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Effect of Treatment on Nutrient Availability

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Background and Disclaimer

The USEPA is revising the Total Coliform Rule (TCR) and is considering new possible distribution system requirements as part of these revisions. As part of this process, the USEPA is publishing a series of issue papers to present available information on topics relevant to possible TCR revisions. This paper was developed as part of that effort.

The objectives of the issue papers are to review the available data, information and research regarding the potential public health risks associated with the distribution system issues, and where relevant identify areas in which additional research may be warranted. The issue papers will serve as background material for EPA, expert and stakeholder discussions. The papers only present available information and do not represent Agency policy. Some of the papers were prepared by parties outside of EPA; EPA does not endorse those papers, but is providing them for information and review.

Additional Information

The paper is available at the TCR web site at:

   http://www.epa.gov/safewater/disinfection/tcr/regulation_revisions.html

Questions or comments regarding this paper may be directed to **TCR@epa.gov.**

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1. Introduction

As discussed in the paper "Total Coliform Rule and Distribution System Issue Papers Overview," EPA plans to assess the effectiveness of the current Total Coliform Rule (TCR) and determine what alternative and/or additional monitoring strategies are available, and to consider revisions to the TCR with potential new requirements for ensuring the integrity of the distribution system. Part of this assessment is to examine how various treatment processes contribute to nutrient availability in the distribution system and the resultant implications for influencing microbial growth in the distribution system, which is the purpose of this paper. As part of this same effort, the USEPA has issued a white paper detailing the public health concerns associated with distribution system bacteria growth entitled *Health Risks from Microbial Growth and Biofilms in the Water Distribution Systems* (2002a).

One of the primary drinking water quality concerns in the distribution system is the presence of microorganisms. The public health impacts of bacteria growth in the distribution system have been explored and well-documented. Distribution system conditions conducive to bacterial growth can result in a loss of disinfectant residual, violation of drinking water regulations focusing on microbial water quality in the distribution system (Total Coliform Rule), and growth of opportunistic pathogens. Opportunistic pathogens are a serious concern because they can cause disease in people with compromised immune systems, such as people with AIDS or cancer, or very young or old people.

The USEPA is concerned with relatively high nutrient levels in drinking water because nutrients may lead to the following drinking water problems:

- Increased levels of microbes, including opportunistic pathogens, in the bulk water, as well as in the pipe biofilm and sediments.
- Loss of disinfectant residual through reactions between disinfectant and nutrients.
- Production of toxic and/or carcinogenic disinfection by-products through reactions between disinfectant and nutrients.
- Unreliability of total coliform sampling due to increased growth of heterotrophic bacteria, resulting in false-positives or false-negative coliform tests. Coliform sampling may also become unreliable due to stimulated growth on pipe biofilms and sediments. These increased numbers may not be represented in coliform samples of bulk drinking water.
- Development of aesthetic problems.

Several studies have investigated the link between microbial growth and nutrient levels. Van der Kooij and Hijnen (1982) and Servais et al. (1995) found that the main factor governing bacterial growth was the presence of bacterial nutrients. In some cases, however, nutrient availability is not the only controlling factor. For example, LeChevallier et al. (1996) studied the relationship between disinfectant residual and assimilable organic carbon finding that systems with high assimilable organic carbon needed to have high disinfectant residuals throughout their systems to control coliforms.

Typically, drinking water utilities control the presence of microorganisms in the distribution system through:

- Treatment to remove microorganisms present in the source water supply;
- Disinfection of drinking water to inactivate microorganisms;
- Maintaining a residual disinfectant throughout the distribution system; and
- Conducting distribution system activities in a manner to prevent contamination.

Utilities normally select treatment for the capability to remove pathogens and other contaminants. Treatment processes are not usually evaluated for their potential to produce a drinking water with low levels of nutrients. It is possible that selected treatments, while meeting criteria for pathogen removal, may produce water with a nutrient supply that can stimulate bacterial growth.

Microorganisms can not be prevented from being present at the drinking water customer's tap through treatment alone. Even if the drinking water at the distribution system entry point were completely sterile, most distribution system piping surfaces have an attached biofilm (LeChevallier et al., 1990), which is where the mass of microorganisms in the distribution system are found. It is also possible for microorganisms to enter the distribution system through events such as cross-connections, main breaks, construction activities, and intrusions. In addition to the presence of a disinfectant residual, controlling nutrients and "starving" the microorganisms present can minimize bacterial growth. Likewise, nutrients do not enter the distribution system through treatment alone, but can enter the distribution system through the pathways mentioned above. Storage tanks are another potential source for nutrients to enter the distribution system.

From the perspective of improving control of pathogens within the distribution system, utilities should consider the implications that their treatment and disinfection practices can have on limiting the nutrient levels of their drinking water. This paper provides a literature review examining the degree that various water treatment processes influence nutrient levels that can promote microbial growth and describes the effects with respect to drinking water quality. The following sections will examine the nutrients of concern, applicable drinking water regulations, and treatment impacts on these nutrients. This paper also discusses these nutrients and treatment impacts on a national level and needs for future research.

2. Nutrients of Concern

Microorganisms in the distribution system can thrive if provided with organic and inorganic nutrients that promote growth (USEPA, to be published). These nutrients are:

- Organic carbon,
- Nitrogen,
- Phosphorus, and
- Metals and other substances.

The critical nutrients for the growth of heterotrophic microorganisms in the distribution system, carbon, nitrogen, and phosphorus, are needed in relative proportions of 100 to 10 to 1, respectively (Geldreich, 1996; van der Kooij and Hijnen 1982, LeChevallier et al., 1996a; Camper, 1996). Control of heterotrophic microorganisms is important because all of the primary pathogens found in drinking water, and most of the opportunistic pathogens in humans, are heterotrophic microbes. Coliforms are heterotrophic, but their growth on standard heterotrophic plate counts can be limited by the presence of other organisms that suppress the growth of coliforms (LeChevallier et al., 1980). Coliform bacteria generally need more nutrients than the bacteria that are enumerated using the heterotrophic plate count method (LeChevallier and McFeters, 1985).

Carbon is typically the growth-limiting nutrient in North American drinking water systems (Camper et al., 2000). Much of the research presented in this paper focuses on the levels of biodegradable organic carbon present in drinking water. This reflects the significance of carbon as limiting nutrient in distribution systems. However, not all bacteria growth is limited by the presence of organic carbon. As described later, the presence or absence of nitrogen, phosphorus, and metals can enhance or limit growth in drinking water distribution systems. For example, a few studies have determined that phosphorus levels could limit microbial growth in the distribution system. Investigators (Sang et al., 2003; Miettinen et al., 1997a) indicate that in some regions, such as Finland, China, Norway, or Japan, phosphorus can be a limiting nutrient in drinking water supply sources. Carbon becomes the limiting nutrient, however, when nitrogen is added. Additionally, some microbes, including opportunistic pathogens, such as *Pseudomonas aeruginosa*, can degrade a range of complex nutrients present in water. Others are more fastidious in their nutritional needs and may be starved by eliminating one important nutrient.

2.1   Organic Carbon Compounds

As discussed above, organic carbon is needed by heterotrophic microorganisms for growth in much larger quantities than other nutrients, and as such, is often the limiting nutrient. Therefore, much of the research on biological stability of treated drinking water focuses on organic carbon (Servais et al., 1993; LeChevallier et al., 1991; van der Kooij, 1992; LeChevallier et al., 1994, LeChevallier et al., 1996a; Camper et al., 2000; van der Kooij, 1997).

2.1.1   Forms of Organic Carbon in Drinking Water

Organic carbon in drinking water, measured as total organic carbon, may be comprised of compounds such as amino, humic and fulvic acids, polymeric carbohydrates, proteins, and carboxylic acids. These organic compounds can be separated into two categories: biodegradable dissolved organic carbons (BDOC) that can be used by heterotrophs as a nutrient; and refractory, or non-biodegradable, dissolved organic carbons (RDOC) which can not be consumed by heterotrophs. AOC is a sub-category of BDOC, the most readily available fraction of the BDOC. Volk and LeChevallier (1999) point out that while amino acids are generally a small proportion of organic carbon in drinking water, these compounds can support a high biomass production per unit substrate, in comparison with other biodegradable organic carbon compound.

For the purpose of assessing carbon compounds that can impact bacterial growth in the distribution system, AOC and BDOC are currently the appropriate parameters to measure (Camper et al., 2000; Hambsch and Warner, 1996; Najm et al., 2000). AOC is an indirect measurement that involves the inoculation of a sterile water sample by two specific bacteria (usually *Pseudomonas fluorescens* strain P-17 and *Spirillum* strain NOX) and monitoring for growth by plate count. This procedure assumes that nitrogen and phosphorus are not limiting, and some variations of the method call for the addition of inorganic salts to assure that carbon is the limiting nutrient. (The AOC method probably underestimates the total amount of easily degradable organic carbon because, among other reasons, the two organisms may not be able to easily degrade certain types of organic carbon that other organisms in the distribution system can easily degrade.) This method is not considered applicable for routine use at utilities due to its complexity. In contrast, biodegradable dissolved organic carbon (BDOC) can be measured by inoculating a sterile water sample with autochthonous bacteria (e.g., a small volume of a nonsterile water sample), and measuring the decrease in DOC concentration due to the carbon oxidization by bacteria. In comparison with AOC, the non-AOC portion of BDOC is likely to be made up of compounds which are more complex and have higher molecular weights (Najm et al., 2000; Camper et al., 2000). Hambsch and Werner (1996) point out that AOC provides a snapshot of the easily available carbon nutrients, while BDOC provides a more complete picture of the nutrient pool available to microorganisms. In addition, since the BDOC method measures the change in DOC directly, the results can be directly compared with TOC, chlorine demand, DBP formation potential and other direct measures. It is important to note that there are a variety of methods available for the measurement of AOC and BDOC, as well as a number of studies that compare the individual methods.

From the standpoint of measuring nutrients that can stimulate bacterial growth in the distribution system, total organic carbon is not as applicable as AOC and/or BDOC. LeChevallier et al. (1991) determined that while TOC appeared to be related to coliform growth in the distribution system, the levels did not decrease as water moved through the distribution system. These results indicate that TOC may not be a good predictor of growth episodes and may not act as a bacterial nutrient, or that most of the total organic material is not readily digestible by microorganisms.

BDOC and AOC do not often closely correlate. This may be due to the significant differences in measurement methodology or the substances comprising these parameters. Camper et al. (2000) surveyed untreated and treated drinking water quality at 64 utilities and found a "weak but significant" relationship between the two parameters. This relationship captures the variation of the compounds measured by these parameters. However, because both types of compounds can eventually be consumed, Camper et al. (2000) recommend that utilities evaluating their drinking water nutrients monitor both AOC and BDOC.

2.1.2 Typical Source Water Levels

Most organic carbon enters water from natural sources, usually dying or decaying vegetation. Thus, the type of source water used as source of supply can influence AOC in the distribution system. Camper et al. (2000) surveyed 64 surface water treatment plants throughout the US and measured a range of AOC of 3 – 806 µg C/L in the source water. AOC was typically 10% of

total organic carbon, on the higher side of the range of 0.1 to 9% cited as typical by LeChevallier et al. (1991). However, the AOC bioassay is not a direct measure of nutrient concentrations, so comparing the AOC number to actual TOC values are typically not appropriate. River supplies were associated with the highest AOC levels, on average 123 µg C/L, and the lowest levels were associated with utilities relying on infiltration galleries or blending surface and groundwaters (average of 41 µg C/L) (Camper et al., 2000). Unless contaminated, groundwater is not associated with a significant presence of organic compounds. In good quality, untreated groundwater, AOC levels are typically very low. Haddix and LeChevallier (2003) indicate that lower levels of AOC may be present in groundwater because microbial activity uses up the BDOC as water moves through the soil.

Organic carbon can reach surface waters through wastewater and industrial effluent, surface water run-off from agricultural areas, and natural organic matter (NOM). Vegetation contributes humic matter through decay, especially in summer months, as does the growth of algae. Nutrients can vary significantly across surface waters and seasonally. Another factor that affected the level of AOC was watershed protection. Sources with full watershed protection had significantly lower AOC levels.

2.1.3 AOC, BDOC, and Bacterial Growth

Studies have shown that AOC and BDOC levels correlate to controlling or enhancing bacterial growth. Table 1 summarizes the levels of AOC and BDOC that have been associated with increased or controlled bacterial growth. As shown, in most of the studies, higher AOC levels are associated with promoting coliform and HPC growth. This potential relationship is dependant upon site specific conditions such as residence time, temperature, pipe material, and disinfectant residual concentrations.

Table 1
BDOC and AOC Levels Enhancing or Controlling Bacterial Growth During Treatment

Citation	Disinfection	Finding
BDOC		
Servais et al., 1993	5 chlorinated and 2 ozonated (not followed by chlorination) systems	Water can be considered biologically stable when BDOC is less than 0.16 mg C/L.
Levi aand Joret, 1990 WQTC procddings	Unchlorinated	Water is biologically stable when BDOC is <0.2 to 0.3 mg/L
AOC		
LeChevallier et al., 1991	Chlorinated	Coliform bacteria growth was limited by AOC of 50 µg C/L.
van der Kooij, 1992, van der Kooij 1997 van der Kooij and Hijnen, 1982	Unchlorinated	Heterotrophic bacteria levels do not increase when AOC is less than 10 µg C/L.
LeChevallier et al., 1994	Chlorinated	AOC levels greater than 118 µg C/L have 57% more positive coliform samples and 16 times higher bacterial levels (on average) than systems with AOC below 82 µg C/L.

LeChevallier et al., 1996b and Camper et al., 2000	Chlorinated	A trend of increasing coliform presence was associated with AOC levels greater than 100 µg C/L.
LeChevallier et al., 1996b	Chloraminated systems	Coliforms were not more likely to occur in systems with AOC greater than 100 µg C/L compared to systems with less than 100 µg C/L.

However, a direct link between levels of BDOC and/or AOC in drinking water and distribution system biological stability is not always apparent. Volk and LeChevallier (1999) concluded that conditions causing distribution system bacterial growth are "complex and site-specific." For example, in one study performed by LeChevallier et al. (1991), a correlation was found between coliform bacteria and AOC in that elevated AOC levels corresponded to elevated coliform levels seven days later. However, in the same study, Lechevallier et al. (1991) found that nutrient levels were not predictive of HPC levels, suggesting that these organisms are not nutrient limited. LeChevallier et al. (1991) found that HPC levels were mainly influenced by temperature and chlorine residual levels.

Distribution system physical and chemical conditions can enhance or diminish the impact AOC has on growth. Research has shown that in addition to AOC (or another indicator of nutrient availability), these factors play a significant role in heterotrophic growth conditions (LeChevallier, 2003):

- Removal of particulate matter by filtration,
- Disinfectant type and level,
- Temperature,
- Corrosion, and
- Pipe materials.

In addition, in a 12-month study of 64 surface water utilities, Camper et al. (2000) found that positive coliform samples were related to these factors:

- Nutrient availability - AOC greater than 100 µg C/L;
- Temperature – Temperatures greater than 59 °F (15 °C); and
- Disinfectant residuals – free chlorine residual of less than 0.5 mg/L or less than 1.0 mg/L in chloraminated systems.

Camper et al. (2000) determined that the interaction of these factors can result in bacterial growth problems. Utilities experiencing none of these conditions are not likely to have problems (a probability of less than 2% of a positive coliform occurrence). In the study, 70% of the positive coliform samples occurred when two or more of the above conditions were in place. A utility with all three factors in place is eight times more likely to have a positive coliform sample than utilities without any of the factors in place.

Camper et al. (2000) indicated that this difficulty in establishing a direct link between organic nutrient levels and bacteria growth in the distribution system may also be due to following:

- Significant influence exerted by other factors present;
- Difficulty in performing laboratory tests;
- Inadequate number of samples; and/or
- Presence of materials that may enhance the environment for growth.

2.1.4   Additional Impacts

Organic compounds in drinking water can cause both public health and aesthetic water quality problems. Certain species of disinfection by-products, which may be carcinogenic, are formed by reactions between the disinfectant and organic materials in drinking water. Some organic compounds form DBPs and exert a chlorine demand, lowering residual concentrations as DBPs are formed. This can result in growth occurrence or the need to use higher quantities of disinfectant. Growth occurrence can cause a regulatory violation and increased potential for pathogen presence. Higher disinfectant levels can cause higher levels of disinfection by-products. Organic compounds are also associated with causing unpleasant tastes and odors in drinking water.

Little research has been done linking the presence of biodegradable carbon to the presence of waterborne pathogens. Researchers have investigated the correlation between organic nutrient levels and *Mycobacterium avium* growth in the distribution system (Falkinham et al., 2001 and Norton et al., 2004). Falkinham et al. 2001 found a correlation between increasing AOC and BDOC levels in the distribution system and increasing levels of *Mycobacterium avium* in the distribution system. Norton et al. (2004) also found that *Mycobacterium avium* was able to grow in waters with relatively low AOC and BDOC levels, >53 µg C/L and > 0.17 mg C/L, respectively. The impact of biodegradable carbon on the potential for regrowth of other opportunistic and frank pathogens has not been fully quantified (Prevost et al., 2005).

2.2   Nitrogen

Nitrogen occurs naturally in source water as organic nitrogen, ammonia, nitrate, and nitrite. Ammonia reaches surface waters through surface water run-off from fertilized fields and agricultural feedlots, and wastewater effluent. Nitrate may be naturally present in groundwater or reach aquifers through percolation of agricultural fertilizers, livestock manure, and surface water run-off. Geldreich (1996) indicated that in groundwater, nitrate concentrations can range from 1.0 to 400 mg/L. Camper (1996) indicates that it is generally assumed that nitrogen is not a growth-limiting factor due to the low concentrations needed for growth and maintenance and high turnover of existing cellular nitrogen. Thus enough nitrogen is usually present for bacteria to meet their nitrogen requirements for growth. Donlan and Pipes (1988) found no correlation between organic nitrogen, ammonia, nitrate, or nitrate, and microbial population density of biofilms in the distribution system. LeChevallier et al. (1991) studied possible microbial nutrients in the distribution system, finding that nitrogen levels did not decrease as water traveled in the distribution system, indicating that it was not consumed by the microorganisms to support growth.

Skadsen (1993) determined that nitrification usually occurs when an excess of ammonia is present in drinking water. This nutrient promotes the growth of nitrifying bacteria which convert

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ammonia to nitrites and nitrates. Nitrification causes increased nitrite and nitrate levels and can interfere with corrosion control by reducing alkalinity, pH, and dissolved oxygen. Nitrification consumes alkalinity at the rate of 8.64 mg/L HCO_3^- (Gujer and Jenkins 1974) for each mg/L of ammonia oxidized. For waters with low buffering capacity, this can reduce pH. Additionally, nitrification produces increased nitrite levels which can interfere with disinfectant residual, presenting a public health concern due to the potential for unchecked bacterial growth. Cowman and Singer (1994) demonstrated that 1.0 mg/L of nitrite exerts a free chlorine demand of 5.0 mg/L. Watson et al. (1989) determined that nitrifying bacteria secrete organic compounds which may stimulate growth of heterotrophic bacteria. Kirmeyer et al. (to be published) points out that nitrifying bacteria even accelerate corrosion by secreting nitric acid. The impacts of nitrification on distribution system water quality are further detailed in the USEPA white paper (undated) entitled *Nitrification*.

Nitrate and nitrite have the potential to pose threats to public health. The USEPA has set Maximum Contaminant Levels (MCLs) for nitrate and nitrite at 10 mg/L and 1 mg/L (as nitrogen), respectively. Nitrate can interfere with the oxygen-carrying capacity of blood in infants, resulting in serious illness, shortness of breath and blue skin. Chronic exposure to nitrite or nitrate can affect the spleen and there is question of whether these compounds are associated with cancer.

2.3   *Phosphorus*

As discussed above, a few studies have demonstrated that phosphorus can be the limiting nutrient in some systems. Sang et al. (2003) investigated the influence of PO_4^{3-}-P on bacterial growth in effluent from pilot-scale drinking water treatment. The results demonstrated that phosphorus became the limiting nutrient when AOC was 200 µg C/L and phosphorus was below 4 µg C/L. Increasing phosphorus above this level resulted in corresponding increases in bacterial growth. Sang et al. (2003) point out that little research exists on controlling distribution bacterial growth through controlling phosphorus presence in drinking water. As described above, Jegatheesan et al.'s (2004) bacterial growth model demonstrated that when nutrients were at low levels or when only carbon and phosphorus were present in significant quantities, phosphorus appears to control the estimated amount of bacterial growth. Miettinen et al. (1997a) conducted a laboratory study of microbial growth in a Finnish drinking water by observing growth occurring after addition of phosphorus. Even a very small amount of phosphorus (1 µg/L of PO_4-P) resulted in increased bacteria growth in drinking waters from groundwater and surface source waters.

In general, phosphorus naturally occurs in groundwater or may be added as part of corrosion control treatment. The range of naturally occurring phosphorus can vary widely. Phosphorus has been found to be present at levels as high as 300 µg/L or as low as 0.1 µg/L (Geldreich, 1996). Miettinen et al. (1997a) indicates that most total phosphorus in drinking water sources is associated with particles. In general, the dissolved total phosphorus portion, which is biodegradable, is present in very small amounts (Miettinen et al., 1997a). Phosphate-based corrosion inhibitors are widely used to control corrosion in drinking water distribution systems. Several studies have shown that orthophosphates and possibly polyphates are bacterial nutrients. Thus, typical concentrations of phosphate-based corrosion inhibitors added (1 to 5 mg P/L) may

stimulate growth if phosphorus is the limiting nutrient as such levels greatly exceed the nutritional requirement of bacteria (Laurent et al., 2005).

High phosphorus levels are not directly associated with adverse public health effects. However, the discharge of phosphates and other phosphorus compounds into inland lakes is of concern because the phosphorus is often the limiting nutrient in surface waters. Introduction of phosphorus often increases the oxygen demand and biomass present in lakes.

2.4 Metals and Other Substances

In addition to carbon, nitrogen, and phosphorus, microorganisms also need trace amounts of iron, sulfur, potassium, magnesium, manganese, and other substances for growth. Metals and other elements can serve as nutrients for distribution system bacteria. Iron and sulfur reducing bacteria are two common types of bacteria found in the distribution system. Iron bacteria are a varied group of microorganisms that can precipitate iron (AWWA, 2004). These bacteria convert Fe^{2+} (soluble iron) to Fe^{3+} (iron precipitate). *Gallionella ferruginea* is one of the most important of several types of iron bacteria which can foul water supplies. Sulfur bacteria reduce sulfur, sulfates, and other forms of sulfur, to hydrogen sulfide gas (AWWA, 2004). In general, both types of bacteria are considered nuisances and are not considered to directly threaten public health. Both iron and sulfur bacteria have been proven to cause odor, taste, and color in distribution water. Slime of iron bacteria will impart a reddish tinge and an unpleasant odor to water (AWWA et al., 1989). These bacteria can cause flow reductions in distribution systems (due to accumulations of ferric hydroxide) and bad tastes and odors (Christian, 1976).

Many researchers have hypothesized that water quality problems typically attributed solely to iron bacteria fouling of wells and distribution systems may be due to the presence of a more diverse microbial community. Iron and sulfur bacteria are not the only producers of slime; they may be associated with slimes of other bacteria (AWWA et al., 1989).

3. Applicable Drinking Water Regulations

Table 2 presents a summary of regulations that are pertinent to the presence of nutrients and bacteria in the distribution system. In general, regulatory limits for nutrients such as nitrate or iron are not set to prevent bacterial growth from occurring in the distribution system. Rather, they represent levels at which the nutrient becomes a direct public health hazard, causes aesthetic problems, or results in other water quality problems.

Table 2
**Federal Drinking Water Regulations Pertinent to the Presence of Nutrients
and Microbes in the Distribution System**

Regulation	Pertinence to nutrients or microbes	Summary of Key Elements
Inorganic contaminant MCLs	Controls levels of nitrate and nitrite.	▪ Sets maximum contaminant level (MCLs) for nitrate and nitrite at the plant effluent. ▪ Sets secondary maximum contaminant level (SMCLs) for iron and manganese.
Surface Water Treatment Rule (SWTR) and Interim Enhanced Surface Water Treatment Rule (IESWTR) and Long Term 1 Enhanced Surface Water Treatment Rule (LT1ESWTR)	Establishes controls for viruses (4-log reduction), *Giardia lamblia* (3 log reduction), and *Cryptosporidium* (2-log reduction). Systems use a combination of filtration and disinfection to accomplish these levels of reduction.	▪ For unfiltered systems: source water turbidity and microbial requirements, watershed protection, disinfection before entry point to the distribution system to meet treatment requirements. ▪ For filtered systems: sets filtration performance (effluent turbidity) and CT inactivation to meet treatment requirements. ▪ Utilities must maintain disinfectant residual through distribution system or meet requirement for heterotrophic bacteria. ▪ Sets limit for turbidity. ▪ Requires pathogen removal. ▪ Specifies treatment technique or watershed control for *Cryptosporidium*.
Total Coliform Rule	Indicates vulnerability of system to fecal contamination and efficacy of treatment.	▪ Sets requirements for distribution system coliform sampling. ▪ Sets acute MCL for fecal coliform and E. coli.
Stage 1 Disinfectant/Disinfection Byproduct Rule	Reduces DBP precursors (TOC) entering the distribution system for some systems; controls trihalomethanes and haloacetic acids.	▪ Remove total organic carbon through enhanced coagulation. ▪ Controls disinfection byproducts in the distribution system. ▪ Sets maximum residual disinfectant levels in the distribution system.
Lead and Copper Rule	Sets PO_4^{-3} addition as one of the optimal corrosion control strategies	▪ Controls corrosion of lead and copper ▪ Requires implementation of corrosion control strategies.

The treatments used to comply with the following rules may have an impact on the nutrient levels in the distribution system:

- *Chemical standards* – The USEPA has set enforceable standards (National Primary Drinking Water Regulations, 40 CFR 141.62) for nitrate-N (1 mg/L), and total nitrate-N and nitrite-N (10 mg/L). The USEPA has also set non-enforceable standards (National Secondary Drinking Water Regulations, 40 CFR 143.3) for iron (0.3 mg/L), manganese (0.05 mg/L), sulfate (250 mg/L), and total dissolved solids (500 mg/L). These non-enforceable standards were set to address issues not associated with public health, such as taste, odor, and color.

- *Surface Water Treatment Rules* – The Surface Water Treatment Rule (SWTR), Interim Enhanced SWTR, and the Proposed Long-Term 2 Enhanced SWTR require all systems using surface water to disinfect and most systems to filter. Nutrients may be removed by filtration and by the pre-treatment processes of coagulation, flocculation, and sedimentation. As discussed later in this paper, disinfectants can oxidize some organic compounds, and sometimes increase the amount of available biodegradable organics.

- *Total Coliform Rule (TCR)* – The TCR requires all systems to monitor for total coliforms at a frequency that depends upon the number of people served. The TCR does not directly affect the nutrient levels or microbial growth on the pipes and sediment. However, if a high nutrient level creates a significant pipe biofilm, coliforms are likely to be part of that biofilm. When coliforms are sloughed off the biofilm into the water, they may be detected by TCR compliance monitoring. The detection of such coliforms may interfere with the TCR by undercutting the utility of total coliforms for detecting problems with treatment or with cross-connections. In contrast, the detection of total coliforms may also prompt identification and control of the problem.

- *Disinfectant and Disinfection By-Product (DBP) Rules* – The Stage 1 DBP and the Proposed Stage 2 DBP Rules set limits on the concentration of potentially toxic/carcinogenic DBPs in the distribution system. The Stage 1 Rule achieves this purpose by requiring removal of TOC through enhanced coagulation before filtration. This process also should remove a significant portion of the carbon and other nutrients that microbes in the distribution system need to proliferate.

While these regulations can impact the presence of nutrients reaching the distribution system, none of them directly regulate drinking water nutrients. As indicated earlier, drinking water suppliers do not typically evaluate a potential change in treatment with respect to its impact on drinking water nutrients. In response to some regulations, utilities may actually increase nutrient levels while implementing a treatment that meets regulations for a different parameter. For example, the majority of disinfecting utilities use free chlorine to control bacterial growth in the distribution system and to meet treatment requirements, per the Total Coliform Rule and Surface Water Treatment Rule. However, chlorine has been shown to increase the levels of BDOC, as discussed in Section 4.4.1. Additionally, as a result of the DBP rule, some utilities are considering changing disinfectant. As described below, some disinfectants can directly affect

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nutrient levels. For instance, chloramination can result in nitrifying conditions in the distribution system.

4. Treatment Impacts on Nutrients of Concern

Some water treatment processes influence the levels of bacterial nutrients entering the distribution system. Additionally, the sequence of these processes can be critical to controlling biodegradable organic carbon. Many of the aspects affecting the efficacy of these processes in producing a biologically stable drinking water have been studied by drinking water researchers. This section describes the impact that various treatments can have on drinking water nutrient levels. Throughout this discussion, the impacts to BDOC and AOC are emphasized due to the significant amount of research existing on these nutrients and because in typical conditions, carbon is the limiting nutrient.

This section describes research that has been performed evaluating the influence of treatment processes on nutrients resulting in decreased bacterial growth in the distribution system. These technologies are discussed:

- Coagulation, flocculation, and sedimentation,
- Powdered activated carbon,
- Filtration – biological and membranes,
- Disinfectants and/or oxidants,
- Corrosion control, and
- Distribution system treatment and operations.

4.1 Coagulation, Flocculation, and Sedimentation

Coagulation is a step associated with pre-treating water prior to conventional and direct filtration. The purpose of coagulation is to form large aggregate particles from smaller particles naturally present in source water. This is accomplished through the addition of chemicals (coagulant, typically alum or other chemicals) that destabilize negatively-charged particles, preventing them from repelling each other and allowing them to form larger particles. Flocculation and sedimentation are the subsequent steps of this process. After coagulation, the water is stirred to facilitate the formation of larger particles, known as floc. The floc are removed from the water through settling during the sedimentation step using conventional filtration or during filtration for direct filtration facilities. In this discussion of coagulation and how it influences nutrient levels in drinking water, it is assumed that "coagulation" includes the formation and removal of large particles. In general, available research does not appear to separate out these steps and nutrient levels are reported after these steps have been completed.

Coagulation is primarily associated with removing the hydrophobic, high molecular weight fraction of organic compounds present in the water typically associated with humics (Owen et al. 1993). Under the Stage 1 DBP Rule, certain surface water systems (and systems under the direct influence of surface water) must enhance their water coagulation or softening process to achieve a specified TOC removal level because coagulation removes natural organic matter.

Table 3 summarizes findings regarding the manner in which coagulation affects nutrients in drinking water.

Table 3
Coagulation and Drinking Water Nutrients

Nutrient and/or Parameter	Findings	Reference
BDOC	*Coagulation removes BDOC.*	
	▪ Coagulation removed almost 30% of BDOC	Camper et al., 2000, and LeChevallier et al., 1996b
	▪ Enhanced coagulation removed an additional 20% of BDOC compared to baseline coagulation.	Camper et al., 2000, LeChevallier et al., 1996b
	▪ Enhanced coagulation removed an average of 38% of BDOC in ten different source waters.	Volk et al., 2000
AOC	*Studies have presented mixed findings.*	
	▪ Neither baseline or enhanced coagulation changed AOC levels in seven of ten sources.	Volk et al., 2000
	▪ Plants using iron-based coagulant had lower AOC levels in treatment plant effluent in comparison to alum or polymer coagulants.	Volk and LeChevallier, 2002
	▪ Coagulation removed 56% of AOC.	Easton and Jago, 1993
	▪ Coagulation removed up to 85% of AOC	Huck et al., 1991
Phosphorus	▪ *Coagulation removes significant portions of phosphorus.*	
	▪ Combined with filtration, 80% of phosphorus was removed.	Sang et al., 2003
Nitrogen	*Coagulation removes significant amounts of nitrogen.*	
	▪ Alum coagulation at treatment plants, with doses of 5 – 10 ppm, removed 25 to 37% of dissolved organic nitrogen.	Esparza-soto et al., 2003

Research findings shown in Table 3 indicate that coagulation is able to remove biodegradable organic carbons (BDOC). This removal may be increased by optimizing coagulation practices or selecting a different coagulant. Camper et al. (2000) reported that, overall, studies have shown that coagulation can be expected to provide partial removal of aldehydes, oxacids, carbolic acids, and amino acids.   Higher molecular weight humic substances are readily removed by coagulation, while smaller sugars and carbohydrates are not removed. Camper et al., (2000) indicate that the BDOC portion removed in coagulation could contain large molecules, humic substances, and/or biodegradable compounds bound to the humic substances removed by coagulation. However, the researchers noted that in the majority of samples, the proportion of BDOC removed with respect to DOC decreased when using enhanced coagulation in comparison to using conventional coagulation.   In general, the investigators point out that enhanced coagulation appears to remove the nonbiodegradable DOC in preference over the BDOC fraction of DOC.   Removal of BDOC may depend on the relative fractions of BDOC and non-biodegradable dissolved organic carbon as well as size of BDOC molecules and what percentage are bound to humic substances.

Investigations into the removal of AOC through coagulation have provided mixed results. AOC removal rates are questionable when aluminum-based coagulants are used because of interference in the AOC P17 test, which may account in part for the variable findings. Camper et al. (2000) found that AOC, composed of small, non-humic molecules, was not changed by coagulation in the majority of water samples. Volk et al. (2000) indicated it was difficult to remove AOC through coagulation. Easton and Jago (1993) found substantial removal of AOC, shown in Table 3, resulted when using coagulation with a long residence time for sedimentation, allowing for biological reactions to take place. LeChevallier et al. (1996) also point to biological reactions as being the reason for Huck et al.'s (1991) findings that up to 85% of AOC could be removed during coagulation. Easton and Jago (1993) found that AOC removal through coagulation was significantly affected if a disinfectant was added prior to coagulation. In their study, coagulation without pre-chlorination resulted in 56% reduction of AOC, on average. However, with pre-chlorination, an average of 11% of AOC was removed. Volk et al. (2000) explain the inability to remove AOC through coagulation as being due to characteristics of organics composing AOC. It appeared that much of the DOC removal in their study was related to large molecular weight, humic molecules. Coffey et al. (1995)'s findings support the idea that biological processes may account for removal of AOC during coagulation/flocculation/sedimentation. After implementing ozonation, 20-48% of AOC was removed by coagulation. However, when chlorination was used for pre-disinfection, no AOC removal occurred. A disinfectant residual may have prevented bacterial consumption of AOC. Phosphorus is much more easily removed through conventional treatment (coagulation, flocculation, sedimentation, sand filtration) than organic compounds (Sang et al., 2003 and Miettinen et al., 1997a).

Enhanced coagulation has been shown to affect nitrification (Harrington et al. 2002). Enhanced coagulation in comparison with conventional coagulation of the same source water resulted in delaying the on-set of nitrification at a four-day residence time. This was attributed to the removal of natural organic matter, which causes chloramine residual instability.

4.2   Powdered Activated Carbon

Utilities may apply powdered activated carbon (PAC) to treatment processes to address taste and odor concerns as well as remove synthetic organic chemicals (Volk and LeChevallier, 2002). Addition of PAC to the clarification process can enhance nutrient removal (Volk and LeChevallier, 2002). LeChevallier et al. (1990) determined that the use of PAC reduces AOC levels. This AOC reduction, along with the reduction in TOC, may contribute to the subsequent chlorine demand reduction that was observed in the distribution system. Camper et al. (2000) found that PAC added in a solids contact clarifier removed 50% more AOC from the same source water comparable to a treatment train using conventional settling basins. Volk and LeChevallier (2002) indicate that the advantage of PAC addition in a solids contact clarifier maximizes the residence time for the PAC, providing a matrix for biological growth. Baudin et al. (1999) and Camper et al. (2000) demonstrate that the application of PAC prior to UF, in a CRISTAL treatment train, can result in significant reductions in nutrients. This is discussed further in the membrane filtration section.

At one utility Najm et al. (2000) studied, the system added CRISTAL (powdered activated carbon used in conjunction with ultra filtration) to the treatment process after ozonation. This significantly affected BDOC, reducing levels from 0.8 mg C/L to less than 0.2 mg C/L (below detection of the TOC analyzer used in this evaluation). Nonetheless, heterotrophic bacteria counts remained essentially the same, still relatively high (up to 1400 CFU/mL for heterotrophic plate counts). The investigators found that although the reduction in organic carbon resulted in the ability to maintain higher chlorine residuals in the distribution system, samples containing low chlorine residuals were likely to have high bacterial counts, indicating that disinfectant residual had a more significant impact on heterotrophic bacteria than did organic carbon levels.

4.3 Filtration

Filtration of source water or of pre-treated water can remove AOC through two mechanisms: biological consumption of nutrients as water passes through the filter and separation of nutrients from treated water through use of a membrane. Research has been conducted to identify how the type of filtration process, media type, and addition of an oxidant can impact nutrient removal. It is important to note that the removal of nutrients by filtration may be counteracted by the subsequent addition of chlorine as a residual disinfectant, which can increase levels of AOC and BDOC as discussed in Section 4.4.2.

Unless biological filtration is being conducted, conventional filtration with media such as sand and anthracite appears to decrease the level of bound nutrients, but not dissolved nutrients. Camper et al. (2000) point out that there has been little research to date on how conventional filtration affects biostability. Research performed by Camper et al. (1996) and Camper et al., (2000) demonstrated that the use of pre-chlorination prior to filtration with sand/anthracite filters resulted in increased AOC levels. BDOC removal through these filters was mixed (Camper et al., 1996; Camper et al., 2000). Volk and LeChevallier (2002) report that as part of their research on 64 utilities, conventional treatment (including pre-chlorination, coagulation, flocculation, sedimentation, and filtration) reduced levels of dissolved organic carbon and increased AOC, especially at sites using sand/anthracite filters. Additionally, some treatment processes removed AOC, BDOC, and DOC. However, this is attributed to biological activity taking place in single-stage GAC/sand filters (Volk and LeChevallier, 2002).

4.3.1 Biological Filtration

In biological filtration, the treatment process includes conditions that will enhance microbial growth. Biological filtration removes nutrients by providing conditions in which microorganisms consume organic carbon prior to entering the distribution system. Biologically active filters are any filter media that allow microorganisms to become attached, usually forming a biofilm coating on or between the media grains. Slow sand (SSF), riverbank filtration (RBF), rapid gravity filtration (RGF), and granular activated carbon (GAC) have been used successfully (USEPA, 2003). These filter media provide physical, chemical, and biological processes that clean the water. Organic removal during filtration can be site-specific because it can be influenced by organic matter quality and quantity and will vary by temperature, season, media type, contact time, and back-washing strategy (Camper et al., 2000).

Researchers have investigated the nutrient removal realized by SSF, RBF, RGF, and GAC (Kuehn and Mueller, 2000; Hambsch and Werner, 1996; Langlais et al., 1991; Volk and LeChevallier, 2002; Coffey et al., 1995). Biological treatment has been shown to remove aldehydes, oxoacids, carboxylic acids, and AOCs (Camper et al., 2000). A summary for each filtration mechanism follows.

- *Slow Sand Filtration (SSF)* – Slow sand filtration consists of passing water through a bed of media (usually sand) at rates of 0.016 to 0.16 gpm/ft^2. These filters can be composed of sand, of mixed media, such as sand and anthracite, or include three different media. The filter bed has a uniform sand mixture of small grain sizes that is able to trap particulates and provides a large amount of surface area for biological growth. Rachwal et al. (1996) point out that slow sand has a specific surface area about 2.5 times larger than that of typical RGF and GAC. Much of the biological treatment occurs in the "schmutzdecke," a layer containing debris, inorganics, and microbial growth, which forms at the top of the filter bed. Removal of NOM in slow sand filters results from a combination of adsorption and biodegradation processes in both the schmutzdecke and deeper in the sand bed (Huisman and Wood, 1974; Collins et al., 1992).

- *Riverbank Filtration (RBF)* – In RBF, water moves from the source, a river, through riverbanks to an aquifer. This slow movement through riverbank and aquifer media filters the water and provides an opportunity for microorganisms to consume nutrients. RBF can be used to remove particles, bacteria, viruses, parasites, pollutants, organic compounds, and inorganic compounds (Kuehn and Mueller, 2000). Depending on the quality of the source water, it may be necessary to follow RBF with further treatment. For instance, GAC would be necessary to treat water after RBF for adsorption of pollutants. In addition to removing organic nutrients, RBF provides conditions for biological nitrification, removing ammonia from source water very efficiently. Kuehn and Mueller (2000) indicate that it is reasonable to expect that with aerobic conditions, RBF can result in a nearly complete removal of ammonia.

- *Rapid Gravity Filtration (RGF)* – RGF passes water through a granular bed at rates of 2-10 gpm/ft^2. These filters can be composed of sand, composed of mixed media, such as sand and anthracite, or include three different media. The USEPA (1999a) points out that while studies of rapid gravity filtration after ozonation have demonstrated AOC removal, most of these studies have measured AOC only and may not provide a complete picture of the biological stability of finished water. As described previously, measuring AOC only would not present a complete picture of the biodegradable organic compounds microorganisms could use for growth and energy.

- *Granular Activated Carbon (GAC)* – Granular activated carbon can remove substances from drinking water through two mechanisms: adsorption or biological treatment. Biological treatment is the more effective manner for removal of nutrients using GAC. Rachwal et al. (1996) note that GAC has a significantly larger molecular internal pore surface than other types of filter media, but these spaces are not large enough to promote biofilm growth. GAC, however, may provide a better surface for biofilm growth than slow sand or RGF because of surface roughness (Rachwal et al., 1996).

Lambert and Graham (1995) reviewed the impacts of SSF on nutrient levels and determined that between 5 and 40% (mean=16%) removal of DOC from raw waters was achieved, with variable results due to differences in plant configurations, season, and source water. SSF also removes between 14 and 40% of AOC (mean=26%), again depending on the plant configuration and season. BDOC removal by SSF was found to be higher, ranging from 40 to 75% (mean=60%).

Nutrient removal rates for RBF vary based on the organic loading of the rivers. AOC removal from Rhine River waters was approximately 80 to 90%, but this may be the result of both biodegradation and dilution with groundwater (van der Kooij et al., 1987). However, AOC removal from the Elbe River, which has a higher organic loading than the Rhine, was 63% by RBF (Kuehn and Mueller). In another humic-rich later, average AOC removal by bank filtration was 69% (Miettinen et al., 1997b). One study looked into nutrient removal rates by RBF in three U.S. utilities and determined that AOC and BDOC were reduced by 50 to 90% (Weiss et al., 2003, 2004).

Research presents varying results on whether GAC-sand filtration removes more AOC than sand-anthracite filters. LeChevallier et al. (1992) investigated the use of biologically active filters in a pilot plant, comparing AOC removal using mixed media (sand-anthracite) and GAC-sand filters. The mixed-media reduced AOC levels by 75% of levels seen after ozonation, and the GAC-sand filters reduced AOC by 86% of levels present after ozonation. Camper et al. (2000) also saw more removal with GAC than sand-anthracite. Krasner et al. (1993) showed that GAC-sand and mixed media achieved comparable AOC removal rates. Pre-disinfection using chlorine reduces the efficiency of GAC filters in removing nutrients because it disrupts the biological processes occurring within the filter (Camper et al., 2000 and Miltner et al., 1992), and the chlorine reacts with the TOC to form AOC and BDOC. Coffey et al. (1995) indicated that RGF, and GAC-biologically active filters appear to exhibit similar biological performance with respect to AOC and BDOC removal. In Volk and LeChevallier's (2002) survey of conventional water treatment plants, treatment plants that use GAC filters generally had lower plant effluent AOC levels (mean of 83 µg C/L) than systems that used sand or anthracite filter media (mean of 110 – 113 µg C/L). However, Volk and LeChevallier (2002) did not compare AOC removal provided by the GAC and anthracite filters only.

Biological filtration is often paired with the application of a pre-oxidant, such as ozone, and the absence of a disinfectant residual. The pre-oxidant is applied for the purposes of disinfecting pathogens, oxidation of iron and manganese, controlling taste and odor, and oxidation of inorganic and organic compounds (LeChevallier et al., 1992). Oxidation of organic compounds in the source water may increase the easily biodegradable nutrient level in the water. Ozonation (but not chlorination) before the biological filtration step will increase the biological activity in the filter, and this increases the efficacy of biological filtration in reducing the easily biodegradable nutrient level. LeChevallier et al. (1992) compared AOC removal in GAC-sand filters between pre-ozonated water and water that had not been pre-ozonated. In this case ozonated AOC was only slightly higher on average than the non-ozonated water (100 µg C/L vs. 92 µg C/L, respectively). Price (1994) found that combining ozonation with biological filtration did increase the biodegradability of organic matter, but also appeared to prevent bacterial growth in the distribution system. Langlais et al. (1991) found that the biodegradation occurring in the

GAC filter was such that BDOC levels of treated water were lower than water prior to ozonation. Coffey et al. (1995) compared the use of GAC/sand after ozonation to using anthracite/sand RGF. In general, both filters removed similar amounts of AOC. However, during short-term chlorination events, the GAC/sand treatment efficacy was not affected, likely due to adsorption of the disinfectant residual, while the sand-anthracite filter's removal efficiency was reduced.

GAC filters in combination with granular media (such as sand) for removal of particles have been shown to produce a biologically stable drinking water (Coffey et al., 1995). GAC is made biologically active by the absence of a residual disinfectant in the filter. Like the other biological filtration applications, GAC may be used with or without pre-ozonation. Biological consumption of nutrients will still occur. However, because ozone degrades recalcitrant organic substances, pre-ozonation increases microbial activity in the GAC and other biological filters.

Oxidant selection may affect nutrient removal. Typically, a key requirement in selection of the pre-oxidant is ensuring that no residual is present when the water reaches the filtration media to allow accumulation of biomass on the media, which is one reason ozone is often used. Wang et al. (1995) compared biomass accumulation on anthracite-sand filters with and without chlorination as a prior treatment step. At the end of 3 months the level of biomass detected on the pre-chlorinated filter was about the same as clean anthracite. The unchlorinated filter had an order of magnitude more biomass. The unchlorinated filter was significantly effective at removing BDOC and AOC. Both AOC and BDOC were higher in the effluent of the chlorinated filter than in the source water. This is the result of both the absence of biological activity in the media and the chlorine reacting with the TOC to form AOC and BDOC

Some research has demonstrated significant nutrient removal for pre-chlorinated GAC filters (LeChevallier et al., 1992). For example, in a comparison of nutrient removal on GAC-sand filters preceded by pre-ozonation or pre-chlorination, both processes resulted in significant nutrient removals. However, pre-chlorination is not a desirable option for GAC biological filtration. Pre-chlorination paired with GAC does not result in less effective biological filtration because the chlorine is quickly decomposed by the GAC through a redox reaction (Urfer et al., 1997). This rapid quenching of chlorine allows biomass to accumulate and, therefore, does not interfere with biological processes.

4.3.1.1 Additional Biological Filtration Issues

To maintain filtration efficacy, biological filters (except SSF) must be backwashed. Backwashing of biological filters can adversely affect biological filtration because it disrupts the biofilm growth in filtering media (Volk and LeChevallier, 2002) through scour or introduction of a disinfectant. As part of backwashing practices, it is important to understand and control how backwashing with chlorinated water impacts the microorganisms present on the biological filter (Huck et al., 2000). Miltner et al. (1995) compared using chlorinated and unchlorinated water to backwash anthracite-sand filters, finding that backwashing with unchlorinated water did not affect biological filtration. However, chlorinated backwash removed biomass at the top of the filter by about 22 percent. This also coincided with an inability to control disinfection by-products and nutrient levels for a period of 12 hours after backwashing. Miltner et al. (1995) determined that because the filter ripening time was relatively short, and filters are usually

backwashed at different times, providing an opportunity to blend water from different filters, these effects are not significant. However, the authors recommended using unchlorinated backwash water (Miltner et al., 1995).

Several design parameters are critical in controlling the performance of biological filters and the nutrient removal raters, including the empty bed contact time (EBCT), the hydraulic loading rate (HLR), media depth, water temperature, the concentration and composition of BOM in the filter influent, support media and operational practices such as backwashing and the use of oxidants in the feed or backwash water (Servais et al., 1991, 1992; Langlais et al., 1991; Miltner and Summers, 1992; Miltner et al., 1992; Prévost et al., 1992; Wang et al., 1995; Coffey et al., 1995; Urfer et al., 1997; Niquette et al., 1998). For example, Prevost et al. (1990) report that 62% - 90% of AOC was removed with a two-minute EBCT. However, twenty minutes were needed to remove more than 90% of the BDOC.

4.3.2 Membrane Filtration

Membrane filtration essentially consists of a thin layer of material which separates water as a function of chemical and physical characteristics when a driving force, such as pressure is applied across the membrane. Microfiltration (MF), ultra filtration (UF), nanofiltration (NF), and reverse osmosis (RO) are membrane processes that rely on pressure as the driving force. MF and UF primarily remove particles from the source water. For instance, MF and UF can be used to replace the conventional coagulation and filtration processes. Membrane removal of substances depends on the molecular size (MF and UF) or molecular weight (NF and RO) cut-off of the given membrane. The molecular weight cut-off is an approximation of the molecular size of a substance that will not be able to pass through the membrane. Some types of membranes are associated with removal of nutrients from drinking water. Both MF and UF are not associated with removal of BDOC from source water, except when a pre-treatment, such as ozone, is applied (Camper et al., 2000).

RO and NF remove biodegradable organic compounds from drinking water (Kartinen and Martin, 2001; Liu et al., 2003; Laurent et al., 1999, Randall and Escobar, 2000). Both RO and NF use semi-permeable membranes that do not have definable pores. Operating pressures for both types of membranes can depend on the dissolved solids in the source water. For example, to use RO to desalt seawater, pressure may need to be as high as 1,000 psi. The typical molecular weight cut-off for an RO membrane is less than 100 daltons. NF uses a flat sheet membrane configured in spiral-wound modules. This process typically operates at 60 – 150 psi. NF molecular weight cut-off limits can range from 200 – 1000 daltons. This type of filtration is associated with removing THM precursors, micro pollutants, humic and fulvic acids, and softening water by removing 80 – 90% of calcium and magnesium ions present. Kruithof (2001) indicates that UF in conjunction with RO can produce a biologically stable drinking water.

Reverse osmosis can remove organics and also remove phosphate and nitrate in source water. Kartinen and Martin (2001) evaluated the use of RO for the purpose of nitrate removal and determined that nearly all of the source water nitrate concentrations could be removed. Liu et al. (2003) compared the nutrient levels of pilot distribution system water that was treated by RO,

NF, conventional treatment with ozonation, and aeration in a pilot-scale distribution system, finding that RO effluent had the lowest AOC levels.

Laurent et al. (1999) documented the changes in treated and distribution system water quality after switching from biologically treated water, including conventional treatment, ozonation, and GAC filtration, to nanofiltration. Effluent water from the NF plant had BDOC levels at or below the detection limit of 0.1 mg C/L for their analyzers. Effluent water BDOC levels prior to implementation of NF were near 1 mg C/L. Laurent et al. (1999) indicated that because of the more biologically stable water, chlorine residuals could be reduced significantly without any increase in biological activity. Randall and Escobar (2000) indicate that BDOC is removed by NF due to molecular size. Treated BDOC levels in water entering the distribution system, which included a portion that did not go through the NF plant, were reduced by 73%-93% after implementation of NF. Distribution system sampling indicated that BDOC remained constant throughout the distribution system, instead of decreasing at areas with higher water ages as before. Researchers pointed out that there was no apparent carbon consumption in the distribution system that could be attributed to bacterial activity.

Escobar and Randall (1999) found that NF was effective in removing much of the DOC present in water, except for the AOC fraction. In their study, essentially no AOC removal was seen using NF. Further research (Randall and Escobar, 2000) indicated that AOC removal by NF is affected by total dissolved solids and pH because AOC removal by NF relies on charge repulsion. Otherwise, AOC molecules are small enough to pass through NF. In both cases, the researchers (Escobar and Randall, 1999; Randall and Escobar 2000) indicated that significant amounts of AOC were passing through. However, the overall pool of carbon had effectively been reduced by NF, reducing the amount of BDOC that could be converted to AOC by microorganisms or reactions with chlorine in the distribution system. Randall and Escobar (2000) indicated that resulting AOC concentrations of more than 95 µg C/L reaching the distribution system did not appear to stimulate growth of the heterotrophic bacteria and coliform populations. This was attributed to high chloramine residual in the distribution system.

Baudin et al. (1999) discuss a treatment train called CRISTAL, which involves using PAC followed by UF. They indicate that BDOC was reduced by at least 70%, producing a non-detectable level of BDOC (less than 0.2 mg C/L). The investigators attribute improved residual maintenance to the reduction in organic matter accomplished by the PAC and UF combination, and in turn, a reduction in biofilm throughout the system. Camper et al. (2000) reported that PAC addition prior to UF, increased removal of DOC by 40% -50%.

Table 4 summarizes the findings on filtration and associated treatments and their influence on nutrients available in the literature reviewed.

Table 4
Summary of Filtration and Nutrient Impacts Based on Literature Reviewed

Treatment Used in Study	Findings	Source
Conventional Treatment with pre-chlorination *Overall Findings: More research would be needed to establish nutrient removal trend.*		
Chlorination, Sand/Anthracite Filters	Increased AOC levels caused by chlorination.	Camper et al., 2000; Camper et al., 1996
	No AOC removal.	Coffey et al., 1995
	Mixed BDOC removal.	Volk and LeChevallier 2002; Camper et al. 2000
Biological Treatment *Overall Findings: Biological filtration using SSF, RBF, RGF, and GAC results in removal of nutrients, specifically AOC.*		
SSF	Can remove up to 40% AOC.	Huck et al., 1998; Sontheimer et al., 1978
	Removes between 14 and 40% AOC (mean-26%), depending on plant configuration and season. Removes 40 to 75% BDOC (mean-60%)	Lambert and Graham (1995)
	Typically removes less than 50% of untreated BDOC.	Collins and Graham, 1994
RBF	Removed 63% of AOC.	Kuehn and Mueller, 2000
	Removed 71% of ammonia.	Kuehn and Mueller, 2000
	Removed of 80 to 90% AOC	Van der Kooij et al., 1987
	Removed of 69% AOC	Miettinen et al., 1997b
	Removed 50 to 90% of AOC and BDOC in three utilities	Weiss et al., 2003, 2004
RGF	Most studies find that AOC removal occurs.	USEPA, 1999a
GAC/Sand Filters	Removed AOC, BDOC, and DOC.	Volk and LeChevallier, 2002
GAC	Removed 30% of AOC, less than RBF.	Kuehn and Mueller, 2000
Ozonation, RGF- Sand/Anthracite	Removed 30-75% of AOC reaching RGF. However, effluent AOC was still same as source water AOC.	Coffey et al., 1995
Ozonation, Sand/Anthracite	AOC removal of 75% from that of influent to filter.	LeChevallier et al., 1992
Ozonation, GAC	AOC levels were lower than those in source water.	Langlais et al., 1991
	Removed 30-75% of AOC reaching GAC. However, effluent AOC was still same as source water AOC.	Coffey et al., 1995
Ozonation, GAC/Sand	AOC removal of 86% from that of influent to filter.	LeChevallier et al., 1992
RGF compared with RBF, and GAC.	Studies presented similar nutrient removal for RGF, RBF, and GAC.	Coffey et al., 1995

Ozonation compared Chlorine, paired with RGF	Ozonation creates significantly higher AOC levels than chlorination (2.3 vs 1.75).	LeChevallier et al., 1992
	Chlorination in addition to biological filtration results in lower AOC levels than ozonation in combination with biological filtration.	LeChevallier et al., 1992
Membrane Filtration *Overall Findings: NF, RO, and UF with PAC can remove organic carbon nutrients. AOC is not removed by NF.*		
NF	Resulting BDOC levels were below the detection limit.	Laurent et al., 1999
	Removed 73% - 93% of BDOC present in source water.	Randall and Escobar, 2000
	May allow AOC to pass through.	Escobar and Randall ;1999; Randall and Escobar, 2000
UF, RO	Can produce a biologically stable drinking water under certain conditions.	Kruithof, 2001
PAC, UF	This treatment process removed at least 70% of source water BDOC.	Baudin et al., 1999

4.4 Oxidation and Disinfection

Typically, disinfectants may be applied during the treatment processes for three main purposes: oxidation; to inactivate pathogens during treatment processes; and to provide a disinfectant residual through the distribution system. As discussed previously, oxidants can also provide benefits such as reducing taste and odor-causing compounds. Regardless of the intended application, most disinfectants are oxidants and as such, react with organic and inorganic compounds present in the water.

Oxidants are added to source waters as the first step in treatment for the purposes of controlling nuisance species, such as iron bacteria; oxidizing iron and manganese; removing tastes and odors; improving coagulation and filtration efficiency; and preventing algal growth in treatment plants (USEPA 1999b). In this manner, oxidation can reduce nutrients available for iron bacteria and manganese-oxidizing bacteria before water reaches the distribution system as well as provide more aesthetically pleasing water to customers. Chlorine or chloramines are applied to all surface water systems, all groundwater systems under the direct influence of surface water, and many groundwater systems to ensure that a disinfectant residual of 0.2 mg/L is present at the entry-point of the distribution system and that a detectable disinfectant residual exists within the distribution system. Chlorine, monochloramine, and chlorine dioxide can provide a disinfectant residual in the distribution system. However, chlorine dioxide is used by few systems (see section 2.3 of U.S. EPA paper *Effectiveness of Disinfectant Residuals in the Distribution System* for estimates of the number of systems that use chlorine dioxide). Ozonation and UV application do not result in a disinfectant residual and, therefore, must be paired with a second disinfectant to ensure a residual in the distribution system.

Depending on source water TOC and the conditions of oxidation, oxidation can have a significant effect on the levels of BDOC and AOC present in the water. Oxidants break down non-biodegradable organic compounds with large molecular weights into smaller compounds that can be hydrolyzed by microorganisms (Geldreich et al., 1996). This can result in increased

AOC and BDOC. As discussed below, ozone can have a significant impact on AOC levels if not followed by biological filtration.

4.4.1 Chlorination

Application of free chlorine as an oxidant and to provide a disinfectant residual can increase the concentration of AOC, (Camper, 1996; LeChevallier et al., 1994; Camper et al., 2000) promoting bacterial growth. Easton and Jago (1993) reported that pre-chlorination dose providing a 1 to 1.5 mg/L free chlorine residual resulted in AOC levels 83% higher than those in the source water (156 µg C/L on average in untreated water). LeChevallier et al. (1992) found that both chlorination before and after treatment increased AOC levels. Post-disinfection increased AOC levels by 20%. In comparison with using ozone as a pre-disinfectant and following with chlorination, LeChevallier et al. (1992) determined that using chlorine for pre-and post-disinfection resulted in lower treated AOC levels, about two-thirds the levels resulting from pre-ozonation and post-chlorination. In addition to increased AOC levels, chlorination forms haloacetic acids, which can be consumed by microorganisms, although these acids do not likely contribute to bacterial growth as levels are regulated.

Other studies have investigated the impact of chlorine on BDOC. While post-chlorination alone has not been found to significantly increase BDOC (Joret et al., 1988; Wang et al., 1995), chlorination of ozonated water increased BDOC levels by 11 percent (Wang et al., 1995). In another study, BDOC did not increase significantly compared to what was present in the raw water, but large increases with residence time in the distribution system, which the authors attributed to partial DOC or pipe material oxidation by available free chlorine (Escobar and Randall, 2001).

While chlorine can increase AOC and BDOC, it can also effectively control microbial growth in the drinking water supply. Gagnon et al. (1998) investigated the effects that biodegradable organic matter and chlorine residual have on bacteria growth in the distribution system. As part of this study a critical amount of chlorine residual, C_{crit}, was defined. If free chlorine residuals are below the C_{crit} for the individual distribution system, then levels of biodegradable organic matter significantly affect distribution system microbial growth. At residual levels greater than C_{crit}, biodegradable organic matter did not promote bacterial growth. As Gagnon et al. (1998) indicate, the C_{crit} can be system-specific, depending on other factors which may promote bacterial growth, such as water age or pipe materials. In a survey of 64 drinking water utilities, Camper et al., (2000) found that chlorine residual at dead-end mains greater than 0.5 mg/L could control coliform growth. However, for some utilities, a much lower C_{crit} is appropriate. After switching to ozone as an oxidant (not followed by filtration), Greater Vancouver Regional District (Ferguson et al., 2001) determined that chlorine residual of 0.1 mg/L throughout the system could control distribution system bacterial growth.

Studies of haloacetic acids, disinfection by-products formed by chlorination and chloramination, have found that these compounds are degraded by heterotrophic bacteria in the distribution system (Williams et al., 1994, 1995). Further information on the effects of treatment on disinfection by-products, including haloacetic acids, can be found in the 2001 USEPA document *Controlling Disinfection By-Products and Microbial Contaminants in Drinking Water*.

4.4.2   Chloramination

Chloramination has the potential to exacerbate nutrient conditions in the distribution system. As described earlier, the potential for biological nitrification in the distribution system is associated with the use of chloramines (Skadsen, 1993). White (1992) points out that organic nitrogen and ammonia nitrogen levels in water as low as 0.3 mg/L can interfere with chloramination. Monochloramine residuals react with the organic nitrogen, forming non-germicidal organochloramines. Decomposition of monochloramine increases free ammonia levels which can be used to provide bacterial nutrients. Woolschlager et al. (2001) modeled disinfection levels in the distribution system for United Water in New Jersey and found that 60% of the available nitrate present was produced by the decay of monochloramine.

Controlled nitrification, through the addition of ammonia as part of biological filtration, prior to entering the distribution system can improve the biological stability of the finished water by providing an environment for biological consumption of nitrogen (Kirmeyer et al., 1995; Rittman and Snoeyink, 1984). This consumption results in fewer nutrients available in the distribution system.

Utilities using free chlorine for the purpose of meeting CT requirements, then adding ammonia for chloramination, may be increasing the levels of BDOC and AOC present in the finished water, in the same manner as chlorination alone. However, there is currently very little data on the levels of AOC and BDOC that form due to chloramination.

The use of chloramines does present several benefits in the distribution system. Levels of total trihalomethane and haloacetic acids (five) are lower when chloramines are used compared to when free chlorine is used for residual disinfection. Also, chloramine residual concentrations are generally more persistent free chlorine residuals, which may help to control biofilm in the distribution system as well as coliform occurrence (U.S. EPA, 1999b).

4.4.3   Ozonation

Several researchers have determined that ozonation partially oxidizes organic compounds present in the source water (DeMers and Renner, 1992; Malley et al., 1994; Glaze, 1987, 1989). These compounds become smaller and more easily biodegradable and result in increased BDOC levels at typical ozone disinfectant doses (Hambsch and Werner, 1996; Carlson and Amy, 1997, 2001; van der Kooij et al., 1982, 1989; Bablon et al., 1987; Servais et al., 1987; Hu et al., 1999; Huck et al., 1991; Bonnet et al., 1992; LeChevallier et al., 1992; Janssens et al., 1984; Gagnon et al., 1997). When followed by biological filtration, the addition of ozone reduces organic carbon content overall. Several studies have concluded that biological filtration is necessary if ozonation is used to avoid regrowth problems in the distribution system (Hu et al., 1999).

Biological filtration is enhanced by pre-ozonation, leading to a more biologically stable finished water (Gagnon et al., 1998; Hambsch and Werner, 1996). The finished water levels of BDOC in pre-ozonated and biologically filtered waters are lower than those of the untreated source water (Hambsch and Werner, 1996; Malley et al., 1994). In some cases, ozonation may improve

nutrient removal when added to a treatment train. Rachwal et al. (1996) compared the removal of AOC and BDOC by SSF, RBF, and RGF with chemical coagulant addition and pre-ozonation. They found that RGF following chemical coagulation and ozonation performed better than RGF without pre-treatment. Langlais et al. (1991) and Miltner et al. (1992) indicate that without additional ozonation or coagulation, SSF alone can reduce the presence of organic matter in treated drinking water. However, for SSF, pre-ozonation can be implemented to promote the biodegradation of BDOC in the biological layer (schmutzedecke) of the filter. Camper et al., (2000) demonstrated that adding ozonation as a pretreatment for PAC/UF has been shown to further increase DOC removals, resulting in up to 99% removal.

However, with no subsequent biological filtration, ozonation may provide nutrients to microorganisms in the distribution system. It is for this reason that many countries require biological filtration to be installed if ozonation is used. For instance, in a study conducted by LeChevallier et al. (1994), systems following ozonation with conventional treatment averaged AOC levels of 252 µg C/L, whereas the system using biological filtration after ozonation had an AOC level of 100 µg C/L. Malley et al. (1994) found that ozonation increased BDOC by a factor of two. In some cases, AOC levels in the distribution system have nearly tripled in comparison to levels prior to ozonation. For example, Greater Vancouver Water District implemented ozonation for disinfection of the unfiltered Coquitlam surface water supply. After ozonation, AOC levels increased from 280 µg acetate-C/L for chlorinated water to 680 µg C/L (Ferguson et al., 2001). In another study of ozonation's short-term and long-term impacts, water quality changes were monitored for the Orlando Utilities Commission, which uses an unfiltered groundwater (Escobar and Randall, 2001). In the weeks after implementation of ozonation, distribution system AOC increased to nearly triple pre-ozonation levels. About one year after ozone implementation, distribution system AOC levels were twice pre-ozonation levels. Wricke et al. (1996) found that at a proportion of 1 mg/L ozone dose per 1 mg/L DOC dose, 25-30% of the DOC would be converted to BDOC.

4.4.4   UV

UV is applied to drinking water treatment as a disinfectant during treatment, but can not be used to provide a disinfectant residual within the distribution system. Research on the effects of UV on organic nutrients are mixed. Kashinkunti et al. (2002) conducted bench-scale tests investigating UV impacts on AOC, finding no apparent overall trend. Shaw et al. (2000) found that UV at lower doses (<130 mWs/cm^2) did not significantly increase or decrease AOC or BDOC in either surface or groundwater levels. Camper et al. (2002) also suggest that at typical doses, UV is not likely to degrade organic matter. However, higher doses of were shown to degrade organic matter and enhance bacterial growth (Kulovaara et al., 1996; Corin et al., 1998). Mofidi et al. (1998) determined that high-intensity pulsed UV increased BDOC levels significantly, nearly doubling the levels present. A decrease in AOC was also seen in several waters in one study at both low and high doses, with dose have no impact on the amount of decrease (Lehtola et al., 2003).

4.4.5 Dechlorination

Some systems using groundwater sources may use a chemical disinfectant to treat the water, but then remove the disinfectant before it enters the distribution system. The disinfectant is used to enhance oxidation of hydrogen sulfide, iron, or manganese but is not used to provide disinfectant residual in the distribution system. Ascorbic acid ($C_6H_8O_6$) is a carbohydrate and an established and recognized dechlorinating agent (Spotts and McClure, 1995). Because this agent is an organic compound, the most significant concern associated with the use of ascorbic acid is the potential for enhanced biological growth within the distribution system. Based on stoichiometric dechlorination requirements, water containing 1 mg/L of chlorine or chloramine will require the addition of 2.48 mg/L of ascorbic acid. The reaction by-product, dehydroascorbic acid, will be present at similar levels within the distribution system. Dehydroascorbic acid is also of nutritional benefit to microorganisms (Mallevialle and Suffet, 1987). There have been no published growth studies using ascorbic acid as a dechlorinating agent.

Brazos and O'Connor (1987) studied biological growth in water samples dechlorinated with inorganic sodium thiosulfate ($Na_2S_2O_3$) (Brazos and O'Connor, 1987). Water samples were collected at the filter effluent, clearwell, and at two locations within the distribution system. The distribution system sample sites correspond to water ages of 36 hours (system maximum) and 18 hours (50% of maximum). Before dechlorination, chloramine concentrations were between 1.2 and 1.6 mg/L as Cl_2 at all locations at the time of sampling. Total and heterotrophic bacteria were analyzed at 24-hour intervals following dechlorination. Heterotrophic bacteria colony counts increased by up to 6 orders of magnitude within 3 days. There are two potential causes for the observed biological proliferation: (1) elimination of the disinfectant residual and/or (2) addition of sodium thiosulfate to the water.

4.5 Corrosion Control

Orthophosphates and polyphosphates are widely used for corrosion control in distribution systems. An initial concern associated with the application of phosphorus as part of corrosion control treatment was that this would be a source of biodegradable nutrients that might stimulate bacterial growth. AwwaRF (1990) provided an example of the addition of phosphate corrosion inhibitors to uncovered drinking water reservoirs that resulted in an increased potential for algae blooms. Several studies have investigated whether these compounds stimulate bacterial growth, with varied and contradictory conclusions. Many researchers have found that phosphorus-based corrosion inhibitors have not been associated with increased distribution system bacterial growth (LeChevallier et al., 1993 and LeChevallier et al., 1994). In fact, these inhibitors have been associated with fewer positive coliform samples (Abernathy and Camper, 1997; USEPA 1999b) due to enhanced corrosion control. The South Central Connecticut Regional Water Authority (USEPA, 1999b) increased their use of zinc metaphosphate from 1 to 2 mg/L. This change in chemical addition increased the total phosphorus levels in the distribution system from 0.31 to 0.43 mg/L. Over the next two years, positive weekly coliform levels dropped from 12 % to 5%. Abernathy and Camper (1997) posit the following reasons for improved bacterial conditions even with an additional bacterial nutrient source:

- The presence of microbial habitat has been decreased by the reduction in mass of corrosion products on the pipe surface.

- Reduced disinfectant demands of existing corrosion products and increased penetration of disinfectant to core of corrosion tubercules.

- Reduction of disinfectant demand of pipe surface and increased presence of disinfectant in outer-reaches of the distribution system.

However, other studies have shown that the addition of phosphates can promote bacterial growth in distribution systems where phosphorus is the growth-limiting nutrient (Miettinen et al., 1997b; Lehtola et al., 2002).

Such variable results are likely due to differences in water quality and nutrient concentrations in the bulk water. Various analytical methods may also have had an impact on the variable results. Overall, for systems with significant corrosion, industry experiences show that corrosion control along with proper residual maintenance may be as important or more important than nutrient levels in controlling microbial growth.

4.6   Distribution System

4.6.1   Booster Chlorination

In general, booster chlorination is the only treatment drinking water suppliers implement within the distribution system. Systems use booster chlorination to supplement disinfectant residuals in problem areas of the distribution system, such as downstream of finished water reservoirs. The effects of booster chlorination on nutrient levels have not been studied.

Tryby et al. (1999) qualitatively evaluated the use of booster chlorination as a means to reduce the chlorine dose applied at the drinking water treatment plant. Through a targeted application of chlorine at problem areas, less chlorine may be needed to maintain a disinfectant residual throughout the rest of the distribution system. Further research is needed to evaluate the effects of a lower overall finished water residual and increased disinfectant residual at specific locations within the distribution system on nutrients.

4.6.2   Distribution System Operations and Maintenance

Distribution system operations, such as reservoir operations and maintenance procedures, can be used to protect distribution system water quality. Additionally, distribution system operations such as flushing, can be used to control distribution system bacteria growth resulting from numerous factors such as treatment breakthrough, production of a biologically unstable drinking water, or intrusion of contaminants into the distribution system. Findings by Camper et al. (2000), LeChevallier et al. (1996), and Gagnon et al. (1998) point to the importance of maintaining a disinfectant residual throughout the distribution system. This may be done in the distribution system by flushing areas subject to long water ages or "cleaning" the distribution system periodically by pigging (a pipeline cleaning technique) or implementation of a comprehensive uni-directional flushing program. Camper et al., (2000) specifically studied the resultant coliform levels when high AOCs, temperatures, and low disinfectant residual conditions occurred. Practices such as flushing dead-end mains regularly and operation of storage tanks and reservoirs such that storage residence times are controlled and mixing is enhanced, can improve residual concentrations.

Distribution procedures should be in place to prevent the entry of microorganisms or other contaminants, such as nutrients, that would exert significant disinfectant demands during activities such as main break repair. The following events can provide an opportunity for entry of microorganisms and/or nutrients to enter the distribution system:

- Cross-connection,
- Intrusion,
- Main installation,
- Main repair,
- Openings in covered reservoirs, and
- Uncovered reservoirs.

To date, there have been no studies specifically on the entry of nutrients into the distribution system, describing how frequently this occurs, the levels of nutrients entering, and their impacts on microorganisms in the distribution system. However, studies have been conducted to investigate the possibility of pathogens entering the distribution system via contaminated water that enters the distribution system through the six mechanisms listed above. Friedman et al. (2004) investigated the volume of water entering the distribution system during low or negative pressure transients (intrusions). Table 5 presents results from two different approaches for quantifying the volume of water entering through 1/8-inch and 1/4-inch orifices. The volumetric method provides the better estimate of how much intruded into the pipe. The tracer method provides the better estimate of how much stayed in the pipe after the pressure transient occurred.

Table 5
Intrusion Volume Comparison of Chemical Tracer and Volumetric Methods[1, 2]

Trial No.	Intrusion Volume for 1/8" Orifice (mL)		Intrusion Volume for ¼" Orifice (mL)	
	Chemical Tracer Method	Volumetric Method	Chemical Tracer Method	Volumetric Method
1	9.9	44.0	64.9	121.0
2	12.8	46.8	52.5	99.0
3	-	49.5	75.4	126.6
4	-	49.5	91.8	121.0
Average	11.4±2.1	47.5±2.6	71.2±16.7	116.9±12.2

[1]Friedman et al., 2004.
[2]Steady state conditions were established at 132 gpm and 30 psi prior to valve closure. The magnitude of the first (and largest) pressure drop in each trial was about 42 psi resulting in a minimum internal head of approximately -12 psi and remaining negative for about 1 second.

Further information on distribution system operations that can prevent intrusion of contaminated water and optimize water quality can be found through the American Water Works Association and American Water Works Association Research Foundation. In many systems, intrusion may not represent a significant addition of nutrients when compared with the global flux of nutrient into the distribution system. However, because the primary concern is preventing the ingress of dirty water into the drinking water system, similar means would be used to prevent the entry of

nutrients into the distribution system via other pathways. Some examples of control methods are (Kirmeyer et al., 2001):

- Application of a risk assessment model to identify, manage, and prevent entry of dirty water;
- Enforcement of a cross-connection control program;
- Maintenance of adequate pressure throughout the distribution system;
- Monitoring water quality and pressure throughout the distribution system;
- Implementation of standard operating procedures and training for distribution system personnel; and
- Regular maintenance and inspections for finished water storage facilities.

5. National-Level Assessment of Control of Nutrients of Concern

Table 6 presents information on the treatment processes discussed in this report and the prevalence of their use according to the USEPA 2000 Community water system survey (USEPA, 2002b). As new drinking water rules have been promulgated since the survey, the distribution of treatment processes has been changing. It is difficult to predict the future distribution of treatment processes and how they may impact nutrient issues on a national basis.

Table 6
National Distribution of Treatment Processes

Treatment Process	Type of Source	Percent of Systems (all sizes)[1, 2]
Chlorination only	Surface	13
	Groundwater	72
Pre-disinfection/Oxidation prior to sedimentation		
Chlorine	Surface	36
	Groundwater	8
Chloramines, Ozone	Surface and Groundwater	< 5
Pre-disinfection/Oxidation prior to filtration		
Chlorine	Surface	24
	Groundwater	8
Chloramines, Ozone	Surface	< 5
	Groundwater	0
Coagulation/Flocculation	Surface	64
	Groundwater	< 5
PAC	Surface	8
	Groundwater	0
Filtration		
Slow sand	Surface and Groundwater	< 5
Rapid Gravity	Surface	18
	Groundwater	< 5
Riverbank filtration	Surface and Groundwater	No information
GAC	Surface	9
	Groundwater	<5
Dual/Multi-media	Surface	45

	Groundwater	<5
Post-disinfection after filters		
Chlorine	Surface	71
	Groundwater	14
Chloramines	Surface	8
	Groundwater	<5
Ozone, UV	Surface and Groundwater	<5
Membranes	Surface and Groundwater	<5
Corrosion Control	Surface	42
	Groundwater	17

[1] Adapted from USEPA, 2002b.
[2] 53,410 community water systems were included in the survey.

6. Further Research

Extensive studies have evaluated the impacts of certain treatment processes on nutrient levels. Treatment processes meriting future research are:

- UV,
- Filtration pre-coats, such as diatomaceous earth,
- Ozonation both with and without subsequent biological filtration,
- Chlorine dioxide,
- Booster chlorination,
- Desalination/deionization,
- Softening,
- Fluoridation, and
- Corrosion control chemicals in the presence of chlorine and chloramines.

Further research is also needed to better understand the net effect of microbial death and lysis to the pool of nutrients available for biological consumption. It is important to understand this contribution with respect to source water nutrient levels and the effects of treatment on nutrient levels. A better understanding of the impact of nutrient levels on the potential for regrowth of opportunistic and frank pathogens is also needed. Finally, while studies have demonstrated that some treatment processes reduce nutrients, it would also be important to determine if other impacts of the same process outweigh this benefit with respect to preventing microbial growth. For instance, RO removes significant amounts of AOC levels, but also increases the water's corrosivity, which can cause biofilm growth.

In some cases, research has been conducted to evaluate the treatment process on natural organic matter, but further information is necessary to determine if the process causes any changes in the levels of biodegradable organic matter. For instance, Pommerenk and Schafran (2002) discuss how pre-fluoridation may severely affect the removal of particles and organic matter when it is added to water prior to aluminum sulfate. However, this does not provide an indication of how biological stability may be affected. A more complete understanding of disinfectant mechanisms on suspended and fixed bacteria, especially on pathogens resulting from intrusion, must also be answered by applied research.

As discussed previously, Camper et al. (2000) determined that a correlation exists between biodegradable organic compounds and source water protection. Further research is necessary to determine how these two are related and whether utilities may use source water protection to provide a more biologically stable drinking water. The impact of climate change and intensive urbanization on nutrient levels should also be examined as part of these efforts because if nutrient levels in the source water change over time, treatment barriers currently in place may no longer be adequate to remove sufficient biodegradable organic matter.

Another area for research is how the composition of the biofilms and specifically the growth of coliforms and pathogens is affected by nutrient level or the make-up of the nutrient pool. Most of the studies to date look specifically at HPC.

Finally, AOC and BDOC are difficult parameters to measure and do not always directly indicate biological stability of water. More research is needed to determine a more effective measurement of a water's biological stability.

7. Summary

This paper provides a review of completed research on the extent that various water treatment processes affect nutrient levels in the distribution system. Organic carbon, nitrogen, phosphorus, metals, and other substances can promote microbial growth. Typically, carbon is considered to be the limiting nutrient in the distribution system. Studies have shown that a direct correlation can exist between the level of AOC or BDOC and the level of microbial growth in the system. However, factors such as disinfectant levels and pipe materials have a significant influence, too.

Some treatment processes influence the levels of nutrients entering the distribution system. Much of the available research focuses on the effects of treatment on AOC and BDOC. In general, coagulation, sedimentation, and flocculation remove phosphorus and are associated with significant removal of BDOC but not AOC. Biological and some membrane filtration applications have been associated with removal of organic nutrients. Disinfectants that are oxidants, such as ozone or chlorine can increase organic nutrient levels. However, when pre-oxidation is paired with treatment such as biological filtration, effluent organic nutrient levels may be lower than source water nutrients. Further research is needed on the impacts of treatment on nutrients and improved measurement of biological stability.

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