbidity measurements per filter operation period or per month allows utilities to establish operational procedures that are effective for each individual system. To allow systems some flexibility for addressing any uncertainty in turbidity measurements but also recognizing that any values above 0.1 NTU may represent an integrity breach, measurements greater than 0.1 NTU for a period of greater than 15 minutes should immediately trigger an investigation of the membrane unit integrity.

3.1.2 Other systems

While this guideline technical document is intended primarily for systems using surface water sources or GUDI that are filtering to meet pathogen removal goals, it is also important to understand the nature of the turbidity and to control its levels in other systems. In some cases, systems may be filtering for reasons other than pathogen removal, such as removing disinfection by-product precursor, improving the effectiveness of subsequent disinfection, or ensuring consumer acceptance. In other cases, systems may have technologies other than filtration in place, such as ultraviolet (UV) disinfection to provide reduction of certain pathogens. For these systems, a turbidity level of 1.0 NTU or less is recommended. Turbidity levels above this value may be acceptable depending on a variety of factors including the source water quality, the nature of the particles causing the turbidity and the design and operation of the treatment system. This should be evaluated on a case-by-case basis to ensure that the appropriate pathogen inactivation is achieved. Assessing whether a water supply and treatment system's performance satisfies requirements sufficient to be protective of public health should be done on a case-by-case basis. The responsible authority may choose to allow turbidity increases for individual systems, in light of a risk assessment that takes into account local knowledge of the system's capabilities and performance.

3.1.3 Groundwater

For systems that use groundwater that is not under the direct influence of surface water, which are considered less vulnerable to faecal contamination, turbidity should generally be below 1.0 NTU. Best practice for these systems includes appropriate well siting, construction and maintenance, as well as monitoring source water turbidity and ensuring that turbidity levels do not interfere with the disinfection and distribution of the water supply. In some cases, a less stringent value for turbidity may be acceptable if it is demonstrated that the system has a history of acceptable microbiological quality and that a higher turbidity value will not compromise disinfection. The responsible authority may choose to allow turbidity increases for individual systems, in light of a risk assessment that takes into account local knowledge of the system's capabilities and performance.

In keeping with the multi-barrier approach to drinking water quality management, systems using groundwater sources should:

- ensure that groundwater wells are properly constructed and maintained, are located in areas where there is minimum potential for contamination and have appropriate wellhead protection measures in place; these source water protection measures protect public health by reducing the risk of contamination of the drinking water source; and
- ensure that treatment is sufficient to achieve a 4-log reduction of viruses by disinfection where required; it is important to confirm that elevated turbidity levels will not compromise any disinfection process in place, including residual disinfection in the distribution system.

3.2 Distribution system

All drinking water systems should monitor and control turbidity throughout the entire distribution system including areas with long retention times, decreased disinfectant residual, or that have demonstrated deteriorating water quality. For effective operation of the distribution system, it is good practice to ensure that water entering the distribution system has turbidity levels below 1.0 NTU. Increases in distribution system turbidity can be indicative of deteriorating water quality and it is good practice to minimize turbidity fluctuations. Increases in turbidity can be sudden or can gradually increase over time. Although some variation in turbidity is normal, increases above typical turbidity levels measured during routine monitoring can provide an indication of potential contamination or stagnation. If an unusual, rapid, or unexpected increase in turbidity levels does occur, the system should be inspected and the cause determined.

Turbidity monitoring is used in conjunction with indicators of microbiological quality, including disinfectant residual and organisms such as *Escherichia coli (E. coli)*, heterotrophic plate counts (HPC) and total coliforms, to verify that there is no evidence of a recent deterioration of the microbiological quality of water in the distribution system.

Turbidity increases can have different origins which vary considerably in the threat they can pose to water quality and public health. It is not possible then to establish an across-the-board maximum value for turbidity in the distribution system to be used to make public health decisions and to expect it to be protective for all situations. The responsible authority may choose to allow turbidity increases for individual systems, in light of a risk assessment that takes into account local knowledge of the system's capabilities and performance.

3.3 Monitoring turbidity levels

While the primary focus of this document relates to monitoring turbidity at the treatment stage, turbidity can also be monitored in combination with other easily measured parameters from source to tap in order to better understand the status of the overall drinking water system and identify changing conditions. In many cases, changes in or exceedances of turbidity levels will trigger sampling for additional parameters that will help provide information on the status of the drinking water system.

3.3.1 Monitoring turbidity of source water

Monitoring turbidity levels in surface water and GUDI sources provides useful information that enhances overall system knowledge. Source water turbidity data are essential to ensure the appropriate design and operation of the treatment plant. Monitoring of the source water can identify changing source water conditions, such as a decline in source water quality, higher loadings of pathogens and increased challenges to filtration and disinfection. It helps establish historic trends that are capable of characterizing changing source water conditions.

Monitoring turbidity levels in groundwater sources provides key information for on-going health protection. Consistently low turbidity levels observed through varying seasons and weather conditions can help provide assurance that the well and aquifer remain less vulnerable to faecal contamination. On the other hand, observed increases in turbidity after a significant rain event, for example, can provide an indication of changes in the groundwater system in the vicinity of the well or a crack in the well casing, thereby prompting the operator to investigate and take corrective action.

3.3.2 Monitoring turbidity in treatment systems

For <u>conventional and direct filtration</u> (i.e., continuous feed of a coagulant with mixing ahead of filtration), source water turbidity levels should be measured at least daily just prior to the point of addition of treatment chemicals. Treated water turbidity levels from individual filters should be continuously measured (with an online turbidimeter) at intervals no longer than five minutes apart at a point in each individual filter effluent line. The combined filter effluent should also be monitored at some point downstream of the combined filter effluent line or the clearwell or tank. If turbidity monitoring occurs after the addition of some chemicals, such as lime, the chemical addition may increase the combined effluent turbidity relative to the turbidity of the water discharged from the filters.

For slow sand or diatomaceous earth filtration, treated water turbidity levels from individual filters should be continuously measured (with an online turbidimeter) at intervals no longer than five minutes apart at a point in each individual filter effluent line. The combined filter effluent should also be monitored at some point downstream of the combined filter effluent line or the clearwell or tank.

For membrane filtration, treated water turbidity levels from individual membrane units should be continuously measured (with an online turbidimeter) at intervals no longer than five minutes apart at a point in each individual filter effluent line. The combined filter effluent should also be monitored at some point downstream of the combined filter effluent line or the clearwell or tank. An individual membrane unit may be defined as a group of pressure vessels, cartridges or modules that are valved and isolated from the rest of the system for testing and maintenance. Consideration should be given in the design of membrane units to ensure that the level of sensitivity is sufficient to detect membrane breaches with turbidity monitoring or other integrity testing.

3.3.3 Monitoring turbidity within treated water storage and distribution systems

Monitoring turbidity in the distribution system can help identify areas where there may be changes to the water quality, such as biofilm growth, suspension of biofilms, release of corrosion products and disturbance of sediments. Monitoring turbidity in the distribution system may also provide an indication of potential contaminant intrusion from leaks, line breaks, pressure fluctuations or backflow. Turbidity within the distribution system can be monitored in conjunction with other parameters, such as pH, disinfectant residual and pressure, which also offer instant results on site. When integrated with routine monitoring activities in this way, deviations from normal conditions can be detected, and drinking water quality throughout the distribution system can be better understood. Similarly, turbidity measurements can inform maintenance schedules and aid in the detection of problems related to the condition of reservoirs, standpipes or holding tanks and infrastructure.

While such monitoring activities will aid in the detection of potential drinking water quality issues, decisions concerning corrective actions or the need for boil water advisories are made at the local or provincial/territorial levels. Such decisions would be based upon a risk management/risk assessment approach, taking into account other water quality parameters and site-specific knowledge. Increases in turbidity levels in the distribution system do not automatically signal the need for the issuance of a boil water advisory. However, unusual, rapid, or unexpected increases in distribution system turbidity can be indicative of deteriorating water quality and should be investigated.

3.4 Use of alternative filtration technology in drinking water systems

A filtration technology other than the technologies mentioned in section 1.0. may be used in a drinking water treatment plant. In cases where pathogen reduction goals need to be met, the treatment technologies selected, including disinfection, should reliably achieve a minimum 3-log reduction for *Giardia lamblia* cysts and *Cryptosporidium* oocysts and a minimum 4-log reduction for viruses. The turbidity values in section 1.0 may not be applicable to alternative technologies such as bag and cartridge filtration. Turbidity levels of filtered water from alternative technologies should be established by the responsible authority taking into account data from challenge testing or other methods used to demonstrate the effectiveness of the filtration technology.

As options evolve through advancements in science and technology, including applications for small systems, waterworks are encouraged to apply validated improvements and optimize existing systems as a matter of best practice. Maintaining current knowledge of best practices and remaining aware of advancements in the drinking water industry are important aspects of the multi-barrier approach to safe drinking water.

3.5 Considerations for exempting drinking water systems from filtration requirements

While it is a fundamental recommendation that all surface water and GUDI sources be filtered prior to disinfection, the decision to exempt a waterworks from this requirement should be made by the appropriate authority based on site-specific considerations, including historical and ongoing monitoring data. The following summary provides a brief description of some of the main considerations relevant to the decision to exempt a waterworks from the filtration requirements:

- *Vulnerabilities assessment*: Ensure a detailed current understanding of hazards inherent to the water source. This may include sources of microbial or chemical contaminants, activities that may impact the water source and historic information on fluctuations in source water quality, which may affect the chosen approach to treatment over time. These characteristics of the watershed or wellhead area should be well documented and maintained in such a way as to inform ongoing risk management considerations.
- *Source water protection*: A thorough understanding of measures being taken by all stakeholders to protect the source water should be maintained and documented over time. This would include the policies and regulatory requirements of agencies such as conservation authorities, municipal and provincial governments and local stakeholder groups, as well as permitted activities or land use in the area, potential sources of contaminants and threats to source water quality.
- *Inspection and verification*: Undertake adequate inspection and preventative maintenance from source to tap on a regular basis. Activities should be well documented such that a history of maintenance, upgrades and optimization approaches can be demonstrated over time. This includes the verification of the proper function and integrity of monitoring devices, treatment and distribution components.
- *Treatment*: Whether or not filtration technology is in place, the drinking water treatment process must still achieve a minimum 3-log reduction of *Giardia lamblia* cysts and *Cryptosporidium* oocysts and a 4-log reduction of viruses. Utilities using surface water or GUDI that are considering not using filtration will need to treat source waters for all three types of organisms (protozoa, viruses and bacteria), using a multi-disinfectant strategy. A possible strategy includes (1) ultraviolet irradiation or ozone to inactivate cysts/oocysts, (2) chlorine to inactivate viruses, and (3) chlorine or chloramines to maintain a residual in the distribution system. Consideration may also be given to strategies that may enhance robustness at the treatment stage. For example, these may include pre-sedimentation or other control strategies for intermittent increases in source water turbidity. The drinking water treatment process will also need to be operated to minimize the formation of disinfection by-products.

- *Distribution*: The distribution system should be appropriately designed, maintained and monitored in accordance with established best practice, and a disinfectant residual should be maintained throughout the distribution system.
- *Contingency or emergency response planning*: Also recommended is a well-developed site-specific response plan for episodes of elevated source water turbidity brought about by extreme weather or other unforeseen changes in source water quality that may challenge the drinking water treatment system in place.

Part II. Science and Technical Considerations

4.0 Identity and sources in the environment

4.1 Description of turbidity

Turbidity is a measure of the relative clarity or cloudiness of water. The turbidity of filtered water is usually measured in nephelometric turbidity units (NTU), using a device called a turbidimeter. Turbidity is not a direct measure of suspended particles, but rather a general measure of the scattering and absorbing effect that suspended particles have on light. The principle behind the method is that a beam of light remains relatively undisturbed when transmitted through absolutely pure water; particles, when present, cause that light to be scattered and absorbed rather than transmitted.

The manner in which particles interfere with light transmittance is dependent on a number of factors, including the size, shape, number, composition, colour and refractive index of the particles, the wavelength (colour) of light that falls on them and the refractive index of the water. Although the interaction appears complex, an important generalization that can be made is that the intensity of the light scattering increases as the turbidity increases (APHA et al., 2012). Because so many factors affect the intensity of light scattering, it is not possible to relate turbidity measurements directly to the number, size or type of particles in the water.

Similar to bacteriological indicator measurements, turbidity measurements are valuable indicators of water quality. High turbidity measurements or measurement fluctuations can be indicative of inadequate water treatment or a problem with water quality (LeChevallier et al., 1981). The main benefits of using turbidity measurements as an indicator are that analysis is rapid and relatively inexpensive, and can be conducted continuously.

4.2 Sources

The sources and nature of turbidity are varied and complex and are influenced by the physical, chemical and microbiological characteristics of the water. Turbidity-causing particles in water can range in size from colloidal dimensions (0.001–1.0 µm) up to diameters on the order of 100 µm. In natural waters, particulate material arises mostly from the weathering of rocks and soils (Gregory, 2006). Significant contributions also come from human activities (e.g., sewage and wastewater releases). Inorganic clays and silts and natural organic matter (decomposed plant and animal substances) make up the most common particulate constituents of water. Other particles include inorganic precipitates, such as metal (iron or manganese) oxides and hydroxides; biological organisms, such as algae, cyanobacteria, zooplankton and filamentous or macroscopic bacterial growths (i.e., biofilms); and naturally occurring asbestos minerals (Mackenthun and Keup, 1970; Kay et al., 1980). Products and materials that come into contact with drinking water during treatment (treatment additives and system components, such as filter materials, pipes, fittings and connections) can also have an effect on turbidity.

Turbidity has different implications for water quality and treatment depending on the nature of the particles involved and the location of the turbidity within the drinking water supply chain. An understanding of the type and source of the turbidity can be valuable when interpreting the impact of some turbidity-related issues. Table 1 summarizes some of the water quality and water treatment implications for different types of turbidity, and Table 2 summarizes some of the more common sources of turbidity.

Table 1: Turbidity type and implications for water quality and water treatment

Type of turbidity	Possible water quality/chemistry implications	Possible treatment implications
Inorganic particles		
Clay, silt mineral fragments, natural precipitants (e.g., calcium carbonate, manganese dioxide, iron oxide)	• Raise/lower pH and alkalinity • Source of micronutrients • Affect zeta potential • Source of metals and metal oxides • Cloudy/turbid appearance • Affect taste	• Major influence on coagulation, flocculation and sedimentation design • Harbour/protect microorganisms • May require chemical adjustments • Can precipitate in the distribution system
Organic particles		
Natural organic matter (decomposed plant and animal debris)	• Source of energy and nutrients for microorganisms • Cause colour	• Increased disinfectant demand • Harbour/protect microorganisms • Potential to form disinfection by-products
Organic macromolecules	• Impart taste and odour • Possess ion exchange and complexing properties; association with toxic elements and micropollutants • Affect pH and zeta potential	• Potential to form disinfection by-products • Major influence on coagulation, flocculation and sedimentation design • Reduce filter runs • Can precipitate in the distribution system
Microorganisms (algae, cyanobacteria, zooplankton, bacteria, protozoa)	• Impart taste and odour • Potential source of toxins (e.g., microcystin-LR) • Can cause microbiologically influenced corrosion in system • Stain fixtures • Aesthetic problems: sloughing of growths (tanks, filters, reservoirs, distribution system)	• Plug filters • Increased disinfectant demand • Need multiple barriers to ensure effective microbial inactivation • Biological growth (biofilm) • Shielding from disinfection

Table 2: Some common sources of turbidity within the drinking water supply chain

Component	Possible sources
Source water	• Surface runoff (SW/GUDI) • Natural weathering of rock formations (GW) • Resuspension of deposited sediment or settled solids (SW/GUDI, GW) • Waste discharges (sewage, wastewater) (SW/GUDI) • Blooms: cyanobacteria/algae (SW/GUDI) • Surface water recharge (GUDI) • Groundwater percolation (GW)
Treatment	• Treatment additives (e.g., coagulants, settling aids) (SW/GUDI) • Precipitation reactions (e.g., iron and manganese removal) (SW/GUDI, GW) • Fines from granular filter materials (SW/GUDI) • Incomplete particle removal during filtration (SW/GUDI, GW)
Distribution system	• Corrosion detachment (SW/GUDI, GW) • Scale detachment (SW/GUDI, GW) • Biological growth/biofilm detachment (SW/GUDI, GW) • Chemical reactions (e.g., precipitation reactions) (SW/GUDI, GW) • Sloughing of biological material from biofilters (SW/GUDI) • Sediment resuspension (SW/GUDI, GW) • Intrusion/main breaks (SW/GUDI, GW)

GW: groundwater; SW: surface water.

5.0 Analytical methods

The turbidity of filtered water is usually measured using the nephelometric method. Nephelometry determines turbidity using the intensity of scattered light measured by a detector that is at 90 degrees to the incident light source. Table 3 lists seven nephelometric methods for the measurement of turbidity in drinking water that have been developed by consensus standards organizations or are approved by recognized organizations. These methods have been developed to standardize instrument design and calibration in order to achieve consistency in turbidity measurements. Depending on the range of turbidity in source water, instruments that conform to these standards may not be appropriate for monitoring turbidity in source water.

The U.S. Environmental Protection Agency (EPA), the American Public Health Association (APHA) / American Water Works Association (AWWA) / Water Environment Federation (WEF), the International Organization for Standardization (ISO) and ASTM International (ASTM) have developed or approved these standardized methods. Utilities should use turbidimeters that conform to one of the methods discussed below when monitoring drinking water.

Table 3: Recognized analytical methods for measuring turbidity in drinking water

Method	Reference	Description
APHA/AWWA/ WEF Standard Method 2130B	APHA et al. (2012)	Tungsten lamp at 2200–3000 K and one or more perpendicular detectors (and filters) with spectral response peak of 400–600 nm; light path less than or equal to 10 cm. Applicable measurement range of 0 to greater than 1000 NTU.
U.S. EPA Method 180.1 Rev. 2.0	U.S. EPA (1993)	Tungsten lamp at 2200–3000 K and one or more perpendicular detectors (and filters) with spectral response peak of 400–600 nm; light path less than or equal to 10 cm. Applicable measurement range of 0–40 NTU.
ISO 7027	ISO (1999)	Tungsten lamp (and filters), diode or laser as radiation source at 860 nm (or 550 nm if sample is colourless) with a perpendicular detector and aperture angle of 20–30 degrees. Two applicable measurement ranges are available, depending on the method selected. The diffuse radiation method has a range of 0–40 FNU. The attenuation of radiant flux has a range of 40–4000 FAU.
GLI Method 2	GLI International Inc. (1992)	Two perpendicular 860 nm light sources alternately pulse each 0.5 seconds, and two perpendicular detectors alternately measure “reference” and “active” signals. Applicable measurement range of 0–40 NTU. The method allows dilution for measurement of samples above 40 NTU.
Hach FilterTrak Method 10133 Rev. 2.0	Hach Company (2000)	Laser diode at 660 nm at 90 degrees to detector/receiver (light path less than or equal to 10 cm), which may use photomultiplier tube and fibre optic cable. Applicable measurement range of 0–5000 mNTUs (0–5.0 NTU).
ASTM D6698-07	ASTM International (2007)	This method is for the online measurement of turbidity below 5 NTU in water. A variety of instrument technologies may be used in this method, including the design features listed in the methods above. Applicable measurement range of less than or equal to 0.02–5.0 NTU.
ASTM D6855-10	ASTM International (2010)	This method is for the static measurement of turbidity below 5 NTU in water. A variety of instrument technologies may be used in this method, including the design features listed in the methods above. Applicable measurement range of less than or equal to 0.02–5.0 NTU or FNU.

FAU: formazin attenuation unit; FNU: formazin nephelometric unit.

A variety of reporting units are available for turbidity, depending on the design of the turbidity instrument that is used. In general, devices that use a tungsten lamp with a colour temperature of 2200–3000 K and measure the scattered light at an angle of 90 degrees to the incident light beam use NTUs. Instruments that measure turbidity in formazin nephelometric units (FNUs) use a light-emitting diode with a wavelength of 860 ± 60 nm as a light source and a detector at 90 degrees to the incident light beam. Instruments that measure turbidity in formazin attenuation units (FAUs) use a light-emitting diode with a wavelength of 860 ± 60 nm and a detector at 180 degrees to the incident light beam. These units are equivalent when measuring a calibration solution; however, each different type of instrument may not produce directly comparable results when measuring the turbidity of a water sample (USGS, 2005).

The U.S. EPA recently reviewed the methods available for measuring turbidity in drinking water and has approved four versions of APHA/AWWA/WEF Standard Method 2130B, which were published in 1991, 1995, 1998 and 2005 (U.S. EPA, 2008). Of the methods listed in Table 3, the U.S. EPA has also approved U.S. EPA Method 180.1 Rev. 2.0, GLI Method 2 and Hach FilterTrak Method 10133 Rev. 2.0.

5.1 Instrumentation

Nephelometric turbidity instrumentation varies in design, range, accuracy and application. The design of nephelometric instruments should take into account the physics of scattered light. The size, shape and concentration of the particles affect the intensity pattern and distribution of the scattered light. Small particles less than one tenth of the light wavelength will scatter light uniformly in both forward and backward directions. As the particle size approaches and exceeds the wavelength of the incident light, more light is transmitted in the forward direction. Because of this intensity pattern, the angle at which the light is measured is a critical factor; the current international standards have determined the most appropriate angle to be 90 degrees for the measurement of low turbidities (generally below 40 NTU) (APHA et al., 2012). Nephelometric turbidimeters can also include ratio technologies which are based on the use of a 90 degree detector in combination with another detector set at a different angle that determine the turbidity of a sample. Ratio technologies can help to compensate for interferences due to colour and particulate absorbance that are common in turbidity measurements (ASTM International, 2011). As noted above, as the concentration of particles increases, more particles reflect the incident light, increasing the intensity of the scattered light. Once the concentration of particles in a sample exceeds a certain level, which is determined by the specific optical characteristics of the process, the particles themselves begin to block the transmission of the scattered light. The result is a decrease in the intensity of the scattered light, which establishes the upper limit of the measurable turbidity (Sadar, 1998). Nephelometers are most effective for measuring light scattered by particles in the 0.2–1 µm size range, with a peak scatter at approximately 0.2 µm. The intensity at which various wavelengths of light are reflected or absorbed is also determined by the colour of the liquid and the reflecting surface. Industry standards require nephelometers to operate in the visible or infrared ranges: 400–600 and 800–900 nm, respectively (ISO, 1999; APHA et al., 2012).

All of these factors, along with the optical geometry of a particular instrument, cause measured values between instruments to vary widely; thus, criteria for instrument design have been developed to minimize these variables. The manufacture of nephelometric turbidimeters is guided by the instrument design requirements that are specified in the standards listed in Table 3.

Measurement technologies other than the nephelometric technique discussed above are available and vary by the light source type, the number of detectors and the detection angles that are used to obtain a turbidity measurement. In particular, different technologies may be more suitable for measuring higher levels of turbidity (generally greater than 40 NTU) or for measuring turbidity in the presence of colour. These technologies include ratio, surface scatter, back scatter, forward scatter and multi-beam techniques. Recently, a consensus-based guide on the application of various technologies for turbidity measurement has been developed and may aid readers in selecting the most appropriate technology for their water type (ASTM International, 2011).

5.2 Instrument performance

Filtered water turbidity is typically well below 1.0 NTU and is often below 0.1 NTU. Certain filtration methods, such as reverse osmosis, can achieve turbidity values that approach those of pure water, in the range of 0.010–0.015 NTU. The sensitivity of turbidimeters and the precision and accuracy of the measurements at low turbidity levels are important aspects in the practical application of turbidity monitoring (Sadar, 1998).

5.2.1 Sensitivity

According to U.S. EPA Method 180.1, GLI Method 2 and APHA/AWWA/WEF Standard Method 2130B, nephelometers designed under these methods should be able to detect turbidity differences of 0.02 NTU or less in waters having a turbidity of less than 1.0 NTU. All three methods state that turbidity readings should be reported to the nearest 0.05 NTU when the turbidity range is 0–1.0 NTU. ISO 7027 (ISO, 1999) indicates that results should be reported to the nearest 0.01 FNU when turbidity is below 0.99 FNU. ASTM D6855-10 for the static measurement of turbidity states that the resolution of the instrument should permit detection of turbidity differences of 0.01 NTU or less in waters with a turbidity of less than 5.0 NTU. Results should be reported to the nearest 0.01 NTU for water with turbidity of less than 1.0 NTU and to the nearest 0.05 NTU for water with turbidity between 1.0 and 5.0 NTU (ASTM International, 2010). ASTM D6698-07 for online turbidity measurements states that turbidity differences of 0.01 NTU or less should be detected in water with a turbidity less than 1.0 NTU and that differences of 0.10 NTU or less should be detected in waters with turbidity between 1.0 and 5.0 NTU. Results should be reported to the nearest 0.01 NTU for water with turbidity less than 1.0 NTU and to the nearest 0.1 NTU for water with turbidity between 1.0 and 5.0 NTU (ASTM International, 2007).

Laser turbidimeters, although more costly, are another option for measuring turbidity and typically have a higher sensitivity than standard nephelometric meters. Hach FilterTrak Method 10133 (Determination of Turbidity by Laser Nephelometry) has an applicable range of 0–5000 mNTU (0–5.0 NTU) (Hach Company, 2000). This method states that the instrument has a sensitivity that should permit the detection of a turbidity difference of 1 mNTU (0.001 NTU) or less in waters having turbidities less than 5.0 NTU. It is suggested that laser turbidimeters are better suited for monitoring treated water from membrane filtration because of the extremely low levels of turbidity that can be achieved using this treatment method. Research has indicated that the increased sensitivity of laser turbidimeters may make them more effective than standard nephelometers at detecting membrane integrity breaches (Banerjee et al., 1999, 2001; U.S. EPA, 2005). More recent studies also suggest that laser nephelometers are capable of measuring early end-of-run filter breakthrough and other very small increases in turbidity that are useful for conventional filtration plant optimization (Sadar and Bill, 2001; Sadar et al., 2009). Sadar et al. (2009) also demonstrated that measurement of a submicrometre (<0.01 µm) particle breakthrough event was possible using a laser nephelometer and that the sensitivity of laser nephelometers was equivalent to that of particle counters.

5.2.2 Performance

Several studies have evaluated the performance of turbidimeters in measuring turbidity in the range of 0.1–0.3 NTU. The U.S. EPA conducted a study of the ability of different types of turbidimeters to measure low turbidity levels by distributing standard suspensions with a reported value of 0.150 NTU to a variety of laboratories. The results indicated that benchtop, portable and online turbidimeters all had a positive bias compared with the true value of the samples provided, with results between 0.176 and 0.228 NTU. This suggests that errors in turbidimeters may be conservative from a filtered water perspective; that is, plants may actually achieve slightly lower levels than those indicated on the meter. The standard deviations on the samples analyzed by each type of meter ranged from 0.0431 to 0.0773 NTU (U.S. EPA, 2003b). Similarly, ASTM conducted an interlaboratory study of static turbidimeters (benchtop or portable). A standard sample with a turbidity of 0.122 NTU was provided to seven laboratories, and the precision and bias of the laboratory measurements were calculated. This study found a laboratory standard deviation of 0.0190 NTU and a single analyst standard deviation of 0.0089 NTU (ASTM International, 2010). This indicates that there may be some variability between measurements obtained from different laboratories; however, when a single analyst is employed, the standard deviation can be quite low.

Letterman et al. (2002) conducted a detailed evaluation of the effect of turbidimeter type, design and calibration method on low-level turbidity measurements. The authors found that factors such as light source and calibration material did not have a significant effect on turbidity measurements using benchtop or portable instruments. The calibration procedure did, however, have a significant effect on the turbidity measurements and resulted in two categories of instruments. One group of instruments (Group A) used a calibration procedure to automatically set a low particle reading sample at either 0.00 or 0.02 NTU. This group of instruments had lower average readings than the second group (Group B) of instruments, which did not automatically assign a predetermined reading to a low particle sample. When the turbidity of a sample was less than 0.15 NTU in the Group A instruments, the Group B instruments measured between 0.00 and 0.02 NTU.

Letterman et al. (2002) also evaluated online turbidimeter performance. The study found poor agreement between different online instruments, with an average range in turbidity measurements of 0.5 NTU. The authors believed that bubble interference may have resulted in some of the discrepancies between instruments. In contrast, ASTM International (2007) conducted an independent intralaboratory study of online instruments and found that the relative standard deviation varied between 7.3% and 12% for different instruments measuring a turbidity standard of 0.1 NTU. Although some degree of interinstrument variability has been demonstrated, it is generally believed that low-level turbidity measurements can be used as a performance indicator for achieving very high quality filtered water (less than 0.1 NTU) and as an indicator of treatment plant optimization within one treatment plant (U.S. EPA, 2006b).

Overall, currently available instruments are capable of measuring turbidity reliably at levels below 0.1 NTU. However, analysts must be aware of the factors that can affect turbidity measurements and be careful to minimize potential sources of measurement error. In addition, low-level turbidity measurement must be accompanied by careful instrument calibration and verification as well as comprehensive standard operating procedures, including rigorous analyst training (U.S. EPA, 2003b).

5.3 Quality assurance/quality control

As discussed above, in order to be able to accurately measure turbidity below 0.1 NTU, rigorous standard operating procedures and a high level of quality assurance and quality control (QA/QC) are required. Utilities should ensure that the appropriate operation, maintenance and calibration programs are in place for all turbidimeters. For example, all utilities should have operating procedures for cleaning turbidimeters, creating or using standards, sampling and calibrating turbidimeters. It is recommended that utilities calibrate online turbidimeters at least quarterly, or more frequently if recommended by the manufacturer. The calibration of turbidimeters should then be verified weekly with the appropriate standard and re-calibrated if the turbidimeter has drifted more than 10% from the value assigned to the standard. Most of the analytical methods listed in Table 3 include detailed information on the preparation of appropriate standards for calibration and the calibration procedure for turbidimeters. Preventive maintenance should also be part of a routine turbidimeter QA/QC program. Weekly inspections and regular cleaning of lenses, light sources, sample reservoirs, air bubble traps and sample lines are important to ensure proper operation of the turbimeter. A detailed discussion of the development of QA/QC programs can be found in the literature (Burlingame et al., 1998; Sadar, 1998; U.S. EPA, 1999, 2004).

Other factors, such as air bubbles, stray light, coloured water and particle contamination, should also be considered in QA/QC programs, as these can cause false high or low readings for turbidity (Burlingame et al., 1998; Sadar, 1998; APHA et al., 2005). In some cases, the factors listed above can have a significant effect on turbidity measurements. A recent study of bubble interference in online turbidimeters found that bubbles can cause turbidity spikes as large as 2.0 NTU, depending on the type of instrument used and the level of gas supersaturation in the sample (Scardina et al., 2006).

Several of the methods listed above also provide guidance on sampling and sample handling. As the turbidity of a sample can change due to changes in temperature and particle flocculation and sedimentation, samples should be analyzed immediately (ISO, 1999; ASTM International, 2010; APHA et al., 2012). It is recommended that samples be analyzed using on-site turbidimeters in the treatment plant or portable turbidimeters when conducting sampling in the field.

5.4 Particle counting

Electronic particle counters are now available that are capable of accurately counting and recording the number of particles as a function of size (often in the 1–150 µm range). Although in some cases there may be a general relationship between particle counts and turbidity at levels below 1.0 NTU, a direct correlation does not exist (Bridgeman et al., 2002).

A simple conversion factor relating particle counts to turbidity is not possible, because the two techniques for their measurement differ fundamentally in terms of discernment. Particle counting measures two characteristics of particulates: particle number and particle size. Samples with identical clarity can be distinguished on the basis of these two features; one sample may contain many small particles, whereas another may contain a few large particles. Turbidity, on the other hand, cannot distinguish between two samples of identical clarity and different particulate composition. It is difficult to correlate turbidity with the particle concentration of suspended matter. As the size, shape and refractive index of particles affect the light-scattering properties of the suspension, they therefore, affect the turbidity (APHA et al., 2012). In addition, turbidimeters can detect particles smaller than 1 µm, whereas the lower size for detection by particle counters is in the range of 1–2.5 µm. As a result, data from the two instruments may not correlate.

Particle counters are an excellent tool for optimizing treatment processes and for detecting the onset of filter breakthrough. They are restricted to performance verification only, and no limit is set as a maximum acceptable concentration for the number of particles in the treated water.

6.0 Treatment technology

Turbidity is reduced by removing particles from the water through several processes, including, but not limited to, settling, coagulation/flocculation, sedimentation, flotation, adsorption and filtration. Adequate filtration can be achieved by a variety of technologies: conventional and direct filtration, slow sand filtration, diatomaceous earth filtration, membrane filtration or an alternative proven filtration technology.

These technologies all employ monitoring of turbidity in the treated water as a tool for assessing the performance of the water treatment processes. However, the levels of filtered water turbidity that are achievable and the associated potential pathogen removal vary depending on the pretreatment and the filtration technology used. Therefore, a different HBTL will apply to each filtration technology. In addition, the interpretation and implications of turbidity monitoring results vary significantly between different filtration technologies. For example, determining the optimal effluent turbidity levels to maintain and interpreting variations in turbidity during filter operation differ between conventional filtration and slow sand filtration. In this case, the two technologies rely on different turbidity removal mechanisms, and the relationship between turbidity reduction and pathogen reduction is also different.

There are many factors that affect the efficiency of turbidity reduction in filtration processes, depending on the type of technology that is being used. Some of these factors include source water quality, filtration rates, chemical pretreatment, filter media size/type and surface characteristics, filter run length, filter maturation, water temperature, filter integrity and backwashing procedures. Utilities need to identify the main factors that affect turbidity reduction for the filtration technology that is being used and optimize the process. Ensuring that filtration processes are performing optimally helps to increase the level of protection from potential contaminants, including pathogens, in the treated water (U.S. EPA, 1998b).

Although turbidity is not a direct indicator of the presence or absence of pathogens in treated water, it is recognized as the most readily measurable parameter to indicate filtration treatment effectiveness (U.S. EPA, 1998a). As such, extensive studies have been conducted on the use of turbidity as a performance and optimization indicator and its relationship to the removal of contaminants, such as pathogens, for a variety of filtration methods. This topic is discussed in greater detail in section 7.1.2. There has also been a significant amount of research examining the filtered water turbidity typically achieved by well-operated and well-maintained filtration plants and its relationship with the removal of pathogens. A discussion of filtered water turbidity levels and the average potential pathogen removal credits for the different filtration technologies that are discussed below is provided in Appendix B. In addition, guidance on the programs and methods that utilities can follow to achieve a lower turbidity target of 0.1 NTU is provided in Appendix C.

6.1 Conventional and direct filtration

The conventional filtration process generally includes chemical mixing, coagulation, flocculation, sedimentation (or dissolved air flotation) and rapid granular filtration. The direct filtration process includes coagulation and flocculation; however, no sedimentation or flotation is used, and flocculated water proceeds directly to filtration. While conventional filtration can be used on a wide variety of source water quality, direct filtration is typically limited to source water with turbidity that is below 15 NTU (MWH, 2005).

In conventional and direct filtration processes, particles are removed by physicochemical filtration. Chemical pretreatment using coagulants, pH adjustment and polymers is essential to conventional and direct filtration processes, destabilizing the negatively charged colloidal particles, such as clays, algae, cysts and viruses. This destabilization allows aggregation of particles to occur via chemical and van der Waals interactions, and the resulting particles are removed during sedimentation and/or filtration (Stumm and O'Melia, 1968; Stumm and Morgan, 1969; Logsdon, 2008). Aluminum and ferric salts are used as primary coagulants. Cationic and anionic polymers are most commonly used as flocculation aids, and both, along with non-ionic polymers, have been used as filter aids. The granular media filter is the most common type of filter used, and it may be a single-medium, dual-media or multi-media design. In both filtration processes, the effectiveness of particle removal is highly dependent on optimization of the chemical pretreatment (Cleasby et al., 1989; Logsdon, 2008). Filter loading rates generally range from 3.0 to 15 m/h, with some high-rate filters capable of 33 m/h (MWH, 2005).

All conventional and direct filtration plants should conduct continuous turbidity monitoring of filter effluent as an indicator of the performance of the treatment process. Continuous monitoring of the effluent turbidity from each individual filter as well as continuous monitoring of the combined filtered water turbidity from all filters are considered operational necessities in order to provide adequate performance data (Cleasby et al., 1992; U.S. EPA, 1998b; Logsdon et al., 2002; Logsdon, 2008). Continuous monitoring of individual filters has been identified as a key factor in achieving low-turbidity filtered water, enabling filter optimization and adequately detecting individual filter turbidity spikes (Cleasby et al., 1989; Renner and Hegg, 1997; U.S. EPA, 1998b). Continuous monitoring is necessary to ensure that each filter is functioning properly, to help determine when to end filter runs and to detect any short-term or rapid increases in turbidity that represent a process failure and a potential health risk. It also allows utilities to obtain a better understanding of routine filter performance, including establishing filter cycle trends and stable operation turbidity levels (Logsdon et al., 2002). In addition, comprehensive data on turbidity levels through all phases of the filter cycle trend are essential to be able to identify decreasing filter performance and to facilitate filter assessments and optimization programs.

The turbidity of filtered water from conventional and direct filtration plants generally follows a characteristic pattern with distinct segments in which turbidity levels vary depending on the filter run time (Amirtharajah, 1988). A filter cycle includes a pre-ripening period in which the turbidity increases due to the influence of post-backwash remnants above and within the filter, followed by a ripening period in which the turbidity decreases and approaches the level maintained during the stable filter operation phase. If a filter is operated for a long enough period of time, the turbidity will eventually start to increase. This is referred to as the end-of-run and breakthrough phases, when ultimately the filtered water turbidity will reach a maximum value (Amirtharajah, 1988; Cleasby et al., 1989; Logsdon et al., 2002). Filter operation periods such as following backwashing and at the end-of-run are generally characterized by increases in turbidity and risk of the presence of pathogens in the filtered water (Huck et al., 2001; Amburgey et al., 2005; Emelko et al., 2005). In general, all filters should be designed so that the filtered water produced immediately after filter backwashing is directed into a waste stream ("filter-to-waste"). However, in cases where this is not possible, other techniques, such as enhanced backwashing, delayed start and gradual filtration rate increases, can mitigate the initial turbidity spike (Logsdon et al., 2002; Amburgey et al., 2003, 2004; Logsdon, 2008). Similarly, during the stable operation phase of filters, unexpected turbidity spikes (rapid increase and decrease in turbidity) may occur as a result of a variety of factors, such as coagulant dosage upsets, pH changes, hydraulic surges (i.e., filtration rate increases), source water turbidity spikes and other operational factors. These spikes can have a significant effect on the passage of pathogens into the filtered water and are discussed in greater detail in section 7.1.2 (Nieminski and Ongerth, 1995; Patania et al., 1995; Huck et al., 2002; Emelko et al., 2003, 2005; Emelko and Huck, 2004). As the risk of the presence of pathogens in filtered water increases during turbidity increases and spikes, it is essential that utilities immediately investigate and determine the cause of any changes in filtered water quality.

Utilities also need to ensure that the filtration process is sufficiently robust to consistently provide high-quality filtered water and ultimately to maximize public health protection. In general, a robust filtration process is one that performs well both under normal operating conditions as well as during periods when filters may be challenged, such as during high source water turbidity events or coagulation upsets (Huck and Coffey, 2002; Li and Huck, 2007); however, robust performance must be carefully defined, as recent studies have indicated that robust turbidity removal may not always be indicative of adequate pathogen removal by filtration (Emelko et al., 2003; Brown and Emelko, 2009). It is essential for utilities to monitor and understand the turbidity levels of each filter throughout its operation to ensure that both stable operation periods as well as periods when filtered water turbidity is expected to be higher are managed appropriately. Systems that are not optimized to reduce stable operation turbidity levels to as low as possible as well as reduce the magnitude and likelihood of peaks or increases in turbidity levels are of particular concern with respect to the passage of pathogens into the filtered water.

6.1.1 Turbidity of conventional and direct filtration effluent

Conventional and direct filtration systems are capable of producing water with a turbidity of less than 0.3 NTU. Well-operated, optimized treatment plants have demonstrated that producing water with a turbidity of less than 0.1 NTU is achievable on an ongoing basis (U.S. EPA, 1997a, 1998a; McTigue et al., 1998; PSW, 2012b). These studies also indicated that maintaining a maximum filtered turbidity level below 1.0 NTU is also readily achievable for conventional and direct filtration plants. Therefore, meeting the HBTL for conventional and direct filtration systems is feasible, and it is expected that the majority of systems will already be meeting this value.

As part of the process for promulgating its Interim Enhanced Surface Water Treatment Rule (IESWTR), the U.S. EPA evaluated historical turbidity performance data from three large data sets encompassing conventional and direct filtration plants across the United States from 1995 to 1996. The analysis indicated that approximately 78% of the systems serving more than 10 000 people attained a 95th-percentile turbidity limit of 0.3 NTU. Maximum monthly turbidity values were below 1.0 NTU in over 94% of the systems that were evaluated (U.S. EPA, 1997a, 1998a). Similarly, a national assessment of particle removal using filtration conducted in 100 conventional and direct filtration treatment plants in the United States during the period from 1994 to 1996 indicated that the median filtered water turbidity did not exceed 0.2 NTU (McTigue et al., 1998). A more detailed examination of the turbidity of filtered water was conducted at a subset of filtration plants (52 plants) where turbidity measurements were taken by the researchers in addition to the turbidity data that was obtained from the filtration plant staff. This data indicated that over 90% of the plants attained 95th-percentile turbidity values below 0.3 NTU. Furthermore, over 85% of the plants did not exceed a maximum monthly turbidity value of 0.3

NTU. This study included a variety of treatment types (i.e., type of coagulant, filter media, etc.), source water characteristics and operating protocols. It should be noted that these data are from historical studies that evaluated the performance of filtration plants at the time, and it may not be indicative of the effluent turbidity levels that filtration plants may have been capable of achieving with the appropriate system optimization.

More recently, data collected by the Partnership for Safe Water (PSW) indicate that approximately 99% of participating surface water and GUDI filtration plants reported monthly 95th-percentile turbidities less than 0.2 NTU (PSW, 2012b). Similarly, 98% of the monthly maximum turbidity values were less than 0.3 NTU. The data in this report were collected from 404 treatment plants in the United States. The systems ranged in size from less than 3500 to over 700 000 people served. Although many of the largest utilities in the United States participate in the PSW, over 50% of the utilities that currently participate serve fewer than 100 000 people. These data indicate that well-operated conventional and direct filtration plants should not have difficulty operating below 0.3 NTU (U.S. EPA, 1997a, 1998a; McTigue et al., 1998; PSW, 2012b).

Several other historical studies examining either the design and operational practices or the performance of conventional filtration plants have demonstrated that producing filtered water with turbidity of less than 0.3 NTU is achievable for well-operated plants. The plants examined in these studies included a wide geographic coverage in the United States and Canada as well as a diversity of raw water types and system sizes (Cleasby et al., 1992; Consonery et al., 1997; Lusardi and Consonery, 1999; Statistics Canada, 2009).

A survey conducted in 2007 of Canadian conventional and direct filtration plants serving drinking water to over 12 million people reported that 79% of plants did not exceed an average treated water turbidity of 0.3 NTU and that 80% of the plants did not exceed a monthly maximum turbidity value of 1.0 NTU (Statistics Canada, 2009). Lusardi and Consonery (1999) conducted an evaluation of 75 conventional, direct and package filtration plants and found that the average 95th-percentile turbidity was 0.2 NTU and that over 90% of the plants did not exceed a maximum monthly turbidity of 1 NTU. The authors found that most plants consistently attained low turbidity levels despite limitations such as system size, plant age or high source water turbidity. In addition, the authors noted that the type of treatment plant (conventional, direct or package) did not have a significant effect on the annual average or maximum monthly filtered turbidity values that could be achieved. Conventional, direct and package treatment plants were all capable of achieving average annual turbidities of 0.2 NTU or lower. Other operational studies at specific plants have indicated that low turbidities in plant effluent are readily achievable when competent operations are in place (Logsdon et al., 2002). It should be noted that although the levels of turbidity reduction that can be achieved in conventional and direct filtration plants have been found to be comparable, other studies have found that particle count and pathogen reduction may be lower in direct filtration plants than in conventional filtration plants (Patania et al., 1995; McTigue et al., 1998). A more detailed discussion on direct filtration and pathogen removal can be found in section 7.1.2.

The U.S. EPA conducted an analysis of smaller systems serving fewer than 10 000 people to determine if these systems would be able to meet a turbidity limit of 0.3 NTU (U.S EPA, 2000, 2002). Data indicated that approximately 46% of smaller systems across the United States were meeting a turbidity limit of 0.3 NTU and that approximately 70% of systems were meeting this limit for 9 months of the year. Similarly, maximum monthly turbidity values were below 1 NTU in 88% of the systems evaluated (U.S. EPA, 2000). Additional studies that were evaluated indicated that between 41% and 67% of smaller systems were meeting a turbidity limit of 0.3 NTU, including systems that were classified as package plants or “pre-engineered” systems (U.S. EPA, 2000). These data suggest that smaller systems may have more difficulty than larger systems in achieving low filtered water turbidity levels. It is recognized that smaller systems have financial and resource limitations that make the operation of filtration plants more difficult. DeMers and LeBlanc (2003) found that operations and maintenance were the primary factors limiting the achievement of low turbidity levels by smaller systems.

6.1.2 Factors affecting conventional and direct filtration effluent turbidity

Many factors can affect the efficiency of turbidity reduction in conventional and direct filtration systems. Some of the main factors, such as non-optimal or no coagulation, lack of filter-to-waste or non-optimized backwashing techniques, intermittent operation, sudden rate changes and operating filters after turbidity breakthrough, can have a significant impact on filtered water turbidity (AWWA, 1991). There is a significant body of reference material that utilities can use to ensure that operational procedures are designed to minimize effluent turbidity under plant-specific conditions (Renner and Hegg, 1997; U.S. EPA, 1998b, 1999, 2004; Logsdon et al., 2002; Logsdon, 2008). The main procedures that have been identified as key factors in ensuring that a filtration plant is well operated are (1) monitoring instrumentation; (2) monitoring filter run performance; (3) managing pretreatment; (4) optimizing backwash; and (5) inspecting filter media (Logsdon et al., 2002).

In addition to the studies that have examined the design and process conditions that can affect the efficiency of turbidity reduction, studies have also examined both the operational and administrative factors that can affect a filtration plant’s ability to achieve lowered filtered water turbidity. In general, these studies demonstrated that the operational and administrative aspects of a plant are the key factors that contribute to successfully achieving low turbidity goals (less than 0.1 NTU) and that, in many cases, large capital expenditures are not required to achieve these goals. Operational factors, such as optimizing chemical pretreatment (coagulant dosage and pH), practising filter-to-waste or other techniques to mitigate the effect of the initial turbidity spike, using filter aids and optimizing filter backwash, are important in achieving low turbidity in finished water. Administrative factors, such as management and operator commitment to achieving low turbidity goals and good operator training procedures, were also identified as key factors (Cleasby et al., 1989; McTigue et al., 1998; Lusardi and Consonery, 1999; DeMers and LeBlanc, 2003).

McTigue et al. (1998) collected turbidity data from 52 filtration plants in order to assess the number of plants that were meeting a 0.1 NTU turbidity criterion. Of the plants that did not meet a 95th-percentile of 0.1 NTU criterion, the authors determined that the majority of the failures (54%) were due to ripening turbidity spikes or end-of-run turbidity spikes. Of the plants that did not meet a 99th-percentile 0.1 NTU criterion, the failures were predominantly associated with only a ripening spike. The authors concluded that for many of the filter runs, a lower turbidity level could have been maintained by providing or extending a filter-to-waste period or ending filter runs sooner. These results are consistent with the goals of either filtering-to-waste or maintaining optimum filter performance following backwash, which are supported by the U.S EPA, AWWA and PSW (Renner and Hegg, 1997; U.S. EPA, 1998b; PSW, 2011). Optimum filter backwash performance involves either conducting filter-to-waste until turbidity levels have returned to 0.1 NTU or less or minimizing the magnitude and duration of the post-backwash spike (ripening) to less than 0.3 NTU, with turbidity returning to 0.1 NTU in less than 15 minutes following backwash (Renner and Hegg, 1997). A number of strategies have been documented in the literature for minimizing filter ripening (post-backwash) turbidity levels (Cleasby et al., 1992; Logsdon et al., 2002, 2005a,b; Amburgey et al., 2003, 2004; Amburgey, 2005; Amburgey and Amirtharajah, 2005; Logsdon, 2008).

In a study of 75 filtration plants in Pennsylvania, variables such as source water quality, plant type and design and operational parameters such as filter rate and coagulant used were examined to determine their effects on filtered water turbidity (Lusardi and Consonery, 1999). Other parameters, such as population served and plant age, were also evaluated. Plants that did not use pretreatment with a coagulant did not achieve low turbidity in the filtered water. This is consistent with other studies that have demonstrated that pathogens are also not effectively removed in plants where pretreatment is not used. The study found that plants that did not use a coagulant, served small systems (less than 3300 people served) or treated water from streams had statistically higher turbidity values relative to all of the plants in the study. Plants using a coagulant were able to consistently achieve low turbidity levels regardless of limitations such as system size, plant age or high source water turbidity. For example, the average annual effluent turbidity for small systems was 0.25 NTU, and the maximum monthly value was 0.40 NTU. The authors suggested that variables such as commitment to achieving low turbidity goals, operator skill level and training were likely important in lowering turbidity levels and that lower levels could be achieved by optimizing operations without making major capital expenditures. Similar results were found in a study of the design and operational practices of 21 conventional filtration plants that enabled them to produce low-turbidity finished water. Some of the key factors that were identified included adopting a low-turbidity goal, optimizing chemical pretreatment, using filter aids and providing good operator training (Cleasby et al., 1989).

Similar results were obtained in a study evaluating the main factors that were limiting smaller systems in Louisiana from achieving optimized goals. The study found that for 53% of systems, operations and maintenance were the top factors limiting optimization, and for 43% of systems, administration was the top factor. In only a few cases (3.5%) were design factors identified as the major limiting factor (DeMers and LeBlanc, 2003). As part of the same study, six plants participated in performance-based training programs and made operational changes, such as installing individual filter turbidimeters, to achieve optimization. Following the training, the average turbidities of the six plants decreased from 0.40 NTU to 0.16 NTU.

6.1.3 Optimization of conventional and direct filtration

Over the last two decades, the use of a treated water turbidity goal of less than 0.1 NTU for individual filter effluent has been increasing, as a way to improve the treatment of surface water or GUDI sources using conventional and direct filtration (Consonery et al., 1997; Renner and Hegg, 1997; U.S. EPA, 1998b; Lusardi and Consonery, 1999; Logsden et al., 2002; PSW, 2012a,b). Extensive research and field studies support optimizing particle removal in conventional and direct filtration plants to maximize protection of public health from microbial contamination (Ongerth and Pecoraro, 1995; Patania et al., 1995; U.S. EPA, 1998b; Huck et al., 2000, 2001, 2002; Emelko et al., 2001b, 2003, 2005). As a result, it is current industry practice to take a proactive approach to plant optimization. This practice includes meeting lower turbidity goals in order to minimize consumers' risk from microbial pathogens. A more detailed discussion of filtration plant optimization and microbial pathogen removal can be found in section 7.1.2.

Data from several studies indicate that many plants have already been achieving filtered water turbidities below 0.1 NTU for a significant period of time (Cleasby et al., 1989; U.S. EPA, 1997a; McTigue et al., 1998; Pizzi, 1998; Lusardi and Consonery, 1999). An assessment of filtration plants across the United States indicated that in the mid-1990s, the median filtered water turbidity of 100 conventional and direct plants was 0.07 NTU. Data from this study also indicated that over 50% of plants were already achieving 95th-percentile turbidities less than 0.1 NTU (McTigue et al., 1998). Other studies have also demonstrated the ability of well-operated conventional and direct filtration plants to achieve filtered water turbidities below 0.1 NTU (Cleasby et al., 1989; PSW, 2012b).

To facilitate achieving a lower filtered water turbidity, many utilities now participate in voluntary optimization programs, such as the Programme d'excellence en eau potable (Program for excellence in drinking water), the PSW and the U.S. EPA Composite Correction Program. The basis of these programs is for each utility to adopt operational and administrative practices that have been demonstrated to improve treatment plant performance (U.S. EPA, 1998b; PSW, 2007, 2011, 2012a). In most cases, treatment plant performance is significantly improved, including lowering effluent turbidity levels, without major capital expenditures (Renner et al., 1993; U.S. EPA, 1998b; Hegg et al., 2000; Ginley, 2006; PSW, 2012b). One of the main components of these programs is a self-assessment procedure in which the utility examines its plant operations and evaluates the level of plant performance with respect to turbidity goals set by the program. The procedure is systematic and results in the identification and correction of the factors that could limit the performance of the treatment plant. These programs have defined optimum filter performance in terms of achieving specific treated water quality goals. The first optimization goal is to achieve effluent turbidities on individual filters of 0.10 NTU or less 95% of the time. The second goal is to minimize the turbidity of the post-backwash filtered water "spike" to no greater than 0.30 NTU, with turbidity returning to below 0.10 NTU in less than 15 minutes following the backwash (Renner and Hegg, 1997; U.S. EPA, 1998b; AWWA, 2009; PSW, 2012b). Typical examples of actions that utilities can take to facilitate optimization are coagulant dosage and pH adjustments, filter run time modifications, slow start or delayed startup of filters following backwashing and extended terminal subfluidization backwash.

A number of reports and studies have demonstrated that when utilities follow an optimization program or implement optimization tools, they are capable of significantly reducing filtered water turbidity. Data collected for the PSW indicate that in 2010–2011, U.S. filtration plants participating in the program reduced finished water turbidity by greater than 60% compared with baseline levels after following a filter self-assessment program for optimization.

In addition, the data indicate that approximately 88% of the monthly 95th-percentile values were below 0.1 NTU (PSW, 2012b). Similarly, the Pennsylvania Department of Environmental Protection found that by identifying weaknesses and optimizing treatment at filtration plants, the number of plants that achieved a filtered water turbidity below 0.2 NTU increased from only 60% in 1988 to over 96% in 1996 (Consonery et al., 1997). Additional studies of the optimization of full-scale conventional filtration plants in North America and the United Kingdom have demonstrated that significant reductions in filtered water turbidity are possible by optimizing existing plants and that a filtered water turbidity goal of less than 0.1 NTU can be achieved consistently (Leland et al., 1993; Hegg et al., 2000; Bayley et al., 2001; Mazloum et al., 2003; Drachenberg et al., 2007). A variety of operational and administrative practices that can limit filtration plant performance have been identified in previous studies and typically include a lack of one or more of the following: optimized chemical pretreatment (coagulant dose and pH adjustment), filter-to-waste, optimized filter backwash, continuous individual filter monitoring, operator training and management commitment to plant performance (Cleasby et al., 1989; Renner et al., 1993; McTigue et al., 1998; Lusardi and Consonery, 1999; DeMers and LeBlanc, 2003).

6.2 Slow sand filtration

The slow sand filtration process generally consists of untreated water slowly flowing by gravity through a bed of submerged porous sand. Below the sand is a layer of gravel for support and an underdrain system that collects the filtered water. The hydraulic loading rates are much lower for typical slow sand filters than for rapid granular filtration and range between 0.05 and 0.4 m/h. In slow sand filtration, filter effectiveness depends on the formation of *schmutzdecke*, a layer of bacteria, algae and other microorganisms on the surface of the sand, and the formation of a biological population (biopopulation) within the sand bed. As raw water passes through the sand bed, physical, chemical and biological mechanisms remove contaminants. The most important removal mechanism has been determined to be the biological processes. As particles are also physically strained, destabilization using coagulants is not required for slow sand filtration to be effective. Without any pretreatment, application of slow sand filtration is typically restricted to raw water sources with turbidity below 10 NTU, although some research indicates that raw water below 5 NTU is preferable (Cleasby, 1991; MWH, 2005; Logsdon, 2008). Effective filtration of raw water with higher turbidity levels has been demonstrated using different forms of pretreatment (Collins et al., 2005; Anderson et al., 2006; DeLoyde, 2007; Gottinger et al., 2011).

Similar to rapid granular filtration, slow sand filtration operates over a cycle. The cycles consist of a filtration stage and a regeneration stage. Breakthrough of turbidity typically does not occur in slow sand filtration, and the filters can operate until the head loss reaches the design limit. Terminal head loss can take weeks to months to occur, at which time the filter is drained and the top 1–2 cm of schmutzdecke is removed and either disposed of or cleaned for reuse (MWH, 2005; Logsdon, 2008). As is the case with conventional filtration, a “filter-to-waste” feature should be provided so that the filtered water immediately after filter cleaning is directed into a waste stream, because the initial improvement period can be as long as 1–2 days.

Although the rate of filtration is low for slow sand filtration, filter performance monitoring using turbidity is still an important tool for ensuring that filters are performing at an acceptable level. Turbidity levels in the filtered water may increase during operation owing to a number of factors, such as increases in raw water turbidity, increased hydraulic loading rate and decreased water temperature. As with conventional filtration, conducting continuous monitoring of individual filter turbidity allows utilities to obtain a better understanding of filter performance, including identifying factors that affect filtered water quality, such as temperature variations, filter maturity and source water turbidity fluctuations.

6.2.1 Turbidity of slow sand filtration effluent

Researchers have observed variation in the ability of slow sand filters to reduce turbidity; however, studies indicate that slow sand filtration plants are able to achieve filtered water turbidity below 1.0 NTU consistently. Studies have also shown that well-operated mature slow sand filters generally produce filtered water with turbidity levels below 0.5 NTU and often approaching 0.1 NTU (Cullen and Letterman, 1985; Collins et al., 1992; Riesenberg et al., 1995; Cleary et al., 2008; Kelkar et al., 2009).

Fox et al. (1984) found that when water was filtered at 0.12 m/h, after an initial ripening period had allowed the biopopulation to become established on new sand, the treated water turbidity was consistently less than 1.0 NTU. Raw water turbidity ranged from 0.2 to 10.0 NTU in this study. Cleasby et al. (1984) reported that typical effluent turbidity was 0.1 NTU, except during the first 2 days after scraping of the schmutzdecke, for raw water turbidity ranging from less than 1.0 to 30.0 NTU. Pyper (1985) observed slow sand–filtered water with effluent turbidity of 0.1 NTU or lower for 50% of measurements and 1.0 NTU or lower for 99% of measurements; raw water turbidity in this study ranged from 0.4 to 4.6 NTU. Several other studies of full-scale slow sand filtration plants have found that water treated using slow sand filtration can typically achieve turbidities below 0.3 NTU (Cullen and Letterman, 1985; Collins et al., 1992). Cullen and Letterman (1985) found that the average turbidity of filtered water from slow sand filtration plants was 0.25 NTU when influent turbidities ranged between 1 and 3 NTU.

Slezak and Sims (1984) reported that approximately 45% of the 27 full-scale slow sand filtration plants they surveyed produced filtered water turbidity of 0.4 NTU or less. The mean influent and effluent turbidity levels of all the plants were 4 NTU and 0.65 NTU, respectively. In an updated survey of 59 slow sand filtration plants in the United States in 1991, Sims and Slezak (1991) found that over 95% of filtration plants were producing water with turbidities less than 1 NTU. This survey also demonstrated that slow sand filtration plants can readily and consistently achieve effluent turbidity levels below 0.5 NTU, with approximately 80% of plants operating below this value (Barrett et al., 1991).

Other full-scale slow sand filtration studies have indicated that plants can maintain treated water turbidity levels well below 1 NTU. One study found that at plant startup, turbidity was initially 1.4 NTU; however, following a 6-month operation period, the average daily turbidity for the plant was 0.4 NTU. The authors attributed the high initial turbidity values to excessive fines in the filter sand. Effluent turbidity values were also observed to increase up to 0.75 NTU following scraping of the filters. Turbidity returned to below 0.5 NTU following approximately 2 months of filter ripening (Riesenberg et al., 1995). Kelkar et al. (2009) found that small-scale slow sand filtration systems were capable of reducing raw water turbidity between 5 and 8 NTU down to below 0.5 NTU at filtration rates of 0.1 and 0.2 m/h.

More recent studies on slow sand filtration have examined modifications to slow sand filtration, including pretreatment using ozonation, roughing filters and post-treatment granular activated carbon, to increase the range of raw water quality that is suitable for slow sand filtration (Collins et al., 2005; Anderson et al., 2006; Jobb et al., 2007; Gottinger et al., 2011). Modified slow sand filtration using ozonation and roughing filtration followed by slow sand filtration has been shown to reduce turbidity to below 0.3 NTU, with effluent turbidity trending to below 0.1 NTU following 2 years of operation (Jobb et al., 2007). Other studies evaluating the reduction of turbidity using a modified slow sand filtration pilot plant demonstrated that raw water turbidity ranging from 1 to greater than 80 NTU could be reduced to below 0.1 NTU in up to 72% of the measurements and to below 0.3 NTU in 100% of the effluent water measurements. Increases in effluent turbidity were observed when raw water turbidity increased above 30 NTU during rain events (Anderson et al., 2006). However, rainfall events resulting in high turbidity in the raw water had less impact on filtered water turbidity with increasing filter maturity (Cleary et al., 2008). Full-scale plants have reported turbidity reductions for raw water with turbidity above 5 NTU to below 0.1 NTU (Gottinger et al., 2011). Data from optimized slow sand filters installed at two small drinking water systems in Saskatchewan were provided by Gottinger et al. (2011). Finished water turbidity at the first plant (roughing filter, slow sand filtration, biologically active filtration) was shown to be less than 0.40 NTU in greater than 75% of the measurements. Finished water from the other treatment (slow sand filtration and biologically active carbon filtration) had an average turbidity of less than 0.10 NTU.

6.2.2 Factors affecting slow sand filtration effluent turbidity

Slow sand filtration can readily achieve an effluent turbidity below 1.0 NTU and in many cases approaching 0.1 NTU. Particulate removal using slow sand filtration may not consistently be as high as with conventional filtration. However, reducing turbidity as low as possible, with a goal of 0.1 NTU, is an important factor in ensuring that a slow sand filtration plant has been properly designed and is being well operated. There are several factors in the design and operation of slow sand filters that affect the filtered water turbidity. Sand size and uniformity, hydraulic loading rate, filter maturity and water temperature can all affect the water quality of filter effluent (Bellamy et al., 1985a; Cleary et al., 2008; Logsdon, 2008).

Design parameters, such as media size and depth as well as how well the media have been washed prior to installation, can affect the turbidity of filtered water. Smaller-sized sand generally yields better particle removal, but also results in greater head loss during filter operation. Several studies have found that excessive fines or sand that has not been pre-washed can contribute to elevated turbidity in filtered water for several months following plant startup (Seelaus et al., 1986; Leland and Damewood, 1990; Riesenberg et al., 1995). The depth of the slow sand bed can affect slow sand filter performance once it has become too shallow as a result of sand removal during repeated scrapings. Once the bed depth has reached approximately 0.5 m, the filter should be re-sanded (Logsdon, 2008).

One of the main operational factors that utilities can adjust to control effluent turbidity in a slow sand filtration plant is the hydraulic loading rate. Several studies have indicated that increased hydraulic loading rates can result in increased effluent turbidity levels (Bellamy et al., 1985a; Riesenberg et al., 1995; Cleary et al., 2008). Bellamy et al. (1985a) found that increasing hydraulic loading rates from 0.12 to 0.40 m/h decreased the turbidity reduction from 32% to approximately 27%. Similarly, in a study of the performance of a full-scale slow sand filtration plant, effluent turbidity increased from approximately 0.5 NTU with an average filtration rate of 0.024 m/h in the winter and 0.10 m/h in the summer up to 0.8 NTU with filter operation at or near the maximum design capacity of 0.24 m/h (Riesenberg et al., 1995). A pilot-scale study conducted on a multi-stage slow sand filter also demonstrated that effluent turbidity was higher (increased from 0.3 to greater than 1 NTU) when the hydraulic loading rate was increased from 0.2 to 0.4 m/h and the raw water turbidity spiked to greater than 50 NTU. This observation was made during colder temperature periods of less than 10°C (Cleary et al., 2008). The authors noted that following several subsequent months of operation, the filter was capable of consistently achieving effluent turbidity levels below 0.3 NTU, even at a higher filtration rate of 0.4 m/h. This was attributed to the increased performance of a more mature slow sand filter and warmer temperatures (Cleary et al., 2008). In general, filter efficiency typically decreases with lower water temperatures, as the biological action in the filter decreases. Utilities will generally need to make adjustments, such as decreasing the hydraulic loading rate to the filters, during periods when the water temperature is lower, so that the overall filter performance is maintained (Logsdon, 2008).

Filter maturity is considered to be one of the most important aspects affecting slow sand filter performance (Barrett et al., 1991). Several studies have indicated that both turbidity and pathogen removal increase as the biological activity in the filter increases following filter maturation (Bellamy et al., 1985a,b; Anderson et al., 2006).

6.3 Diatomaceous earth filtration

Diatomaceous earth filters consist of a vessel that contains many filtration devices called filter elements or leaves. Filter elements can be placed in a pressure vessel, or they can be used in an open tank if a pump is provided with suction attached to the filter effluent piping to cause a pressure differential across the filter elements in the tank. The filter elements support a porous membrane or fabric referred to as a septum that holds the filter cake during filtration. Typical filtration rates are lower than for rapid granular filtration and range from 1.3 to 5 m/h (MWH, 2005). Without any pretreatment, application of diatomaceous earth filtration is typically limited to raw water sources with maximum turbidity values between 5 and 10 NTU. It is suggested that, when turbidity is caused by inert silt/clay particles, diatomaceous earth filtration may be applied to water at the higher end of the range; however, when the source of turbidity is organic or compressible particles such as alum or iron floc, the lower turbidity limit may be more appropriate (Fulton, 2000).

To begin a filter run, the septum is coated with a thin layer of diatomaceous earth (precoat) about 3 mm thick. To prevent turbid water from clogging the filter, a small amount of diatomaceous earth is continually added as body feed to maintain a permeable filter cake. Filtration occurs through the cake to the inside of the filter element, where it is collected in a channel and exits the element. As the filter run progresses, the body feed and raw water particles deposit at the surface of the cake, forming a new filtering surface and increasing the thickness of the cake. Particulate removal occurs primarily at the surface of the cake through straining, and particles as small as 1 µm can be removed, depending on the media used. Once the head loss across the filter cake becomes too great or the filter cake begins to slough, the filter is removed from service. The filter coat is then washed off using a backwash process and disposed of. New diatomaceous earth is applied, and the cycle starts again (MWH, 2005; Logsdon, 2008).

As discussed above, the diatomaceous earth filtration cycle includes the precoat step, filtration period and backwash. At the start of a filter run, there may be slightly elevated turbidity as the fine, inert diatomaceous earth matter that has not been stabilized in the precoat is sloughed into the filtered water. However, turbidity generally decreases slightly through the filter run as the cake thickness increases. Once the filter run has started, generally there is no breakthrough of turbidity as long as the flow that holds the cake to the septum is not interrupted. Disturbance of the filter cake as a result of hydraulic surges should generally result in termination of the filter run (Fulton, 2000).

Filter performance monitoring using turbidity is an important tool for ensuring that diatomaceous earth filters are performing at an acceptable level. Turbidity levels in the filtered water may increase during operation owing to a number of factors, such as uneven precoating and disturbances to the cake, and require continuous monitoring of the filter effluent to ensure that the filters are operating well.

6.3.1 Turbidity of diatomaceous earth filtration effluent

As with slow sand filtration, well-operated diatomaceous earth filtration plants are readily capable of producing filtered water with turbidity of less than 1 NTU and in many cases can achieve filtered water turbidity below 0.1 NTU. Logsdon et al. (1981) reported that turbidity reductions of 56–78% to achieve filtered water with turbidity below 0.5 NTU were attained with a diatomaceous earth pilot plant when raw water turbidity ranged from 0.95 to 2.5 NTU. Pyper (1985) reported an average turbidity reduction of 75% with an effluent turbidity of 0.5 NTU. A study of the performance of a full-scale diatomaceous earth filtration plant found that raw water turbidity between 1 and 3 NTU was reduced to between 0.3 and 0.5 NTU in the filtered water effluent (Ongerth, 1990).

More recent pilot-scale studies evaluating particle and *Cryptosporidium* removal using diatomaceous earth filtration found that influent turbidity ranging from 0.7 to 1.1 NTU could readily be reduced to less than 0.1 NTU. Generally, the filter performance improved during the course of a run, with turbidity decreasing to less than 0.1 NTU approximately 20 minutes following the start of precoating and reaching less than 0.07 NTU after 200 minutes of filter operation (Ongerth and Hutton, 2001).

6.3.2 Factors affecting diatomaceous earth filtration effluent turbidity

Diatomaceous earth filtration can readily achieve an effluent turbidity below 1.0 NTU and in many cases approaching 0.1 NTU. Particulate removal using diatomaceous earth filtration may not be consistently as good as conventional filtration. However, reducing turbidity to as low as possible with a goal of 0.1 NTU is an important factor in ensuring that a diatomaceous earth filtration plant has been properly designed and is being well operated. There are several factors in the design and operation of diatomaceous earth filters that can affect the filtered water turbidity. Factors such as the diatomaceous earth size or grade, precoat thickness, hydraulic loading rate, pressure fluctuations and integrity of the cake can all affect the water quality of filter effluent (Lange et al., 1986; Fulton, 2000; Ongerth and Hutton, 2001).

Lange et al. (1986) found that the grade of diatomaceous earth used affected filter performance. For the finest diatomaceous earth grade with a median particle size of 7.5 µm, turbidity reduction was close to 100%; however, for coarser grades with a median particle size of 22 µm, a 10% reduction was observed. The authors noted that the source water turbidity varied between 4 and 10 NTU and was caused by colloidal clays. The authors also expected improved turbidity reduction if the source water turbidity was caused by larger particles. Schuler and Ghosh (1990) also demonstrated that the use of different grades of diatomaceous earth resulted in significant variations in turbidity reduction.

Lange et al. (1986) found a slight decline in turbidity reduction at higher hydraulic loading rates when a coarser-grade diatomaceous earth was used as the filter aid. However, other pilot-scale testing found that increasing hydraulic loading rates from 2.5 to 5.0 m/h resulted in a minor decrease in filtered water turbidity (Ongerth and Hutton, 2001). This study also found that pressure fluctuations at the filter (due to variations in the peristaltic pump) caused effluent turbidity to increase from approximately 0.05 to 0.2–0.4 NTU.

The use of pretreatment or the addition of other filter aids such as alum-coated diatomaceous earth or polymer has been shown to reduce the turbidity of effluent from diatomaceous earth filtration plants. In a pilot-scale study, the use of alum-coated diatomaceous earth resulted in turbidity removal ranging from 66% to 98.8%, in contrast to removal ranging from 11% to 17% for diatomaceous earth without alum coating (Lange et al., 1986). In a similar pilot-scale study, the addition of chemical coagulants and polymers to the precoat and body feeds resulted in improved turbidity reduction. This study found that influent turbidity less than 1 NTU could be reduced to below 0.1 NTU (Schuler and Ghosh, 1990).

In a full-scale study, the addition of a cationic polymer filter aid to an existing diatomaceous earth filtration plant achieved finished water turbidity levels of less than 0.1 NTU from influent values greater than 6 NTU. The finished water turbidity levels of the filtration plant prior to addition of the polymer averaged 0.3–0.4 NTU; however, the plant had difficulty operating at high raw water turbidity levels (greater than 10 NTU), which normally resulted in plant shutdown (Cartnick and Merwin, 2004). Other full-scale plant data have demonstrated that modifications to an existing plant, such as relocating the slurry feed line injection point as well as replacing the filter septums, could improve filtered water turbidity from close to 1 NTU to an average finished water level of 0.25 NTU (Sweed, 1999).

6.4 Membrane filtration

Four membrane treatment processes are currently used in the water industry: microfiltration, ultrafiltration, nanofiltration and reverse osmosis. The most appropriate type of membrane for water treatment depends on a number of factors, including targeted materials to be removed, source water quality characteristics, treated water quality requirements, membrane pore size, molecular weight cut-off, membrane materials and system/treatment configuration (Jacangelo, 1991). The distinction between the types of membrane processes can be subjective and can vary by membrane manufacturer; however, the following classifications can generally be made (MWH, 2005; AWWA, 2007):

- Reverse osmosis: a high-pressure membrane process originally developed to remove salts from brackish water. The reverse osmosis process is based on diffusion of water through a semi-permeable membrane as a result of a concentration gradient. Reverse osmosis membranes are considered to be non-porous and are used to remove dissolved solids, such as sodium, chloride and nitrate, from water.
- Nanofiltration: a low-pressure reverse osmosis process for the removal of larger cations (e.g., calcium and magnesium ions) and organic molecules. Nanofiltration membranes are also typically considered non-porous and are reported to reject particles in the size range of 0.5-2 nm.
- Ultrafiltration: a lower-pressure membrane process characterized by a wide band of molecular weight cut-off and pore sizes for the removal of small colloids, particulates and, in some cases, viruses. Ultrafiltration membranes typically have a pore size range of 0.01–0.1 µm.
- Microfiltration: a low operating pressure membrane process used to remove particulates, sediment, algae, protozoa and bacteria. Microfiltration membranes typically have a pore size range of 0.1–10 µm.

As with most filtration processes, microfiltration and ultrafiltration have a repeating filtration cycle. As the filtration cycle begins, water is filtered through the membrane, and solids begin to accumulate on the influent side of the membrane. As the amount of solids on the side of the membrane increases, the transmembrane pressure needed to maintain a constant flux increases. Filtration typically proceeds for a set period of time, or until a specified transmembrane pressure is reached. Backwashing is then initiated to remove the surface cake that has been deposited during the filtration cycle (AWWA, 2005; MWH, 2005).

In ultrafiltration and microfiltration, water is filtered through a thin wall of porous material. The main mechanism for removal of particulate matter is through straining or size exclusion, and the types of contaminants that are removed depend partially on the pore size or molecular weight cut-off of the membrane. Research has also demonstrated that contaminant removal is affected by adsorption and cake formation on the membrane (AWWA, 2005; MWH, 2005).

Reverse osmosis and nanofiltration are pressure-driven membrane processes that are based on preferential diffusion to achieve separation of dissolved solutes from water. Reverse osmosis and nanofiltration can also remove particulate matter, although these technologies are not intended specifically for this purpose. High particulate loading can cause these types of membranes to foul rapidly. Therefore, these processes include pretreatment to remove particulate matter in the raw water prior to reverse osmosis or nanofiltration. Filtration of particulates and dissolved solids occurs when high pressure is applied to the influent side of the membrane and water is forced through the membrane surface, while the particulates and a large percentage of dissolved solids are rejected. The pressure needed to operate reverse osmosis and nanofiltration systems is partially dependent on the total dissolved solids concentration and the temperature of the feedwater (MWH, 2005; AWWA, 2007). Reverse osmosis is a continuous filtration, and there is no periodic backwash cycle. Prefiltration and/or the addition of a scale-inhibiting chemical may be required to protect membranes from plugging effects, fouling or scaling. Typically, reverse osmosis and nanofiltration systems are preceded by filtration by 5–20 µm cartridge filters to reduce the particulate load on the membranes and achieve an influent water quality with turbidity below 1 NTU (AWWA, 2007). A “filter-to-waste” feature should be provided for initial startup and commissioning of the membrane system and for emergency diversion in the event of a membrane integrity breach.

In principle, membrane filtration is an absolute barrier to remove any particle that is larger than the exclusion characteristic of the membrane system. However, any breach in the integrity of a membrane or leak in the system could allow particulate matter such as pathogens through the filter. Broken membrane fibres, leaking o-rings and cracked glue joints are some of the integrity breaches that can result in the passage of microorganisms and other contaminants into the treated water. Therefore, integrity testing is an essential component of membrane filtration operation (U.S. EPA, 2001b, 2005).

Membrane integrity testing is based on procedures that can assess whether a membrane system is completely intact or there has been a breach or leak that is compromising the performance of the system. Integrity testing falls into two general categories: direct and indirect. Direct methods are procedures applied directly to the membrane or membrane module to determine whether there is an integrity breach and, if there is, its source. Indirect testing is a surrogate measure of integrity based on monitoring the water quality of the filtrate. Indirect testing is generally conducted continuously, whereas direct testing is conducted at a lower frequency, such as daily (U.S. EPA, 2001b, 2005). A wide range of direct (pressure-based tests, acoustic sensor tests, etc.) and indirect (turbidity, particle counting, surrogate challenge tests, etc.) tests are available for membrane filtration plants. Comprehensive reviews of the different testing methods are available (Sethi et al., 2004; Guo et al., 2010).

Monitoring turbidity in the effluent of membrane filtration systems is one possible indirect integrity testing method. As the quality of the effluent from membrane filtration systems is consistently very high and generally does not vary with raw water fluctuations, an increase in turbidity of the filtrate, as revealed by monitoring, can be indicative of an integrity problem. The use of turbidity monitoring as an indirect integrity test has several advantages and disadvantages over other test methods. The main advantages of turbidity monitoring are that it can be conducted continuously, measurements between meters are relatively consistent, operators are familiar with it and it has lower costs. The main disadvantage of turbidity monitoring is that standard nephelometric turbidity meters are relatively insensitive to minor breaches in membrane integrity compared with other indirect methods. The use of laser turbidimeters has been suggested as a better alternative for membrane filtration monitoring, as the detection limit is lower and laser turbidimeters have been shown in some cases to be significantly more sensitive than nephelometric meters in detecting membrane breaches (Banerjee et al., 2000, 2001; U.S. EPA, 2001b; AWWA, 2005). This is discussed in greater detail in sections 5.0 and 6.4.2.

It has been suggested that turbidity is not sufficient as the sole method for monitoring membrane filter integrity as it does not provide adequate sensitivity for detection of small pinholes in membrane fibres and because of the lack of resolution between the raw and filtrate values (Sethi et al., 2004; AWWA, 2005; MWH, 2005; Gitis et al., 2006; Guo et al., 2010). In general, turbidity is accepted as part of an overall integrity monitoring program that includes both indirect and direct testing. The usefulness of turbidity monitoring in immediately identifying a major membrane system integrity breach has resulted in its widespread use in membrane filtration plants. Some organizations, such as the U.S. EPA, have identified turbidity monitoring as the default method for continuous indirect integrity monitoring unless an alternative method is approved by the state. As part of the U.S. Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR), continuous turbidity monitoring is required in addition to daily direct integrity testing as part of an overall system verification program (U.S. EPA, 2005, 2006b).

6.4.1 Turbidity of membrane filtration effluent

All membrane filtration processes are highly effective at reducing turbidity provided that the membranes are intact. In general, microfiltration and ultrafiltration processes achieve filtered water turbidity of less than 0.1 NTU (Adham et al., 1996; Laine et al., 2000; AWWA, 2005; Guo et al., 2010). As the primary use of reverse osmosis and nanofiltration processes in drinking water treatment is not for particulate removal, turbidity data for these types of systems are generally not reported; however, these processes can achieve very low filtered water turbidity.

One of the main advantages of microfiltration and ultrafiltration systems is their ability to produce low-turbidity filtrate consistently. The American Water Works Association reported on the turbidity of filtrate from over 72 microfiltration and ultrafiltration plants between 1989 and 2001. The results indicated that microfiltration and ultrafiltration membranes produce very high quality water regardless of the influent turbidity. The median filtrate turbidity for all of the plants was 0.06 NTU and the median of the maximum reported filtrate turbidity was 0.08 NTU. The evaluation also demonstrated that turbidity reduction was similar with or without coagulant addition and for all membrane types and manufacturers (AWWA, 2005). A similar study of over 70 microfiltration and ultrafiltration plants worldwide determined that regardless of the influent turbidity levels, microfiltration and ultrafiltration systems were capable of reducing turbidity to below 0.1 NTU (Adham et al., 1996). The U.S. EPA has also reported that most microfiltration and ultrafiltration systems produce filtrate water consistently in the range of 0.03–0.07 NTU as measured by conventional turbidimeters (U.S. EPA, 2001b, 2005).

6.4.2 Factors affecting membrane filtration effluent turbidity

Membrane filtration is an absolute barrier to remove any particle that is larger than the exclusion characteristic of the membrane system. However, any breach in the integrity of a membrane or leak in the system could allow particulate matter into the filtrate and therefore increase the turbidity. There are many possible sources of breaches to the integrity of membrane filtration systems, such as holes in membrane fibres and leaking o-rings; however, the ability of turbidity monitoring to detect breaches can vary significantly.

Adham et al. (1995) found that a number of factors can affect the sensitivity of turbidity for detecting a breach, including the type of microfiltration or ultrafiltration system, the number of modules linked to a single instrument, the number of fibres per module, the hydraulic configuration and other system-specific parameters. When the membranes were intact, the permeate turbidity of the four systems that were tested was in the range of 0.02–0.04 NTU. Turbidity increases were easily discernible, even with a pinpoint integrity breach in one fibre for the cross-flow membranes with between 500 and 2000 fibres; however, no change in turbidity was observed under a variety of breach conditions for the transverse membrane with 22 400 fibres. This study showed that dilution (number of fibres) and module flow mode were important factors determining the ability of turbidity to detect minor integrity breaches.

Two other studies that reported integrity testing data for full-scale plants indicated that turbidity monitoring is limited in its ability to detect integrity breaches. Kothari and St. Peter (2000) demonstrated that cutting up to 200 fibres in a membrane rack resulted in an increase in turbidity of only 0.01 NTU. Similarly, Landsness (2001) reported an increase in turbidity from an intact membrane value of 0.024 NTU up to 0.037 NTU when 200 fibres were cut in the membrane. However, the turbidity in the entire train of eight racks did not show any change and remained at 0.012 NTU. Both of these studies demonstrated that the sensitivity of turbidity monitoring for detecting minor to moderate integrity breaches is limited.

Sethi et al. (2004) conducted a comprehensive assessment of low-pressure membrane integrity monitoring tools. The study evaluated several indirect and direct integrity testing methods in six ultrafiltration or microfiltration full-scale plants, including an analysis of the sensitivity, reliability, costs and implementation capacity of each method. The results indicated that both standard nephelometric turbidity and laser turbidity lacked the sensitivity to detect the levels of breach that were investigated in the study. The levels of integrity breach that were examined ranged from 1 cut fibre up to 0.0025% cut fibres in a rack. The authors suggested that the less sensitive integrity monitoring methods, such as turbidity monitoring, should be considered as warning methods for severe losses in integrity, rather than as routine monitoring tools.

Data reported by Farahbakhsh et al. (2003) support the use of conventional turbidity monitoring as a method for detecting large integrity breaches in membrane systems. This study reported on the results of online integrity monitoring in which a major integrity breach of greater than 60 broken fibres out of 28 500 fibres in a membrane produced an increase in turbidity from 0.04 to 0.2 NTU.

In contrast to the Sethi et al. (2004) study, several authors have suggested that laser turbidimeters are a suitable alternative for membrane filtration monitoring, as the detection limit is lower and the sensitivity can be several orders of magnitude higher than with conventional turbidimeters (Banerjee et al., 2000, 2001; U.S. EPA, 2001b; AWWA, 2005). Banerjee et al. (2000) demonstrated that a laser turbidimeter was capable of detecting an intentional breach in a microfiltration system. One cut fibre out of 5000 in a membrane cartridge was detected by an increase in turbidity from 14 mNTU to over 250 mNTU. Laser turbidity systems equipped with sensors that can be installed on each membrane rack have also been used for the detection of integrity breaches at the module and fibre level (Naismith, 2005).

Since most membrane filtration systems consistently produce water with turbidity below 0.1 NTU, utilities should consider a sustained increase in turbidity above 0.1 NTU as an indicator of a potentially serious integrity breach. In general, when utilities are using turbidity monitoring for integrity testing, they should also use a more sensitive direct integrity testing method, such as pressure decay testing, to enable the detection and location of potential minor integrity breaches (Sethi et al., 2004; MWH, 2005).

6.5 Other technologies

6.5.1 Bag and cartridge filtration

Bag filtration and cartridge filtration are alternative technologies that can be used for the reduction of particulate matter, including turbidity, in drinking water. These technologies do not have a turbidity guideline value, as there is a wide variation in the turbidity reduction that can be achieved, and studies have not found a relationship between turbidity or other parameters such as media pore size or pressure drop on the removal efficiency of protozoa (U.S. EPA, 2006b). However, as many small drinking water systems use bag and cartridge filtration technologies, a brief description of the processes and turbidity reduction and monitoring is provided below.

Bag filtration and cartridge filtration are considered to be pressure-driven physical separation processes that remove particles greater than 1 µm using a porous filtration medium. Bag filters are typically constructed of a woven bag or fabric filtration medium that is placed in a pressure vessel. As water flows from the inside of the bag to the outside, contaminants are filtered out of the water. Cartridge filters are typically made of a semi-rigid or rigid wound filament that is housed in a pressure vessel in which water flows from the outside of the cartridge to the inside. Systems can be constructed with either single or multiple filters within one pressure vessel. It is recommended that all components used in bag and cartridge filters be certified under NSF International (NSF)/American National Standards Institute (ANSI) Standard 61: Drinking Water System Components—Health Effects. This standard ensures the material safety and performance of products that come into contact with drinking water (NSF/ANSI, 2012a).

Bag and cartridge filters remove particles in the water by physically screening those that are greater in size than the filter medium pore size. Bag filters typically have pore sizes that range from 1 to 40 µm, and those of cartridge filters typically range from 0.3 to 80 µm; therefore, selection of the type of filter that is most suitable for a system depends partially on the size of the particles and the level of turbidity in the source water (U.S. EPA, 1997b, 2003c).

Generally, bag and cartridge filters are used in small and very small drinking water systems as primary filtration systems; more recently, however, bag and cartridge filters have been used in larger systems as secondary filtration processes following existing primary filtration to obtain supplemental contaminant removal. When bag or cartridge filtration is used as a primary filtration method, the raw water is often prefiltered to remove larger particles before the bag or cartridge filtration step. In some cases, bag and/or cartridge filters are placed in series, with larger pore size units (greater than 10 µm) placed first followed by smaller pore size units (1–5 µm) as final filter units (U.S. EPA, 1997b). As a secondary filtration step, only smaller pore size units are used. Although bag and cartridge filters can accommodate some high-turbidity source water, generally the turbidity should be below 10 NTU for effective filtration (U.S. EPA, 1997b; Cleasby and Logsdon, 1999).

As there is a wide range in the pore sizes of bag and cartridge filters, the level of turbidity reduction is also highly variable. A study by Li et al. (1997) demonstrated that, depending on the type of bag filter used, turbidity removal could vary between 0.03-log and 1.89-log removal. Filtered water turbidity values in this study ranged from 0.14 to 9.87 NTU. Although turbidity has its limitations as an indicator of filter failure in bag and cartridge filtration, it is nonetheless recommended as a performance indicator for these systems. The frequency of monitoring may vary depending on the source water quality; however, at a minimum, effluent turbidity should be monitored daily (Cleasby and Logsdon, 1999; U.S. EPA, 2003c).

6.5.2 Additional strategies

A number of additional strategies are available for reducing turbidity in source water. These include, but are not limited to, riverbank filtration, lime softening, pre-sedimentation and dual-stage filtration. Generally, these processes are used early in a drinking water treatment train to reduce the level of particulates in the water for subsequent treatment and to enhance the overall particulate removal capabilities of a plant. In most cases, turbidity can be used to monitor the effectiveness of these processes. More detailed discussions on the use of these technologies for turbidity reduction can be found in Kawamura (2000), Ray et al. (2002) and U.S. EPA (2010).

6.6 Residential-scale treatment

Generally, it is not recommended that drinking water treatment devices be used to provide additional treatment to municipally treated water. In cases where an individual household obtains its drinking water from a private well, a private residential drinking water treatment device may be an option for reducing turbidity concentrations in drinking water. It should be noted that microbiological contamination of a well water supply may occur in conjunction with routinely high turbidity measurements and/or sudden increases in turbidity. Therefore, the microbiological aspects of the water quality should be considered prior to selection of a drinking water treatment device.

Health Canada does not recommend specific brands of private residential drinking water treatment devices, but it strongly recommends that consumers use devices that have been certified by an accredited certification body as meeting the appropriate NSF/ANSI drinking water treatment unit standards. These standards have been designed to safeguard drinking water by helping to ensure the material safety and performance of products that come into contact with drinking water. Certified devices for the reduction of turbidity from drinking water in residential systems generally rely on carbon filtration and reverse osmosis treatment processes.

Certification organizations provide assurance that a product conforms to applicable standards and must be accredited by the Standards Council of Canada (SCC). In Canada, the following organizations have been accredited by the SCC to certify drinking water treatment devices and materials as meeting NSF/ANSI standards:

- Canadian Standards Association International (www.csa-international.org);
- NSF International (www.nsf.org);

- Water Quality Association (www.wqa.org);
- Underwriters Laboratories Inc. (www.ul.com);
- Quality Auditing Institute (www.qai.org); and
- International Association of Plumbing & Mechanical Officials (www.iapmo.org).

An up-to-date list of accredited certification organizations can be obtained from the SCC (www.scc.ca).

NSF/ANSI Standard 53 (Drinking Water Treatment Units—Health Effects) is applicable to the reduction of turbidity in drinking water. For a drinking water treatment device to be certified to Standard 53, it must be capable of reducing a turbidity level of 11 NTU ± 1 NTU to not more than 0.5 NTU (NSF/ANSI, 2011).

NSF/ANSI Standard 58 (Reverse Osmosis Drinking Water Treatment Systems) is also applicable to the reduction of turbidity in drinking water. For a drinking water treatment device to be certified to Standard 58, it must be capable of reducing a turbidity level of 11 NTU ± 1 NTU to not more than 0.5 NTU (NSF/ANSI, 2012b). Certified reverse osmosis systems are intended for point-of-use installation only. Reverse osmosis systems are installed at the point-of-use, as larger quantities of influent water are needed to obtain the required volume of treated, which is generally not practical for residential-scale point-of-entry systems. In addition, water that has been treated using reverse osmosis may be corrosive to internal plumbing components; therefore, these devices should be installed at the point-of-use.

Before a drinking water treatment device is installed, the water should be tested to determine general water chemistry and verify the level of turbidity. Periodic testing on-site by a water treatment specialist using a portable turbidimeter should be conducted on both the water entering the treatment device and the water it produces to verify that the treatment device is effective. Devices can lose removal capacity through usage and time and need to be maintained and/or replaced. Consumers should verify the expected longevity of the components in their treatment device as per the manufacturer's recommendations.

7.0 Relationship between turbidity and water quality characteristics

7.1 Microbiological characteristics

The microbiological quality of water can be significantly affected by turbidity. Microorganisms are considered particles themselves, occupying size categories ranging between small particles and colloidal material (MWH, 2005). In the environment, microorganisms become intimately associated with soil and waste particles, either settling together or becoming directly attached to particle surfaces. They subsequently are transported to waters through the same mechanisms as for particles, which include both environmental and treatment system mechanisms (see Table 2 above). As a result, turbidity measurements have become a useful indicator of water quality in raw water, treated water and the distribution system. Information on the rationale behind log removal credits can be found in Appendix B.

7.1.1 Relationship between turbidity and the presence of microorganisms

Surface waters may experience events leading to sudden fluctuations in turbidity and pathogen concentrations. Some of these events (e.g., heavy precipitation, wastewater discharges, flooding) may be unpredictable, while others (e.g., spring snowmelt, onset of a recognized rainy season) can be seasonal and have some degree of predictability. It has been well-documented that rainfall-mediated runoff can lead to significant increases in turbidity, faecal indicator and pathogen concentrations (Ferguson et al., 1996; Atherholt et al., 1998; Kistemann et al., 2002; Dorner et al., 2007). Atherholt et al. (1998) observed that rainfall-related increases in concentrations of *Giardia* cysts and *Cryptosporidium* oocysts in a New Jersey river watershed were significantly correlated with turbidity measurements. Curriero et al. (2001) and Naumova et al., (2005) have reported evidence of statistically significant associations between elevated or extreme precipitation events and waterborne disease outbreaks in the United States and the UK respectively. A general link between turbidity and pathogens may exist, such that weather-influenced sources of contamination are known to exist in a watershed, and a spike in raw water turbidity may serve as a warning of an increased pathogen challenge. However, it should also be noted that low turbidity in surface waters does not automatically indicate the absence of pathogens. Research has not provided evidence of any direct correlation between surface water turbidity and pathogen concentrations. The strength of any association between these two elements will be dependent on area-specific factors, such as the nature and degree of the pathogen (faecal) inputs and the soil types involved. Dorner et al. (2007) observed weak correlations between wet weather pathogen concentrations and turbidity measurements in the Grand River watershed (Ontario), further concluding that the findings were the result of regional variations in pathogen sources. St. Pierre et al. (2009) similarly did not find strong connections among the prevalence and quantities of *Campylobacter* spp., thermotolerant coliforms and *E. coli* or turbidity values within river and stream water samples from Quebec's Eastern Townships.

In groundwater, turbidity is generally low and is often associated with inorganic metal oxides, geological material such as clay particles and macromolecular components of dissolved organic carbon such as humic acids (Puls et al., 1991; Backhus et al., 1993; WHO, 2011). In some cases, elevated turbidity observed during sampling of groundwater wells has been associated with an elevated clay mineral content (Puls et al., 1993) and increases in metal concentrations such as iron and aluminum (Abbott, 2007). The growth of iron and sulfur bacteria can also cause turbidity increases through the deposition of significant amounts of iron and sulfur precipitates and the production of bacterial slimes (APHA et al., 2012). More recently, a study found that faecal indicator bacteria were present in bedrock monitoring well samples collected at the onset of sampling. In this study, turbidity between 1 and 3 NTU corresponded with the presence of faecal coliforms and *E. coli* (Kozuskanich et al., 2011). Overall, there is insufficient scientific data to suggest a specific turbidity value that provides an indication of the presence of pathogens in groundwater. However, for turbidity in drinking water systems supplied by groundwater it is best practice to generally be below 1.0 NTU. This helps to ensure that turbidity levels do not interfere with the disinfection and distribution of the water supply.

Treatment and disinfection methods are capable of producing drinking water with a negligible risk of disease transmission. Water of low turbidity is in general a good indication of treatment effectiveness, but specific turbidity values do not reflect the presence or absence of pathogens. A survey of Canadian municipal drinking water supplies for *Giardia* and *Cryptosporidium* (Wallis et al., 1993) indicated that cysts and oocysts could be detected in low numbers in treated water from 9 out of 10 municipalities, and in waters with turbidity measurements below the HBTL of 0.3 NTU. Positive samples were less common from municipalities that used filtration. Keswick et al. (1984) reported on the detection of enteric viruses in conventionally treated drinking water from a heavily polluted river source in the United States. Four of nine dry season samples meeting the turbidity standard that existed at that time (1.0 NTU), as well as the standards for total coliform and residual chlorine, had culturable virus (rotavirus and enteroviruses). None of the 14 rainy season samples met turbidity, total coliform or residual chlorine standards, and all contained culturable virus. A collaborative survey of viruses in drinking water from three major urban areas in Canada (Montreal, Ottawa and Toronto) was conducted by Payment et al. (1984). Viruses were detected in 37–72% of raw water samples, but none were detected in finished water samples, which met all turbidity (1.0 NTU), bacteriological and residual chlorine limits.

Increased distribution system turbidity can be indicative of microbiological problems such as intrusion, detachment of biofilm or deposits. Several studies have documented correlations between increasing levels of plate count microorganisms and increased turbidity (Snead et al., 1980; Goshko et al., 1983; Haas et al., 1983). An increase in HPC bacteria can indicate a breakdown in a treatment barrier, deterioration in water quality or post-treatment contamination. Goshko et al. (1983) noted a positive correlation between turbidity and HPC in water samples collected from the distribution systems of several small community supplies. Similarly, Power and Nagy (1999) reported a positive correlation between increased turbidity and increased total coliform and HPC in a distribution system experiencing bacterial regrowth. Changes in pressure or flow can also contribute to the release of soft deposits, resuspension of sediments, detachment of biofilms or intrusion of external contaminants, which can create increases in distribution turbidity and bacteria levels (LeChevallier et al., 2003; Lehtola et al., 2004, 2006). Turbidity measurements can be used as an indication of changes to distribution system conditions, but should not be automatically interpreted as an indication of an unsafe water supply. An early investigation of distribution system turbidity–bacteria relationships found no correlation between turbidity levels above or below 1.0 NTU and the frequency of coliform detection (Reilly and Kippin, 1983). In a study by Lehtola et al. (2004), soft deposits influencing turbidity and bacteria levels contained high numbers of HPC bacteria, but were negative when tested for coliform bacteria and Norwalk-like viruses.

Turbidity results do not provide an indication of water safety but are useful as an indicator of the need to further investigate the cause of the turbidity. Measurements should be used by operators as a useful tool for monitoring plant operations and distribution system conditions. Other useful tests include those for coliform bacteria, HPC and disinfectant residuals.

7.1.2 Relationship between turbidity reduction and microorganism removal in treated water

Filtration is an important barrier in the production of safe drinking water. Depending on the type of filtration technology that is used, protozoa, bacteria, viruses and particles are removed by porous media by becoming attached to the filter grains, through physical straining or by biological mechanisms. Physical removal is particularly important for the enteric protozoa *Giardia* and *Cryptosporidium* and enteric viruses. *Cryptosporidium* oocysts are not effectively inactivated by chlorine disinfection, and inactivation of *Giardia* cysts with free chlorine requires high concentrations or long contact times (Health Canada, 2012). Filtration is the most practical method for achieving high removals of these organisms. Enteric viruses can pass through most filtration barriers relatively easily because of their small size. Chemical coagulants are often utilized to produce virus-adsorbed flocs that are larger in size and thus can be more easily removed through filtration.

There is no precise relationship between the magnitude of turbidity reduction and the removal of pathogens. Some authors have documented positive and statistically significant correlations between turbidity reduction and parasite removal with rapid granular filtration methods (LeChevallier and Norton, 1992; Nieminski and Ongerth, 1995; Dugan et al., 2001).

However, the bulk of the data indicate that the relationship is not proportional (i.e., a one-to-one relationship). Dugan et al., (2002) reported that in optimized conventional filter challenge runs, turbidity reduction was consistently lower than oocyst removals. Huck et al. (2002) observed that two pilot plants of comparable design and optimized to yield similarly low effluent turbidity (less than 0.1 NTU) demonstrated a 2-log difference between their *Cryptosporidium* removal capabilities. Patania et al. (1995) commented that turbidity reduction, particle removal and cyst or oocyst removal are each largely dependent upon their individual concentrations in source waters. As these can each vary considerably from source to source, a universal relationship should not be expected (Patania et al., 1995). This is further complicated by the fact that the process of coagulation/flocculation fundamentally changes the particle numbers and characteristics, making it difficult to track the reduction of specific particles.

Inherent differences between treatment technologies and their operation can also contribute to the observed differences between turbidity and pathogen removal. For example, as discussed with slow sand filtration, aside from the media and filtration rate differences, the schmutzdecke also presents a complex biological community that is capable of degrading certain types of organic matter (MWH, 2005). Further, it has been suspected that in this biologically active region, predation of bacteria by certain protozoa (Lloyd, 1996; Hijnen et al., 2004; Unger and Collins, 2008) and predation of protozoan (oo)cysts by zooplankton (Bichai et al., 2009) may play a role in the removal of these organisms. It should be similarly recognized that the water turbidity and the associated removal of different pathogen types are also dependent on the pretreatment and the filtration technology used.

In general, it has been demonstrated that good removals of *Giardia* cysts and *Cryptosporidium* oocysts can be achieved when water of low turbidity is produced. Various filtration technologies can achieve good turbidity reduction and good removal of protozoan (oo)cysts.

7.1.2.1 Conventional filtration

A considerable amount of research has been conducted on the filtered water turbidity achievable by conventional filtration and the attainable physical removal of pathogens. Published full-scale study data (LeChevallier et al., 1991; LeChevallier and Norton, 1992; Kelley et al., 1995; Nieminski and Ongerth, 1995; McTigue et al., 1998; Nieminski and Bellamy, 2000) and pilot-scale study data (Logsdon et al., 1985; Patania et al., 1995; McTigue et al., 1998; Dugan et al., 2001; Harrington et al., 2001; Emelko et al., 2003; Huck et al., 2004; Assavasilavasukul et al., 2008) indicate that conventional filtration can achieve *Giardia* cyst and *Cryptosporidium* oocyst removals from greater than 1.4 log to greater than 5 log and virus removals from 1.6 log to greater than 3 log.

Data from pilot-scale studies conducted by Patania et al. (1995) showed that a 5-log *Cryptosporidium* removal could be achieved with conventional filtration systems optimized for turbidity reduction and particle removal. Huck et al. (2002) and Emelko et al. (2003) similarly showed greater than 5-log *Cryptosporidium* removal for pilot-scale conventional systems under optimized conditions and stable filtration (filter effluent turbidities below 0.1 NTU). McTigue et al. (1998) conducted a survey of 100 full-scale water treatment plants in the United States with the purpose of developing nationwide estimates of treatment capabilities and pathogen removal. The median *Cryptosporidium* removal value reported for the 100 plants was 1.7 log. However, the authors commented that an estimate of the attainable *Cryptosporidium* removal was limited by the typically low raw water concentrations encountered in the study. Turbidity measurements were collected at only 52 of the plants participating in the survey, with the median turbidity for any filter run at any plant never exceeding 0.2 NTU.

A review of the available information on *Cryptosporidium* removals through granular media filtration was conducted by Emelko et al. (2005). It was concluded that the body of data taken as a whole suggests that, when optimized for turbidity removal, granular media filters can achieve *Cryptosporidium* removals of close to 3 log or better.

7.1.2.2 Direct filtration

Data from full-scale (Nieminski and Ongerth, 1995) and pilot-scale (West et al., 1994; Nieminski and Ongerth, 1995; Ongerth and Pecoraro, 1995; Patania et al., 1995; Brown and Emelko, 2009) investigations have shown that optimized direct filtration can achieve removals of *Giardia* and *Cryptosporidium* (oo)cysts ranging from 2 log to greater than 4 log. In full- and pilot-scale experiments, Nieminski and Ongerth (1995) observed removals of 3 log for *Giardia* cysts and close to 3 log for *Cryptosporidium* oocysts with filter effluent turbidities of 0.1–0.2 NTU. The authors commented that direct filtration, when optimized, can provide a degree of control of *Giardia* and *Cryptosporidium* comparable to that seen with conventional filtration. Brown and Emelko (2009) demonstrated that pilot-scale in-line filtration preceded by stable, optimized (less than 0.1 NTU) coagulation was capable of achieving 4-log median removal of *Cryptosporidium* oocysts. Suboptimal coagulation (50% dosage, 0.2–0.3 NTU) resulted in a reduction in median oocyst removal by 2–3 log (Brown and Emelko, 2009). In contrast, Patania et al. (1995) found that removals of *Giardia* and *Cryptosporidium* by direct filtration were 0.8–1.8 log lower than those attained by conventional filtration during pilot-scale studies. Available data have indicated that sedimentation can accomplish microorganism removals on the order of 0.5–1.0 log for *Cryptosporidium* (Kelley et al., 1995; Edzwald and Kelley, 1998; Dugan et al., 2001) and 0.5 to greater than 3 log for viruses (Rao et al., 1988; Payment and Franco, 1993; Havelaar et al., 1995).

7.1.2.3 Slow sand filtration

Information on achievable filtered water turbidity corresponding to pathogen removals has been lacking. Published pilot-scale studies have indicated average physical removal capabilities for well-operated slow sand filters ranging from greater than 3 log to greater than 4 log for both *Giardia* cysts and *Cryptosporidium* oocysts (Bellamy et al., 1985a; Schuler and Ghosh, 1991; Hall et al., 1994; Timms et al., 1995; Hijnen et al., 2007). Pilot-scale slow sand filtration removals of 1–2 log enterovirus (Slade, 1978) and less than1 – 2.2 log MS2 (Anderson et al., 2009) have been reported. Schuler and Ghosh (1991) noted that slow sand filtration can achieve greater than 3-log removal of *Cryptosporidium* and *Giardia* and that a filter effluent turbidity of 0.3 NTU is attainable concurrently. In a series of slow sand filtration pilot-scale experiments, Hall et al. (1994) observed *Cryptosporidium* removals of 2.8–4.3 log (mean 3.8 log) with filtered water turbidity values ranging from 0.2 to 0.4 NTU in three of the four filter trials. In another pilot-scale investigation, Bellamy et al. (1985a) observed greater than a 99.9% (3-log) removal of *Giardia* cysts, but only a 27–39% reduction in turbidity. The low turbidity removal was attributed to the existence of fine clay particles native to the source water used in the test.

Recent Canadian studies have investigated the capability of multi-stage slow sand filters for removal of turbidity (Anderson et al., 2006), *Cryptosporidium* and *Giardia* (DeLoyde et al., 2006) and viruses (MS2) (Anderson et al., 2009). Pilot-scale systems consisting of roughing filtration and two slow sand filters in series were utilized in the experiments. In the turbidity experiments (Anderson et al., 2006), filtered water turbidities achieved in the filter effluents (SSF1, SSF2) were less than 0.3 NTU in 90.4% (SSF1) and 98.7% (SSF2) of the measurements and less than 1.0 NTU in 99% (SSF1, SSF2) of the measurements. Raw water turbidity values observed during the study period were less than 5 NTU in 61% of the measurements; however, spikes exceeding 20 NTU and occasionally reaching 80 NTU were noted (Anderson et al., 2006). During the protozoan challenge testing (DeLoyde et al., 2006), reported log removals ranging from 2.0 log to greater than 5.2 log for *Cryptosporidium* and from greater than 2.4 log to greater than 4.9 log for *Giardia* . The authors noted that removals increased with increasing filter maturation and that *Giardia* cysts were removed to a greater degree than *Cryptosporidium* oocysts. Lastly, in MS2 removal experiments, Anderson et al. (2009) observed average log removals ranging from 0.1-0.2 log for the roughing filters and 0.2 log to 2.2 log for the slow sand filters. Slow sand removal of MS2 was shown to be less effective in cold water at a high filtration rate.

7.1.2.4 Diatomaceous earth filtration

A small number of pilot-scale studies have evaluated the effectiveness of diatomaceous earth filtration for the removal of *Cryptosporidium* and *Giardia*. Logsdon et al. (1981) reported 2- to 4-log reduction of *Giardia* cysts, with filter effluent turbidity values spanning from 0.31 to 0.76 NTU. Schuler and Ghosh (1990) found greater than 3-log reductions of both *Cryptosporidium* and *Giardia*, with filter effluent turbidity values consistently below 0.2 NTU. The authors observed higher log reductions with *Giardia* than with *Cryptosporidium* and noted that *Cryptosporidium* removals were further improved when a chemical coagulant (alum) was added. Ongerth and Hutton (1997) observed average removals of greater than 5 log to greater than 6 log during testing of *Cryptosporidium* removal provided by three different grades of diatomaceous earth (median pore sizes of 5.0, 7.0 and 13.0 µm). The efficiency of *Cryptosporidium* filtration was shown to improve with increasing grades (smaller median particle sizes and lower permeability) of diatomaceous earth (Ongerth and Hutton, 1997). An indication of the corresponding turbidity values was not provided.

Ongerth and Hutton (2001) demonstrated average removals of *Cryptosporidium* greater than 6 log with filtration rates of 2.5 and 5 m/h and effluent turbidity ranging from 0.06 to 0.12 NTU. This study also found that pressure vibrations due to an undampened peristaltic feed pump caused the effluent turbidity to increase up to 0.4 NTU. Under these conditions, *Cryptosporidium* removals were still in the range of 5.0–5.8 log. Although particulate removal using diatomaceous earth filtration generally occurs through straining, several authors have demonstrated that *Cryptosporidium* and *Giardia* reductions can still be greater than 3 log even at effluent turbidities above 0.4 NTU (Logsdon et al., 1981; Ongerth and Hutton, 2001). Logsdon et al. (1981) attributed the observed high cyst reduction with a corresponding low turbidity reduction to very small particles that could pass through the filter cake while larger cysts were strained out by the diatomaceous earth.

7.1.2.5 Bag and cartridge filtration

Bag and cartridge filters (pore size typically 0.2–10 µm) are capable of removing some protozoan cysts and oocysts, but bacteria and viruses are small enough to pass through. Published studies for these technologies have reported *Cryptosporidium* removals in the range of 0.5–3.6 log (U.S. EPA, 2006b).

7.1.2.6 Membrane filtration

Microfiltration (pore size: 0.1–10 µm) and ultrafiltration (pore size: 0.01–0.1 µm) represent the most commonly used membrane processes. Microfiltration membranes are effective in removing protozoa and most bacteria, but not viruses, unless preceded by a coagulation step. Published reports have indicated log removal capabilities on the order of greater than 4.0 log to greater than 6.0 log for *Cryptosporidium* and *Giardia*, 4.0 log to greater than 6.0 log for *E. coli* and 0.0–2.0 log for viruses (MS2) (Jacangelo et al., 1995; NSF, 2000a, 2002, 2003). Ultrafiltration membranes have pore sizes small enough to remove protozoa, bacteria and viruses. Reported log removal efficiencies have ranged from greater than 5.0 log to greater than 7.0 log for *Cryptosporidium* and *Giardia*, from 2 to greater than 6 log for viruses (MS2) and up to 7.0–8.0 log for *E. coli* (Jacangelo et al., 1991, 1995; NSF, 2000b,c).

Nanofiltration membranes (0.5–2 nm) and reverse osmosis membranes are generally considered non-porous and are capable of rejecting particle sizes much smaller than those of ultrafiltration membranes. Comparatively fewer studies on the microorganism removal capabilities of these two technologies have been published in the literature. Lovins et al. (1999) reported variable results during microorganism challenge testing of two different nanofiltration technologies, one possessing a cellulose acetate membrane and the other a composite thin-film membrane. The composite thin-film membrane systems were shown to produce greater than 4–5 log removals of bacteria (*Clostridium perfringens* spores), protozoa (*Cryptosporidium* oocysts, *Giardia* cysts) and viruses (MS2), whereas the cellulose acetate membrane accomplished removals of only less than 2 log for each of the three groups. Regarding reverse osmosis membranes, Mi et al. (2004) reported bacteriophage MS2 removals of greater than 5 log, whereas Gagliardo et al. (1997a,b) observed removals of greater than 4.8 log for both *Cryptosporidium* and *Giardia* and from 2 log to greater than 5 log for viruses (MS2) during challenge testing experiments. Lozier et al. (2003) demonstrated between greater than 6-log removal to complete removal of MS2 using reverse osmosis membranes and between 3 and 5.5 log removal using nanofiltration membranes. Owen (1999) commented that imperfections in manufacturing and the inherent distribution of pore sizes for all separation processes can contribute to less than complete removal of microorganisms.

7.1.3 Optimized filtration

Optimizing treatment conditions for turbidity reduction and particle removal also optimizes cyst and oocyst removal (Hall et al., 1994; Ongerth and Pecoraro, 1995; Patania et al., 1995; Dugan et al., 2001; Huck et al., 2002). In a pilot study on the effects of coagulation conditions on *Cryptosporidium* removal by conventional treatment, Dugan et al. (2001) observed that log removals under optimized conditions (mean turbidity 0.08 NTU, range 0.02–0.15 NTU) were several orders of magnitude higher than those under suboptimal conditions (mean turbidity 0.31 NTU, range 0.13–0.66 NTU). Huck et al. (2001, 2002) examined the effects of sub-optimal coagulation and end-of-run conditions at two conventional pilot plants. Sub-optimal coagulation conditions resulted in an increase in the mean turbidity from 0.05 NTU to 0.17 NTU, with a corresponding 2-log decrease in the removal of *Cryptosporidium* to less than 1-log removal. Similarly, under end-of-run conditions *Cryptosporidium* removals decreased from an average of 5.5-log to 2.0-log when the mean turbidity increased from 0.03 NTU to 0.21 NTU. Ongerth and Pecoraro (1995) reported that direct filtration removals of *Giardia* and *Cryptosporidium* declined by 1.5 log in a filtration run that was intentionally conducted at suboptimal coagulation conditions. The average filter effluent turbidity for the suboptimal run was 0.36 NTU, compared with 0.02–0.09 NTU for runs that were optimized. The filter ripening period has also been identified as period of potential increased risk for *Cryptosporidium* in filtered water. Amburgey at al. (2005) identified a general trend towards increased *Cryptosporidium* passage during the ripening period that corresponded with elevated turbidity in the filter effluent. New pilot studies found that *Cryptosporidium* in backwash remnant water may pass through filters during ripening and result in up to a 1 log decrease in removal.

Filtration systems should be operated to reduce turbidity levels to the lowest levels possible. Water suppliers should strive to achieve a treated water turbidity target of 0.1 NTU at all times. Pilot studies with conventional treatment have demonstrated that removal of *Giardia* cysts and *Cryptosporidium* oocysts is maximized when treatment is optimized to meet a filter effluent turbidity goal of 0.1 NTU or less (Nieminski and Ongerth, 1995; Patania et al., 1995; Huck et al., 2002). This goal is consistent with the findings of the assessment behind the U.S. EPA's LT2ESWTR and with recommendations made by the PSW and the Programme d'excellence en eau potable (Program for Excellence in Drinking Water). The LT2ESWTR provides guidance on turbidity levels achieving the greatest *Cryptosporidium* log removals and specifies additional credit for public supplies meeting a filter effluent turbidity standard of 0.15 NTU with no individual filter measurement greater than 0.3 NTU in two consecutive measurements 15 minutes apart (U.S. EPA, 2006b). Similarly, among the criteria used by the PSW as representing excellence in water treatment is a filter effluent turbidity of less than 0.10 NTU in 95% of measurements with a maximum filtered water turbidity of 0.30 NTU.

There is a paucity of data pertaining to additional pathogen removal capabilities of other filtration types (e.g., slow sand, diatomaceous earth) when operating at very low turbidity levels. These processes remove particles by mechanisms other than conventional filtration. In general, optimizing processes to reduce filter effluent turbidity as low as possible will maximize pathogen removal. Schuler and Ghosh (1990) observed that diatomaceous earth removals of oocysts and turbidity were further improved when a chemical coagulant (alum) was added. In experiments with a coarse grade of diatomaceous earth (median particle size 26 µm), the addition of alum concentrations of 0.01–0.02 g/g diatomaceous earth improved filter effluent turbidities from 0.16–0.20 NTU to 0.02–0.06 NTU and improved detectable oocysts per 100 gallons (379 L) from 1–6 oocysts to less than or equal to 1 oocyst.

Increases in filter effluent turbidity during filter operations can signal the potential for the passage of unwanted organisms. Conventional filtration pilot studies have demonstrated that during periods of coagulation disruption or filter breakthrough, moderate increases in turbidity can be accompanied by increased passage of cysts or oocysts (Logsdon et al., 1985; Patania et al., 1995). Patania et al. (1995) reported that a rise in filter effluent turbidity from below 0.1 NTU to between 0.1 and 0.3 NTU correlated to up to a 1-log decline in oocyst removal capability. Emelko et al. (2003) observed that during end-of-run and early breakthrough periods, removal of seeded oocysts declined by 2–3 log while turbidity levels were increasing, but still below 0.1 NTU. It is evident from these studies that during filter operations, even at turbidity levels below the HBTL, changes in effluent turbidity levels are important as an indicator for the potential breakthrough of pathogenic organisms.

For membrane filtration, filter optimization is not focussed on reducing turbidity in the filter effluent; rather the focus is on factors such as reducing fouling rates or reducing trans-membrane pressure so that water production is optimized. However, ensuring that adequate pathogen removal is occurring during filter operation is linked with verifying that membranes are intact using a combination of indirect and direct integrity monitoring.

In general, it is difficult to link various degrees of integrity loss in membrane filters with specific reductions in pathogen log removals (U.S. EPA, 2001b). Some studies have, however, demonstrated that minor breaches to integrity can have significant impacts on pathogen removal. Jacangelo et al. (1997) examined the impact of artificially breached ultrafiltration and microfiltration pilot plants on the removal of protozoa. The results indicated that when one fibre was cut per membrane module, the removals of *Giardia* and *Cryptosporidium* decreased from greater than 6-log down to between 1.2 to 4.2 log. The authors noted that membranes with the highest number of total fibres per unit and a transverse flow mode were the least affected by a membrane integrity breach. The corresponding turbidity increases following the membrane integrity breaches also varied with each membrane unit. In some cases, significantly lower log removals (approximately 2.0 to 2.5-log) of *Giardia* and *Cryptosporidium* were observed when turbidity increased from approximately 0.03 NTU up to 0.07 NTU. Kitis et al. (2003) studied the impact of compromised reverse osmosis and nanofiltration units on the removal of MS2. The results indicated that log removals decreased from greater than 6.0 for the intact membranes down to 2.9 and less than 2.0 for reverse osmosis and nanofiltration, respectively.

Since it is difficult to quantify the microbial risk associated with various levels of membrane integrity loss, utilities should focus on the immediate detection of any breach in membrane integrity as a way to minimize the potential for breakthrough of pathogenic organisms (U.S. EPA, 2001b).

7.1.4 Log removal credits

A table outlining the average potential removal credits estimated for *Giardia*, *Cryptosporidium* and viruses when treated water meets the turbidity HBTL specified in this document can be found in Appendix B.

7.1.5 Effect of turbidity on disinfection

Disinfection of drinking water supplies requires contact of the disinfectant with microorganisms at an appropriate concentration and for an appropriate contact time. If there is interference with contact, then the effectiveness of inactivation will be reduced. In some cases, this reduction can be significant.

Particulate matter can protect viruses, bacteria and protozoa from the effects of disinfection either by reducing the transmittance of the disinfectant (e.g., scattering ultraviolet [UV] light or reacting with oxidizing disinfectants) or by shielding microorganisms that have become attached to or enmeshed within the particle surface.

Factors important in influencing particle–organism associations include the type of microorganism, the particle chemical composition and the respective sizes and surface charges of each. Both organic and inorganic sources of turbidity can protect microorganisms from disinfection (WHO, 1984). Organic turbidity sources appear to provide greater interference with chlorine disinfection, whereas particles with high UV absorbance (either organic or inorganic in nature) can provide better protection against UV inactivation. Large particles (greater than several micrometres) can provide protection for bacteria (Berman et al., 1988; Kollu and Örmeci, 2012), whereas very small particles (less than 1 µm) are capable of harbouring viruses (Hejkal et al., 1979).

In studies involving chlorine disinfection, Hoff (1978) reported that disinfection curves for chlorine inactivation of polioviruses adsorbed on bentonite clay (7.1 NTU) or precipitated with aluminum phosphate (5.0 NTU) were similar to those for virus only (0.15–0.28 NTU) and showed no indication of a protective effect. In contrast, the data showed a pronounced protective effect for virus associated with Hep-2 (human carcinoma) cells at a turbidity of 1.4 NTU. Free virus (0.15 NTU) exposed to chlorine (3.0 mg/L) was reduced by more than 5 log in under 2 minutes, whereas cell-associated virus (1.4 NTU) exposed to chlorine (range of 2.0–3.0 mg/L) had only a 3-log reduction in virus numbers after 5 minutes. A longer-term experiment conducted by the authors showed that roughly 20 minutes was required for a 5-log inactivation of cell-associated virus by chlorine (3.0 mg/L initial concentration), compared with less than 2 minutes for a 5-log reduction of free virus. The chlorine concentration in the cell-associated suspension declined from an initial concentration of 3.0 mg/L to 1.5 mg/L after 20 minutes. Ohgaki and Mongkonsiri (1990) examined the effects of virus–floc associations on chlorine disinfection efficiency. RNA coliphage Qβ entrapped within alum flocs (turbidity values not indicated) was observed to be noticeably protected from chlorine disinfection. The T99 value (contact time required for 99% inactivation) for flocculated phage (43 seconds) was observed to be nearly 3 times the value of that for freely dispersed phage (13 seconds) at a chlorine concentration of 0.4 mg/L. Barbeau et al. (2004) reported that kaolinite clay turbidity at 5 NTU did not produce a significant impact on the inactivation of MS2 phage and *Bacillus subtilis* spores with free chlorine. LeChevallier et al. (1981) studied the efficiency of chlorination in inactivating coliforms in unfiltered water supplies and found a negative correlation with turbidity. A model predicted that an increase in turbidity from 1 NTU to 10 NTU would result in an eight-fold decrease in the disinfection efficiency at a fixed chlorine dose.

Chlorine dioxide studies conducted by Scarpino et al. (1979) suggested that adsorption of poliovirus to bentonite had a definite protective effect on inactivation at turbidities greater than 3 NTU and temperatures of 25°C. Virus associated with cells demonstrated no protective effect at turbidities from 1 to 3 NTU and temperatures from 5°C to 25°C.

In a study involving ozone, Sproul et al. (1979) showed that alum and bentonite clay afforded little protection to *E. coli*, poliovirus or coxsackievirus at 1.0 and 5.0 NTU, whereas faecal material and, in particular, Hep-2 cells did provide protection.

Studies conducted with UV have investigated the potential impacts of turbidity particles on obstructing light transmission. Batch et al. (2004) reported that when UV absorbance was accounted for in the dose calculation, relatively low turbidity (0.1–0.3 NTU) had no significant effect on UV inactivation of MS2 in finished drinking water samples. Passantino et al. (2004) reported that UV disinfection was effective in inactivating MS2 seeded into unfiltered surface waters having turbidities ranging from 0.1 to 10 NTU, as well as in synthetic waters with 12 NTU montmorillonite clay turbidity and algal concentrations of 42 000 cells per millilitre . The authors did observe that compared to synthetic waters, natural waters required slightly higher UV doses to maintain the same level of phage inactivation (Passantino et al., 2004). In studying the effects of particles on UV transmission, Christensen and Linden (2003), noted that the mean UV dose delivery in raw water samples decreased between 5 and 33 percent when turbidity increased from 1 to 10 NTU. The authors further commented that increases in turbidity due to raw water spikes or filter breakthrough can negatively impact delivery of the UV dose and may compromise disinfection if not properly accounted and adjusted for during operation. Reporting on the results of a research project conducted for the city of Winnipeg, Wobma et al., (2004) noted that sediments from natural source waters caused no significant change in MS2 inactivation or UV reactor performance at turbidity levels up to 4.0 NTU. However, a turbidity level of 13 NTU was reported to interfere with UV disinfection efficiency. As part of the same study (Wobma et al., 2004), the authors noted that plankton counts had an effect on UV transmission and dose delivery, and that a higher dose was required to achieve the same level of MS2 inactivation as samples where plankton counts were not high.

The influence of turbidity particles on shielding microorganisms from UV inactivation has also been studied. It had been suggested (Templeton et al., 2005) that specific steps to enmesh the organisms with the particles (e.g., by encouraging coagulation) are necessary in order to investigate the impact of particle association of microorganisms on disinfection. Templeton et al. (2005) observed that humic acid flocs provided a measure of protection to MS2 and T4 phage from UV inactivation, whereas kaolin clay flocs had a negligible effect. Log inactivations for MS2 phage (UV doses of 40 and 80 mJ/cm^2) and T4 phage (UV doses of 2 and 7 mJ/cm^2) reported for the control samples (no humic acid or coagulant added) were at least 1 log greater than those reported for the humic acid flocculated samples (coagulation with either alum or ferric chloride). Turbidity values in this study were elevated, ranging from 70 to 100 NTU. The authors noted that humic acid particles absorb very strongly in the UV range, whereas kaolin clay particles have been observed to have low UV absorbance. Subsequently, it was concluded that the UV-absorbing content of particles is of importance for the survival of particle-associated viruses during UV disinfection (Templeton et al., 2005).

Templeton et al. (2007) also conducted an investigation of the passage of particle-associated phage through a dual-media (anthracite–sand) filter and the effect on UV disinfection. It was reported that humic acid–MS2 flocs reduced UV inactivation by a statistically significant degree, whereas kaolin–MS2 flocs did not. Documented median UV log reductions were on the order of 0.5–1.5 log less for humic acid flocculated samples compared with kaolin flocculated samples across the various filtration cycle stages (ripening, stable operation, end of cycle). The turbidities were less than 0.3 NTU for samples collected during stable operation and between 0.3 and 1.0 NTU for samples collected during ripening and end of filter cycle. The authors also noted that in unfiltered influent samples (range of 4.4–9.4 NTU), UV disinfection of phage in the presence of humic acid flocs was reduced by a statistically significant degree (roughly 0.5 log) compared with particle-free water (Templeton et al., 2005, 2007). Templeton et al. (2008) reviewed the evidence of the impacts of particle-associated viruses on disinfection processes. The authors postulated that the effectiveness of chemical and UV disinfection may be dictated more by the particle type (size, structure, chemical composition) and disinfectant type applied, than by the turbidity values themselves.

Liu et al., (2007) reported that natural turbidity particles (i.e., no coagulation or filtration) ranging from 12 to 32 NTU had little to no impact on UV inactivation of spiked *E. coli*, whereas the presence of flocs led to significantly lower UV disinfection (average reduction in activation of greater than 1 log). From these findings, the authors cautioned that UV disinfection could potentially be compromised if flocced particles were to pass through filtration and reach the UV unit. Gao and Hu (2012) similarly reported on the potential for floc particles to interfere with UV disinfection, noting a statistically significant protective effect of particles on enmeshed MS2 phage at turbidity values of 5 NTU.

Work by Mamane-Gravetz and Linden (2004) demonstrated that *Bacillus* spores within aggregates of montmorillonite clay (alum coagulation) could be protected from UV irradiation to a statistically significant degree compared with non-aggregated spores (no alum). It was also suggested that the protective effects were more pronounced in natural surface waters than in laboratory-simulated water. Differences in UV log inactivations reported between aggregated and non-aggregated spores were 1.4–1.6 log for natural waters and 0.2–0.4 log for simulated waters.

The effects of particles and aggregation under conditions similar to their natural state have also been investigated. Several authors have reported that natural particulate matter and aggregates can lower the inactivation rate of UV, but that this occurs mostly at elevated particle concentrations and is less significant in waters with low turbidity (Amoah et. al., 2005; Caron et al., 2007; Liu et al., 2007). The report from a study conducted for the Greater Vancouver Regional District in their Coquitlam watershed indicated that UV light was effective in achieving the target log reduction of greater than 3 log for *Cryptosporidium* at turbidity levels as high as 50 NTU (Clancy Environmental Consultants, Inc., 2007). The authors noted that the test organisms interacted with the particulate material through passive contact. The data also demonstrated evidence of shielding of MS2 phage and heterotrophic bacteria from UV disinfection, as UV-exposed particles were shown to release viable organisms when subjected to a dissociation procedure. Although the impact on UV inactivation was shown to be minimal, the authors similarly stated that caution would be recommended if a turbidity spike from an organic fraction of suspended material were to occur. Amoah et. al. (2005) reported that an increase in turbidity particles from naturally-occurring particulate matter to 20 NTU was associated with reductions in UV inactivation on the order of 0.8 log for *Cryptosporidium* and 0.4 log for *Giardia*. The effect of particles at turbidity values of less than 10 NTU was small and difficult to measure. It was noted that although a high level of inactivation of both parasites was achieved, complete elimination of infectivity was only observed in a small number of exposure trials. The authors concluded from the findings that interactions with natural particulate matter could result in reduced UV inactivation, but that the extent of the effect would depend on the characteristics of the turbidity particles native to individual source waters.

Using a synthetic system designed and controlled to simulate natural particle bioflocculation, Kollu and Örmeci (2012) observed that the presence of flocs was a significant factor in influencing *E .coli* inactivation at high UV doses (40, 80 mJ cm^2) and for larger particles (11, 25 µm). It was also demonstrated that even in the absence of particles, self-aggregated *E. coli* could survive exposure to a UV dose of 80 mJ/cm^2.

In a study specific to groundwater, Templeton et al. (2006) examined the impact of iron particles on the inactivation of bacteriophage by UV light. Both raw and preserved (amended with ethylenediaminetetraacetic acid to prevent iron precipitation) groundwater samples having a mean iron content of 1.3 mg/L were air oxidized, stocked with either bacteriophage MS2 or T4 and exposed to UV light. The authors observed that turbidity-causing iron oxide particles in the raw sample (2.7 NTU) protected both phages from UV inactivation to a small but statistically significant degree. Differences in log inactivations from raw to preserved samples were 0.2 log less for MS2 at a UV dose of 40 mJ/cm^2 and roughly 0.5 log less for T4 at a UV dose of 2 mJ/cm^2 (Templeton et al., 2006). The authors commented that the fact that iron particles demonstrated an effect at relatively low turbidity suggests that some types of inorganic particles may be capable of protecting viruses from UV inactivation. It was further noted that iron is a strong absorber of UV light (Templeton et al., 2006).

The potential for compromising disinfection can exist where a spike in turbidity occurs or if a particle aggregate or floc harbouring microbial pathogens were to pass through the system to reach the UV unit (Clancy Environmental Consultants Inc., 2007; Liu et al., 2007). Factors influencing the UV disinfection process include the number, size and chemical composition of particles, the nature and degree of the associated microorganisms and the type of disinfectant being applied (Templeton et al., 2005, 2008; Caron et al., 2007). It is recognized that different particles may differ in their ability to harbour and protect pathogens, and that the characteristics of the native particulate matter can differ considerably between water sources.

A turbidity value of 1.0 NTU for water entering the distribution system is recommended. Historically, 1.0 NTU or less has been recommended to ensure the effectiveness of disinfection (LeChevallier et al., 1981; WHO, 1984). Available data indicate that disinfection technologies can be effective in inactivating microorganisms when turbidity is present at higher values. Similarly, it has been proposed that the nature of the effects of particles in shielding microorganisms is a complex process that is not completely understood, and one that turbidity alone is not completely sufficient to explain (Caron et. al., 2007). As a result, the current body of evidence is not sufficient to be able to make general conclusions about turbidity levels which affect disinfectant efficacy. The recommended value of 1.0 NTU represents a risk management decision based on the assessment that it improves treatment and disinfection, is easily achievable and reflects best management practice as part of an overall commitment to risk reduction. It is advised that water suppliers strive to achieve turbidity that is as low as possible at all points in the supply chain.

7.1.6 Effect of turbidity on microbiological testing

The presence of turbidity particles can interfere with the detection and enumeration of bacteriological indicators of water quality (*E. coli*, total coliforms, HPC bacteria).

When testing for bacteriological indicators using membrane filtration, high turbidity can hinder filtration and possibly prevent the analysis of an appropriate sample volume. Additionally, turbidity particles having multiple bacterial cells attached to their surface disrupt the one cell–one colony principle of bacterial counting. In this situation, a single colony can develop from a particle containing many cells. This leads to an underestimation of bacterial numbers, because fewer cells than were actually present would be recorded. Deposits of particulate material on the membrane filter can also obstruct bacterial counts by causing poor colony development (i.e., colonies running together) or by masking desired diagnostic reactions (e.g., the development of colour or fluorescence). In an early study of the effects of turbidity on coliform recovery, Herson and Victoreen (1980) observed that turbidity was not a hindrance to the growth of coliforms on membrane filters, but did result in colonies being more difficult to recognize.

With the multiple-tube fermentation method, bacteria associated with particles can also interfere with the determination of the most probable number, similarly resulting in an underestimation of the true counts.

Routine pathogen testing of raw and finished waters is typically not practised, but collection and analysis of source water samples can be performed to provide information on organism concentrations and appropriate treatment requirements. When using methods for detection of enteric viruses and protozoa, turbidity can cause the clogging of filters, difficulties with the recovery of particle-adsorbed organisms and interference effects during the microscopic examination of protozoa (U.S. EPA, 2001a, 2006a).

7.2 Chemical characteristics

The chemical quality of water can also be influenced by turbidity. Table 1 above summarizes some common effects on water chemistry caused by different turbidity types. Inorganic turbidity particles can affect water pH, alkalinity, metal concentrations and the activity of some disinfectants. For plants using aluminum salts, increased residual particulate aluminum concentrations may be generated. Investigations have found that when treatment is properly optimized, low filtered water turbidity (less than 0.15 NTU) results in a very low aluminum residual (Letterman and Driscoll, 1988; Jekel, 1991).

Because of their adsorption capacity, clay particles can entrap inorganic and organic compounds, including metals and pesticides, and can influence the water's chemical characteristics. The reduction of turbidity particles through conventional filtration or equivalent technologies minimizes the contribution of particulate concentrations to the chemical characteristics of water. Technical information on specific chemical contaminants can be found in the individual Health Canada guideline technical documents.

Organic turbidity particles can similarly affect water pH, alkalinity and water chemistry. Among the particle types, the natural organic matter (humic) component of turbidity is considered to be of most importance in terms of its ability to affect chemical water quality. Natural organic matter is able to bind substantial amounts of metal and hydrous oxides together, forming complexes. A review of metal–natural organic matter (humate) complexes, the mechanism of their formation and their properties is provided by Schnizter and Kahn (1972). Organic chemicals such as pesticides can also be adsorbed onto natural organic matter particulates. The bonding in some chemical–natural organic matter complexes can be strong enough to interfere with the recovery and detection of the chemical contaminants.

The chlorination of water containing organic matter can produce disinfection by-products (DBPs), notably trihalomethanes (THMs) and haloacetic acids (HAAs)—groups of chemical compounds that may have health implications for humans. Strategies for addressing turbidity have implications related to controlling the potential formation of DBPs. These include precursor removal as a result of optimizing filtration and the limiting of formation through the modification of disinfection strategies (adapted chlorine application or the use of alternative disinfectants). Vrijenhoek et al. (1998) examined the effectiveness of enhanced coagulation for removing particles and THM precursors. The authors noted that significantly more THM precursors were removed during enhanced coagulation and at pH 5.5 and that removal of particles and turbidity increased substantially at alum doses above 20 mg/L.

7.3 Physical characteristics

Research has demonstrated that there is no specific relationship between turbidity reduction and particle removal (Patania et al., 1995; McTigue et al., 1998; Huck et al., 2002). The removal or reduction of either of these components is dependent upon the raw water and treatment process concentrations. Only a general turbidity–particle count correlation exists, whereby reducing turbidity increases particle removal and vice versa.

Turbidity measurements and particle counts are alike in function in that they are both approximate indicators of pathogen removals, but they are not exact surrogates. Measurements of turbidity have been traditionally relied upon as the main indicator of filtration performance because of the lower instrumentation costs, simplicity of information and ease of use. However, there is growing interest in the use of particle counters in monitoring water treatment efficiency. Similar to turbidity, particle counts have shown decreased removal during suboptimal filter operations as well as demonstrating that small spikes can be coincident with increased pathogen passage (Huck et al., 2002). Particle counts can be viewed as an additional tool for water suppliers to further optimize treatment. For example, it has been suggested that with conventional treatment, particle counters—as a result of their sensitivity—can provide advanced warning of turbidity problems during early filtration breakthrough (Huck et al., 2002).

A considerable body of evidence suggests that a large part of colour in water arises from colloidal particles. These tiny particles have physical and chemical properties that allow them to stay suspended in the water, rather than settling down or dissolving. Early research (Black and Willems, 1961; Black and Christman, 1963) used electrophoretic studies to demonstrate the predominantly colloidal nature of colour in water; it has been claimed that about 50% of colour is due to a "colloidal fraction" of natural organic matter (humic) substances (Pennanen, 1975). True colour is therefore defined as the colour of water from which turbidity has been removed (Sadar, 1998). In terms of the visual detection of turbidity, there is increasing visual detection at 5.0 NTU and above, which many consumers may find unacceptable.

The relationship between high turbidity, in both raw and filtered water, and taste and odour has also long been recognized (Atkins and Tomlinson, 1963). Algal growths, actinomycetes and their debris also contribute to taste and odour problems (Mackenthun and Keup, 1970).

8.0 Health considerations

8.1 Microbial

The most important health-related function of turbidity is its use an indicator of the effectiveness of drinking water treatment processes, particularly filtration, in the removal of potential microbial pathogens. Several studies have evaluated the relationship between drinking water turbidity, pathogen occurrence and/or gastrointestinal illness in the population. The body of evidence indicates that there is not a universal mathematical relationship through which turbidity values can be used to predict an expected rate of gastrointestinal illness in a population. Significant increases in turbidity appear to have more relevance as a potential predictor of the potential for illness. Even so, it is the water industry's assessment that turbidity is an invaluable parameter for its functions in source assessment, drinking water system control and as an indicator of potential increases in concentrations of bacteria, *Giardia* cysts and *Cryptosporidium* oocysts (MWH, 2005).

Many drinking water–related outbreaks of gastrointestinal illness have coincided with reports of elevated turbidity levels (Kent et al., 1988; MacKenzie et al., 1994; Atherton et al., 1995; British Columbia Centre for Disease Control, 1996; PHAC, 2001; O'Connor, 2002). The 1993 outbreak of cryptosporidiosis in Milwaukee (Wisconsin) was preceded by a dramatic increase in turbidity at one of the city's drinking water treatment plants (MacKenzie et al., 1994). Heavy rains, flooding and a treatment plant overwhelmed by turbidity were identified as contributing factors to the Walkerton, Ontario, outbreak in 2000 (O'Connor, 2002). Increased finished water turbidity due to a malfunctioning solids contact unit was noted around the time of the 2001 outbreak of cryptosporidiosis in North Battleford, Saskatchewan (PHAC, 2001). Logsdon et al. (2004) have identified treatment issues, such as degraded filtered water quality (e.g., high turbidity) following filter ripening and turbidity breakthrough, as factors that can increase the risk of a waterborne outbreak.

Outbreaks have also been linked to municipal supplies where no treatment irregularities were reported and where water quality parameters (including turbidity) were below the acceptable limits recognized at the time (Hayes et al., 1989; Maguire et al., 1995; Goldstein et al., 1996). An outbreak of cryptosporidiosis in Clark County, Nevada (Goldstein et al., 1996), was associated with a drinking water facility that possessed state-of-the-art treatment capabilities and produced water of better quality than the current U.S. standards at the time of the occurrence.

Post-outbreak troubleshooting performed at the Carrollton water treatment plant (Hayes et al., 1989; Logsdon et al., 1990) suggested non-optimized filtration and backwashing techniques may have led to increased passage of *Cryptosporidium* oocysts.

Investigations have been conducted to examine the potential association between the turbidity levels of public drinking water supplies and the rate of endemic (non-outbreak-related) gastrointestinal illness in the community. Schwartz et al. (1997, 2000) compared fluctuations in daily average turbidity levels with reported gastrointestinal illness–related hospital uses (emergency room visits and hospital admissions) for elderly and pediatric patients in the city of Philadelphia, Pennsylvania. Treated water turbidity levels were well below the regulated limits over the entire study period, having an average value of less than 0.20 NTU. Associations between turbidity and illness reporting were observed for turbidity values lagged by 4–6 and 10–13 days for children and 9–11 days for elderly patients. From the data, the authors further estimated that increases in turbidity of 0.04 NTU (roughly one quarter of the total range) correlated to a 9% increase in hospital admissions for elderly patients and up to a 31% increase for pediatric admissions.

A similar study was conducted by Aramini et al. (2000) in the city of Vancouver, British Columbia. Increases in raw water turbidity in the Greater Vancouver Regional District water supply (predisinfection, no filtration) were observed to correlate with increased illness rates when lagged at 3–6, 6–9, 12–16 and 21–29 days. The authors suggested that variations in turbidity exceeding 1.0 NTU (the previous Canadian guideline value) could explain as much as 2% of gastrointestinal illness–related physician visits and up to 1.3% of gastrointestinal illness–related hospitalizations.

Egorov et al. (2003) examined daily variations in drinking water turbidity and gastrointestinal illness among a study cohort in Cherepovets, Russia. Drinking water was shown to be in compliance with existing microbiological standards over the entire study period. However, the authors reported that local public health officials consider the water to be microbiologically unsafe and advise the public to boil their drinking water. Turbidity recorded during the study exceeded 1 NTU more than 80% of the time. The authors determined that individuals who reported drinking non-boiled tap water had statistically significant elevated risks of gastrointestinal illness at lags of 1, 2 and 7 days. The subset of participants who reported consuming only boiled drinking water did not demonstrate such significant association.

A group of related studies also retrospectively examined the possibility for a gastrointestinal illness-turbidity relationship to have been present at and around the time of the Milwaukee outbreak. Morris et al. (1996) reported that during the outbreak, cases of gastroenteritis were closely associated with drinking water turbidity at a lag of 7 days among children and 8 days among adults. In a follow-up analysis (Morris et al., 1998) determined that in the 434 days leading up to the outbreak, gastrointestinal events among children and adults living in the service area of one of the treatment plants (the North Plant, where a higher average effluent turbidity was observed over that period) were strongly associated with turbidity lagged by 8 days and 9 days respectively. Lastly, Naumova et al. (2003) reported a strong association between gastrointestinal illness-related hospital admissions among the elderly and drinking water turbidity lagged by 5 to 6 days. In each of the studies (Morris et al., 1996, 1998; Naumova et al., 2003), the authors concluded that the lag times observed were consistent with the incubation period for *Cryptosporidium*.

Some other investigations have failed to find evidence of a link between turbidity and endemic illness. A study equivalent to the Vancouver study was conducted in the city of

Edmonton, Alberta (Lim et al., 2002). The researchers found no significant relationship between lagged finished water turbidity values and reported rates of gastroenteritis among city residents. Most recently, Tinker et al. (2010) reported finding no association between filtered water turbidity values and rates of gastrointestinal illness during a time-series comparison of drinking water turbidity and gastrointestinal illness–related emergency department visits in the city of Atlanta, Georgia. A modest turbidity–illness association was noted by the authors when raw water turbidity values were examined.

Turbidity and community gastrointestinal illness linkages have also been examined using other surveillance mechanisms. Gilbert et al. (2006) reported an association between treated water turbidity and gastrointestinal illness–related calls to a health information telephone line. Beaudeau et al. (1999) found a positive correlation between raw water turbidity increases and increases in sales of over-the-counter anti-diarrheal medicine in the city of Le Havre, France.

Mann et al. (2007) conducted a systematic review of the literature on the subject of drinking water turbidity and endemic gastrointestinal illness. In summing up their findings, the authors noted that to date, study results have been varied: relationships between drinking water turbidity and community gastrointestinal illness have been observed in some studies, whereas other studies did not support these findings. The authors further noted that methodological differences between the studies may help explain some of the contradicting results. Presently there is no standard approach for the analysis of associations between turbidity level and health outcomes, making it difficult to directly compare studies.

8.2 Chemical

Particulate matter in water is generally not considered to pose a chemical health risk. The types of particles that are most frequently encountered are not regarded as significant chemical hazards.

There are some indirect links between the chemical quality of turbidity particles and health that can be noted as a result of particles interacting with other chemical contaminants. Clay and natural organic matter particles can adsorb heavy metals as well as some pesticides, such as dichlorodiphenyltrichloroethane (DDT), chlordane and dieldrin (Health Canada, 1995; Ritter et al., 2002). It is known that adsorbed chemicals can dissociate from particles upon experiencing a change in conditions, such as pH changes. Therefore, the possibility exists that when particles enter a different environment, such as the stomach, release of the adsorbed contaminants could occur.

Nevertheless, at the finished water turbidity levels specified in this document, it is not expected that particulate chemical contaminants will be in sufficient concentrations to present a chemical health hazard. In addition, the minerals and metals most commonly encountered (e.g., calcium, manganese, iron, aluminum) are either considered essential nutrients or have not demonstrated evidence of adverse health effects attributed to drinking water ingestion that would result from any concentration that may occur at turbidity levels recommended herein (Health and Welfare Canada, 1987a,b,c; Health Canada, 1998). In general, food and occupational routes are considered more significant contributors to metal and pesticide exposures (Ritter et al., 2002).

9.0 Distribution system

Turbidity, along with other water quality parameters, is frequently monitored to help guide the operation and maintenance of distribution systems. Several studies have also identified turbidity as a useful indicator for assessing the integrity of distribution systems (Kirmeyer et al, 2000, 2001; U.S. EPA 2006c). Consequently, turbidity should be included in routine monitoring of the distribution system so that deviations from normal conditions can be detected. Turbidity within the distribution system can be monitored in conjunction with other parameters, such as pH, disinfectant residual, *E. coli*, HPC, total coliforms and pressure to obtain a better understanding of the source of turbidity and thus, the appropriate corrective actions to take when turbidity increases are observed.

Turbidity can serve to signal potential contamination problems or difficulties within a distribution system. Increased distribution system turbidity can be indicative of breaches to the distribution system integrity, such as main breaks, backflow, intrusion, cross connections or detachment of biofilm, which may compromise the microbiological quality of the water (Kirmeyer et al., 2000). As discussed in Section 7.1.1, several studies have documented correlations between increasing levels of plate count microorganisms and increased turbidity (Snead et al., 1980; Goshko et al., 1983; Haas et al., 1983, Power and Naby, 1999). Turbidity may also increase due to hydrant opening, system maintenance and repairs, and valve failures. One study noted that turbidity was repeatedly above 1 NTU at a routine sampling site due to a valve that had been closed creating a dead-end condition in the system (Burlingame and Johnson, 2002).

Increased turbidity has also been associated with the release of corrosion products or disturbances of deposits (U.S. EPA, 2006d). Burlingame and Johnson (2002) reported a statistical correlation between distribution system samples with turbidity greater than 2 NTU and iron concentrations greater than 0.3 mg/L. Distribution systems can also experience heavy loading of sediments with the potential for accumulation of inorganic contaminants in the distribution system when source water turbidity is elevated. In particular, groundwater and other unfiltered source waters where the influent turbidity was greater than 1.0 NTU have been identified as systems where significant levels of sediments may be introduced to the distribution system (U.S. EPA, 2006d). Discoloured drinking water in the distribution system is often attributed to the presence of colloidal and particulate iron which can originate from both distribution system materials and source water (Schock and Lytle, 2011).

Although turbidity measurements cannot automatically be used to interpret the safety of water in the distribution system, a goal to maintain turbidity values below 1.0 NTU has been proposed in several publications (Geldriech, 1996; Burlingame and Johnson, 2002; Friedman et al., 2005). In addition, several case studies of utilities using 1.0 NTU or less as a value to trigger an investigation of distribution system integrity have been documented (Kirmeyer et al., 2001; Burlingame and Johnson, 2002). The concept of optimization of the distribution system has recently been introduced to the water industry (Friedman et al., 2005, 2010; Lauer, 2010). An important aspect of distribution system optimization plans is the development of water quality and operating goals. A turbidity level below 1.0 NTU has been identified as one potential goal for utilities to use for routine monitoring and operations, release to service of water mains, maintenance of water quality at dead-ends and consumer acceptance at the tap (Friedman et al., 2005).

Excessive turbidity has often been associated with unacceptable tastes and odours. Turbidity in excess of 5 NTU also becomes visually apparent and may cause consumers to object to the water. In some cases, if the level of turbidity is not addressed and the organic loading is not reduced in advance of applying certain chemicals, other health-related contaminants (e.g., DBPs) may be formed or released. Every effort should be made to keep the turbidity as low as reasonably achievable in the distribution system by minimizing turbidity entering the distribution system and conducting routine maintenance activities such as flushing and cleaning the pipelines.

10.0 Rationale

The most important health-related function of turbidity is its use as an indicator of the effectiveness of drinking water treatment processes, particularly filtration, in the removal of potential microbial pathogens. Effective removal or inactivation of microbial pathogens is best achieved when water of low turbidity is produced. High turbidity values or measurement fluctuations can be indicative of inadequate water treatment or disturbances in the distribution system. Reducing turbidity to as low as reasonably achievable and minimizing fluctuations are most protective of public health.

Turbidity is neither a direct indicator of the presence or absence of pathogens in treated water nor a direct indicator of potential health risks from consumption. It is recognized as a readily measurable parameter to indicate the effectiveness of filtration in removing pathogens. Turbidity reduction, particle removal and pathogen removal are each largely dependent upon the source water quality and the selection and operation of the treatment technology. Although turbidity levels should be kept as low as reasonably achievable, treatment limitations are a key consideration in establishing guideline values for turbidity.

The HBTL are intended to apply to representative samples of individual filter effluent turbidity. Filtration is a dynamic process; as such, brief fluctuations in turbidimeter measurements or other circumstances that cannot reasonably be prevented through process optimization may not allow measured turbidity values to be below the applicable HBTL 100% of the time. These turbidity limits are expected to be achievable by most filtration plants and, in combination with disinfection, should provide an acceptable level of protection from pathogens (i.e., bacteria, protozoa, viruses) in the finished water.

Systems whose source is either surface water or groundwater under the direct influence of surface water (GUDI) should strive to achieve a treated water turbidity target from individual filters or units of less than 0.1 NTU at all times. This applies to drinking water produced by systems that use conventional, direct, slow sand, diatomaceous earth or membrane filtration technologies. Where this is not achievable, the treated water turbidity levels from individual filters or units should be less than or equal to 0.3 NTU for conventional and direct filtration; less than or equal to 1.0 NTU for slow sand or diatomaceous earth filtration; and less than or equal to 0.1 NTU for filtration systems that use membrane filtration. These HBTLs are expected to be met in at least a certain proportion of measurements. Assessing whether a system's performance satisfies the HBTL in at least 95% or 99% of turbidity measurements requires the collection of data over a period of time. Analysis needs to be conducted to determine whether further actions are needed to improve filter effluent turbidity. Actions will be dependent on site-specific considerations. Never to exceed values are also specified for each treatment process, because readings above this value suggest a significant problem with filter performance, and should be investigated and addressed immediately.

For systems using a groundwater source, turbidity should generally be below 1.0 NTU. Best practice for these systems includes appropriate well siting, construction and maintenance, as well as monitoring source water turbidity and ensuring that turbidity levels do not interfere with the disinfection and distribution of the water supply. In some cases, a less stringent value for turbidity may be acceptable if it is demonstrated that the system has a history of acceptable microbiological quality and that a higher turbidity value will not compromise disinfection.

Turbidity can impact disinfection and the effective operation of distribution systems. Achieving low levels of turbidity immediately prior to where disinfection is applied is the best method to minimize potential interference with disinfection as well as to reduce sediment loading to the distribution system. Therefore, it is considered best practice for turbidity to be below 1.0 NTU in water entering the distribution system.

All drinking water systems should monitor and control turbidity throughout the entire distribution system including areas with long retention times, decreased disinfectant residual, or that have demonstrated deteriorating water quality. Increases in distribution system turbidity can be indicative of deteriorating water quality. If an unusual, rapid, or unexpected increase in turbidity levels does occur, the system should be inspected, the cause determined and appropriate corrective actions taken.

Health Canada will continue to monitor new research in this area and recommend any changes to the guideline technical document that it deems necessary.

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Appendix A: List of acronyms

ANSI	American National Standards Institute
APHA	American Public Health Association
ASTM	ASTM International
AWWA	American Water Works Association
CDBP	chlorinated disinfection by-product
DDT	dichlorodiphenyltrichloroethane
EPA	Environmental Protection Agency (U.S.)
FAU	formazin attenuation unit
FNU	formazin nephelometric unit
GLI	GLI International (formerly Great Lakes Instruments)
GUDI	groundwater under the direct influence of surface water
GW	groundwater
HAA	haloacetic acid
HBTL	health-based treatment limit
HPC	heterotrophic plate count
IESWTR	Interim Enhanced Surface Water Treatment Rule
ISO	International Organization for Standardization
LT1ESWTR	Long Term 1 Enhanced Surface Water Treatment Rule
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Rule
MEC	Microorganism Elimination Credit
NSF	NSF International
NTU	nephelometric turbidity unit
PSW	Partnership for Safe Water
QA/QC	quality assurance and quality control
SCC	Standards Council of Canada
SW	surface water
SWTR	Surface Water Treatment Rule
THM	trihalomethane
UV	ultraviolet
WEF	Water Environment Federation

Appendix B: Log removal credits

Table B.1 shows the average potential removal credits estimated for *Giardia*, *Cryptosporidium* and viruses when treated water meets the turbidity values specified in this guideline technical document. These log removals are adapted from the removal credits established by the U.S. EPA as part of the LT2ESWTR (U.S. EPA, 2006b) and the Long Term 1 Enhanced Surface Water Treatment Rule (LT1ESWTR) Disinfection Profiling and Benchmarking Technical Guidance Manual (U.S. EPA, 2003a). Exact pathogen removal efficiencies will be dependent on the particulars of the water to be treated and the treatment process. Specific log reduction rates can be established on the basis of demonstrated performance or pilot studies. Facilities that believe they can achieve a higher log credit than is automatically given can be granted a log reduction credit based on a demonstration of performance by the appropriate regulatory agency. Under the multi-barrier approach to drinking water treatment, pathogen physical log removal credits should be used in conjunction with disinfection credits to meet or exceed overall treatment goals. Specific information pertaining to disinfection requirements can be found in the technical documents for enteric protozoa (Health Canada, 2012) and enteric viruses (Health Canada, 2011).

Table B.1: *Cryptosporidium*, *Giardia* and virus average removal credits for various treatment technologies meeting the turbidity values specified in the *Guidelines for Canadian Drinking Water Quality*

Technology	*Cryptosporidium* removal credit[a]	*Giardia* removal credit[b]	Virus removal credit[c]
Conventional filtration	3.0 log	3.0 log	2.0 log
Direct filtration	2.5 log	2.5 log	1.0 log
Slow sand filtration	3.0 log	3.0 log	2.0 log
Diatomaceous earth filtration	3.0 log	3.0 log	1.0 log
Microfiltration[d]	Demonstration using challenge testing	Demonstration using challenge testing	No credit[e]
Ultrafiltration[d]	Demonstration using challenge testing	Demonstration using challenge testing	Demonstration using challenge testing
Nanofiltration and reverse osmosis[d]	Demonstration using challenge testing	Demonstration using challenge testing	Demonstration using challenge testing

[a] Values from U.S. EPA LT2ESWTR (U.S. EPA, 2006b), p. 678.
[b] Values based on review of AWWA (1991); U.S. EPA (2003a); Schuler and Ghosh (1990, 1991); Nieminski and Ongerth (1995); Patania et al. (1995); McTigue et al. (1998); Nieminski and Bellamy (2000); DeLoyde et al. (2006); Assavasilavasukul et al. (2008).
[c] Values from U.S. EPA LT1ESWTR Disinfection Profiling and Benchmarking Technical Guidance Manual (U.S. EPA, 2003a), p. 62.
[d] Removal efficiency demonstrated through challenge testing and verified by direct integrity testing.
[e] Microfiltration membranes may be eligible for virus removal credit when preceded by a coagulation step.
Note: The values specified in section 1.0 do not apply to bag and cartridge filtration. *Cryptosporidium* and *Giardia* removal credit may be established by the responsible authority based on demonstration using challenge testing.

***Cryptosporidium* removal credits**

When developing the LT2ESWTR, the U.S. EPA conducted an assessment of the available information on *Cryptosporidium* occurrence and treatment (U.S. EPA, 2005). As with the previous IESWTR and LT1ESWTR, the U.S. EPA indicated that the focus was preferentially placed on *Cryptosporidium* owing to the difficulty of removal through treatment, high infectivity and high chlorine resistance. For conventional filtration, the U.S. EPA concluded that plants in compliance with IESWTR turbidity requirements (combined filter effluent 95th-percentile value of ≤ 0.3 NTU; maximum value of 1.0 NTU) will achieve a minimum 2-log removal of *Cryptosporidium* and that most filtration plants will achieve median reductions close to 3 log (U.S. EPA, 2006b). Making its recommendations, the U.S. EPA cited recent studies on the performance of various treatment technologies in the removal of *Cryptosporidium* (McTigue et al., 1998; Patania et al., 1999; Emelko et al., 2000; Huck et al., 2000; Dugan et al., 2001).

The U.S. EPA (2005, 2006b) also discussed studies of treatment plant performance in removing total particle counts and aerobic spores as indicators for estimating *Cryptosporidium* removal, citing the findings of Dugan et al. (2001), Nieminski and Bellamy (2000) and McTigue et al. (1998). Dugan et al. (2001) reported that aerobic spores and total particle counts were conservative indicators of *Cryptosporidium* removal across sedimentation and filtration, with full-scale plants reporting average reductions of close to 3 log for both parameters. Nieminski and Bellamy (2000) found that aerobic spores were good indicators of treatment effectiveness, but that spore removals did not entirely correlate with protozoa removals. In an evaluation of raw and finished water from 24 utilities, the authors noted average removals of 2.8 log for aerobic spores, 2.6 log for *Giardia* and 2.2 log for *Cryptosporidium*. McTigue et al. (1998) found a strong relationship between removals of *Cryptosporidium* and particles larger than 3 µm, with data showing a median particle removal of approximately 3 log.

The U.S. EPA also communicated the findings of their assessment of studies on *Cryptosporidium* removal when effluent turbidity was in the range of 0.1–0.2 NTU. The rationale was that treatment plants, in order to ensure compliance with a filter effluent turbidity value of 0.3 NTU, would target turbidity values in this range for their operations. Analyzing the summary data from four pilot-scale investigations, Patania et al. (1995) reported a median *Giardia* removal of 3.3 log when filter effluent turbidity was greater than 0.1 NTU. A similar relationship was observed for *Cryptosporidium* (Patania et al., 1995). Dugan et al. (2001), in a pilot-scale assessment of conventional filtration conditions, observed filter runs with effluent turbidity between 0.1 and 0.2 NTU and corresponding removals of greater than 3.2 log and 3.7 log for *Cryptosporidium* oocysts.

An evaluation of existing conventional filtration data was also conducted by the Dutch KIWA research group (KIWA, 2007). The exercise was performed as part of a project to develop estimates of the microorganism removal capacity for processes used in drinking water treatment. Under the group's assessment, individual studies were weighted according to the scale of the process involved (full scale, pilot scale or bench scale), the quality of the experimental conditions and the overall quality of the data. The weighted studies were then interpreted to generate values for the microorganism elimination credits (MECs) for individual filtration technologies. Average MECs for conventional filtration were estimated at 3.4 log (range of 2.1–5.1 log) for *Giardia*, 3.2 log (range of 1.4–5.5 log) for *Cryptosporidium* and 3.0 log (range of 1.2–5.3 log) for viruses.

In assessing the available data to establish log removal credits for various technologies, both the U.S. EPA and KIWA assessments and findings from pilot-scale studies by Patania et al. (1995) and Huck et al. (2002) were reviewed. The log removal credits established are listed in

Table B.1. In a 2002 study, Huck et al. found that the average *Cryptosporidium* removals were significantly reduced under suboptimal coagulation. The authors further observed that when coagulant was absent for a short duration, *Cryptosporidium* removals were impaired by several log units, but that a 2-log oocyst removal was still maintained. During pilot-scale seeding experiments, Patania et al. (1995) noted that during breakthrough, *Giardia* removal decreased by 0.5 log, but a 3-log cyst removal was still maintained. No impact was observed on the capacity for removal of *Cryptosporidium* oocysts. Nieminski and Ongerth (1995) observed average log reductions for *Cryptosporidium* and *Giardia* of 3.0 log and 3.4 log, respectively, for pilot scale and 2.3 log and 3.3 log, respectively, for full scale, when the treatment plant was producing water with filter turbidity ranging from 0.1 to 0.2 NTU. In a summary of the data from an investigation of the removal of waterborne pathogens by pilot-scale conventional filtration, Xagoraraki et al. (2004) reported that filter effluent turbidity samples (occurring during ripening and filter breakthrough) ranging from 0.2 to 0.3 NTU corresponded with a median *Cryptosporidium* removal of 1.8 log (range of 1.2–2.6 log). Decreasing turbidity to below 0.2 NTU resulted in improved log reductions. However, an increased turbidity of up to 0.5 NTU did not produce a noticeable change in the median, maximum or minimum removal values.

Pilot-scale studies in which filter log removal capabilities were determined using low pathogen concentrations were also assessed in establishing log removal credits for various technologies, outlined in Table B.1. Concerns raised in the literature (Assavasilavasukul et al., 2008) that the estimation of filter log removal capabilities can be limited by the influent pathogen concentration in full-scale studies and that concentrations used in pilot-scale seeding studies may not reflect typical full-scale conditions were also considered. McTigue et al. (1998) conducted a series of pilot-scale spiking experiments with varying influent *Cryptosporidium* and *Giardia* concentrations. This study demonstrated that removals averaged 4 log for the filters and were not shown to be significantly affected by cyst and oocyst concentrations, which ranged from 10^1–10^3 per litre using both grab samples and continuous sampling. Pilot-scale studies measuring removals of *Cryptosporidium* and *Giardia* at low influent concentrations were also conducted by Assavasilavasukul et al. (2008). Mean log removals calculated from grab samples at low concentrations (10^0–10^3 pathogens per litre) ranged from 1.2 to 2.0 log for *Cryptosporidium* and from 1.5 to 2.6 log for *Giardia*. Mean log removals calculated from continuous sampling (sampling 288 L) at low concentrations (10^0–10^3 pathogens per litre) ranged from 1.4 to 2.3 log for *Cryptosporidium* and from 1.8 to 3.2 log for *Giardia*. Log removals for treatment trains that achieved pathogen concentrations below the detection limits were observed (undetectable cysts/oocysts per 10 L for grab sampling and undetectable cysts/oocysts per 288 L for continuous sampling), suggesting the capability for greater log removals, but only data with detectable cysts/oocysts were included in the analysis.

Based on its review, Health Canada agrees with and has subsequently adopted assumptions for *Cryptosporidium* log removal credits for conventional filtration similar to those of the U.S. EPA. It was concluded from the review that there still exists some uncertainty in the literature regarding the possible magnitude of additional log removal credits for full-scale facilities achieving turbidities of less than 0.1 NTU (Ongerth and Pecoraro, 1995; Assavasilavasukul et al., 2008). As a result, additional credits are not specified at this time.

For slow sand and diatomaceous earth filtration, the U.S. EPA in its LT2ESWTR assessment concluded that both technologies, when well designed and properly operated and in compliance with turbidity performance standards established under the 1989 Surface Water Treatment Rule (SWTR) (U.S. EPA, 1989) (≤ 1 NTU in at least 95% of measurements; and a maximum of 5 NTU), will be able to achieve *Cryptosporidium* removals similar to those attained with conventional filtration plants. As with conventional filtration, the U.S. EPA asserted that these technologies are capable of median *Cryptosporidium* removals close to 3 log.

KIWA's (2007) assessment of the microorganism removal capacity of slow sand filters estimated considerably higher log removal credits for *Cryptosporidium* (average 4.8 log, range of 2.7 to greater than 6.5 log).

In reviewing the small number of studies available for slow sand filters (Schuler and Ghosh, 1991; Hall et al., 1994; Timms et al., 1995; Hijnen et al., 2007) and diatomaceous earth filters (Schuler and Ghosh, 1990; Ongerth and Hutton, 1997) as well as the U.S. EPA (2006b) and KIWA (2007) assessments, it was determined that the U.S. EPA approach is appropriate for estimating the log removal credits for *Cryptosporidium* achievable through these filtration technologies. This approach subsequently adopted similar assumptions for log removal credits achievable with these technologies assigned in Table B.1.

For cartridge and bag filtration, it was determined that the U.S. EPA's assessment (U.S. EPA, 2006b) is appropriate—that the performance of these alternative filtration technologies varies among individual manufacturers and that it is currently not possible to propose general removal credits for these technologies.

***Giardia* and virus removal credits**

The log removal credits for *Giardia* and viruses in Table B.1 are adapted from the removal credits established by the U.S. EPA in the LT1ESWTR Disinfection Profiling and Benchmarking Technical Guidance Manual (U.S. EPA, 2003a). In developing the LT2ESWTR, the U.S. EPA extended the requirements in this manual to this rule. In reviewing the available data, it was noted that the *Giardia* and virus credits in the manual were derived from a small number of studies that were available at the time of the U.S. EPA assessment (AWWA, 1991). It was also noted that the credits were intended for a higher 95th-percentile turbidity performance standard of 0.5 NTU, recommended under the U.S. EPA's SWTR. Lastly, in the documentation, the U.S. EPA used a conservative approach to assigning filtration credits and requiring the remainder of the total inactivation credits to be achieved through disinfection, as part of the multiple barrier concept (AWWA, 1991).

Recent studies of pathogen removal with conventional, direct, slow sand and diatomaceous earth filtration technologies have demonstrated log reduction capabilities for *Giardia* similar to, and in many cases greater than, those demonstrated with *Cryptosporidium* (Schuler and Ghosh, 1990,1991; Nieminski and Ongerth, 1995; Patania et al., 1995; McTigue et al., 1998; Nieminski and Bellamy, 2000; DeLoyde et al., 2006; Assavasilavasukul et al., 2008). On the basis of the currently available data, it has been determined that the data support filtration log removal credits for *Giardia* being the same as the log removal credits established for *Cryptosporidium*.

For viruses, information on the removal capabilities of the different filtration technologies has been limited. Recent data available on the removal of viruses and their surrogates (MS2 phage) by pilot-scale studies using conventional filtration (Rao et al., 1988; Harrington et al., 2001; Xagoraraki et al., 2004) are supportive of the virus log removal credits established in the LT1ESWTR Disinfection Profiling and Benchmarking Technical Guidance Manual (U.S. EPA, 2003a). Estimated virus removal credits established by KIWA (2007) were 3.0 log (range of 1.2–5.3 log) for conventional filtration and 2.2 log (range of 0.6–4.0 log) for slow sand filtration. Based on this information, it has been determined that there is not sufficient evidence to suggest the need to revise the virus filtration credits based on those in the LT1ESWTR Disinfection Profiling and Benchmarking Technical Guidance Manual (U.S. EPA, 2003a).

For bag, cartridge and membrane filtration, it was determined that the U.S. EPA's (2006b) assessment is appropriate—that the performance of these alternative filtration technologies varies among individual manufacturers and that it is currently not possible to propose general removal credits for these technologies.

Challenge testing

As indicated in Table B.1, cartridge and bag filtration can obtain log removal credits for *Cryptosporidium* and *Giardia* with the appropriate challenge testing. Under the U.S. EPA's LT2ESWTR, bag and cartridge filtration processes may receive a 1-log removal credit for *Cryptosporidium* for bag filtration that shows a minimum of 2-log removal in challenge testing and a 2-log removal credit for cartridge filtration showing a minimum of 3-log removal in challenge testing (U.S EPA, 2006b). Challenge testing is product specific; therefore, each manufacturer or third party can challenge test the filter unit to obtain a removal rating. For facilities wishing to find out more information, resources describing requirements for bag and cartridge filter challenge testing procedures include the U.S. EPA's LT2ESWTR Toolbox Guidance Manual (U.S. EPA, 2010) and the joint NSF/U.S. EPA Protocol for Equipment Verification Testing for Physical Removal of Microbiological and Particulate Contaminants (NSF, 2005).

Microfiltration, ultrafiltration, nanofiltration and reverse osmosis can receive log removal credit for *Cryptosporidium*, *Giardia* and nanofiltration and reverse osmosis can receive log removal credit for viruses if the process establishes a removal efficiency through challenge testing that can be verified by direct integrity testing and undergoes periodic direct integrity testing and continuous indirect integrity monitoring during use. The maximum removal credit that a membrane filtration process is eligible to receive is equal to the lower value of either the removal efficiency demonstrated during challenge testing or the maximum log removal value that can be verified through the direct integrity test (i.e., integrity test sensitivity) used to monitor the membrane filtration process (U.S. EPA, 2005, 2006b). For facilities wishing to find out more information, resources describing requirements for membrane filter challenge testing procedures include the U.S. EPA's Membrane Filtration Guidance Manual (U.S. EPA, 2005) and the joint NSF/U.S. EPA Protocol for Equipment Verification Testing for Physical Removal of Microbiological and Particulate Contaminants (NSF, 2005).

Appendix C: Guidance for achieving turbidity targets

Filtration systems should be designed and operated to reduce turbidity levels as low as possible. Research and field studies support optimizing particle removal in filtration plants to maximize protection of public health from microbiological contamination. Accordingly, filtration systems that use conventional, direct, slow sand or diatomaceous earth technologies should strive to achieve a treated water turbidity target of less than 0.1 NTU at all times.

In order for utilities to achieve a treated water turbidity target of less than 0.1 NTU, the filtration technology needs to be appropriately designed and the process must be optimized. Utilities may achieve plant optimization by following plant optimization programs and setting plant-specific filter performance goals. There are a number of voluntary programs and resources that utilities can use to help achieve filter optimization and ultimately a turbidity target of 0.1 NTU. Some of the programs that are available for conventional and direct filtration plants include the Partnership for Safe Water (PSW), the Programme d'excellence en eau potable (Program for excellence in drinking water) and the U.S. EPA Composite Correction Program (U.S. EPA, 1998b; PSW, 2012a; Réseau Environnement, 2012). In addition, there are a number of comprehensive documents that can aid utilities in optimizing their filtration processes (Renner and Hegg, 1997; U.S. EPA, 1998b; Logsdon et al., 2002; Logsdon, 2008).

Canadian utilities can join the PSW directly through the American Water Works Association (AWWA). The equivalent program is offered for French speaking utilities by Réseau Environnement through participation in the Programme d'excellence en eau potable. In these programs, utilities complete a variety of exercises, including data collection, analysis and a plant self-assessment. Another one of the key components of the program is to conduct filter performance monitoring. Utilities may benefit from considering the filter performance goals set by the PSW when trying to achieve a turbidity target of 0.10 NTU (PSW, 2011). The following selected PSW goals are set for achieving the Excellence in Water Treatment Award level, for plants demonstrating optimized in filter performance:

- Filtered water turbidity less than 0.10 NTU 95 percent of the time based on values recorded at 15 minute time intervals (or more frequent);
- Maximum filtered water turbidity goal equal to or less than 0.30 NTU;
- Maximum backwash recovery period goal of 15 minutes (time turbidity is above 0.10 NTU); and
- Combined filter effluent turbidity of less than 0.10 NTU 95 percent of the time.

For filtration technologies such as slow sand and diatomaceous earth, a similar approach to data collection, filter self-assessment and performance goal setting can be used to help achieve a filtered water target of 0.10 NTU or less. The factors that affect the performance of these types of technologies are discussed in sections 6.2.2 and 6.3.2. This information can be used in the filter self-assessment process to help identify performance-limiting factors, which can then be modified to facilitate filter optimization. In addition, the PSW individual filter performance goals outlined above can be used as the basis for establishing plant-specific goals for slow sand and diatomaceous earth filtration technologies.