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Distributing drinking water without disinfectant: highest achievement or height of folly?*

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ABSTRACT: Preservation of the microbial quality of drinking water during distribution is a major objective in water supply. A disinfectant residual reduces regrowth but is not sufficiently effective against recontamination. It may cause taste and odour problems and result in the presence of compounds with toxic properties. Furthermore, the maintenance of an effective residual throughout the distribution system is hampered by the disinfectant decay caused by pipe materials and compounds present in the water. Prevention of microbial and chemical recontamination thus requires good engineering practices in the distribution system. Regrowth can be limited by distributing biostable drinking water and by applying biostable materials in contact with drinking water. Ensuring microbiological safety and controlling regrowth with these measures results in a better quality drinking water.

INTRODUCTION

Drinking water is transported from treatment facilities to the consumer's tap through a distribution system with long pipes and large surface areas, in contact with the drinking water on one side and the environment on the other. The water quality that is initially achieved by water treatment may change during transportation in this system. The nature and extent of these changes in quality depend on the composition of the water itself, its interactions with the internal surfaces of the distribution system, and external influences, e.g. outside contamination. Microbiological water quality aspects can play a major role in these changes. In many countries drinking water is therefore distributed with a disinfectant residual to limit microbial water quality deterioration.

Microbial water quality problems

Epidemiological studies in the USA have shown that the recontamination of treated water during its distribution has significantly contributed to several outbreaks of waterborne diseases. In the period from 1971 to 1985, 16% of 502 reported outbreaks were due to distribution or storage deficiencies [1]. From 1989 to 1992, 13% of 60 reported outbreaks were related to distribution problems, and acute gastrointestinal illness of unknown aetiology was observed as the most frequent symptom [2,3]. The major distribution deficiencies mentioned in these studies are: cross-connection, back siphoning, and contamination during repair or during storage. In the UK, 7 of 21 outbreaks due to microbial contamination of the distribution system have been recorded in public supplies in the period 1937–86 [4]. *Salmonella* and *Campylobacter* were the disease-causing organisms in four of these outbreaks. Payment *et al.* [5] concluded from an epidemiological study that 14–19% of the cases of gastrointestinal illness were due to tap water contamination, and that the distribution system may be an important source of disease-causing organisms.

Pathogenic micro-organisms in drinking water distribution systems may also originate from regrowth. Opportunistic pathogens such as *Legionella* species [6,7], *Mycobacterium* spp. [8–11] and *Pseudomonas* spp. [12] can multiply in water systems and are responsible for water-borne disease in many countries. The free-living protozoan *Acanthamoeba* which originates in tap water systems may be a cause of eye infections (keratitis) [13]. Furthermore, heterotrophic bacteria with one or more virulence factors have been observed in drinking water [5].

The multiplication of nonpathogenic micro-organisms in drinking water during distribution is also undesirable: (i) the regrowth of coliforms is a frequent cause of noncompliance with legislation [14], (ii) heterotrophic plate count (HPC) values may exceed guideline values, (iii) aesthetic problems resulting from excess biological activity in the distribution systems, e.g. brown water, taste and odour, invertebrates, and (iv) corrosion and the deterioration of materials may cause technical problems.

Chemical disinfection of drinking water during distribution

Many water supplies in the USA, in the UK and in other European countries are distributing drinking water with a disinfectant residual with the main purpose of limiting regrowth. Chlorination is the most widespread technique, but chlorine dioxide is also commonly used in the USA [15] and in European countries [16]. Chloramine is applied on a large scale

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in the USA but rarely in European countries. The chlorination of drinking water results in the formation of toxic halogenated organic compounds, including trihalomethanes [17], haloacetates and haloacetonitriles [18]. Furthermore, chlorination impairs the taste and odour of the water. Free chlorine itself is perceptible even at concentrations below 0.05 p.p.m. [19]. The use of chlorine dioxide results in the presence of chlorate and chlorite [18] and can also cause taste and odour complaints.

Free chlorine residuals of 0.1–0.2 mg/L remaining in the drinking water for at least several hours give CT values of 10–25 mg.min/L. Such CT values are effective against freely suspended Gram-negative bacteria and viruses but much higher values are needed to inactivate protozoans [20]. However, observations in practice have shown that micro-organisms such as coliforms are frequently observed in the presence of a free chlorine residual [21,22]. It is likely that particles and aggregates present in biofilms and sediments protect these organisms from bactericidal effects [21,23]. Chloramine is even less effective against viruses than free chlorine. Hence, a disinfectant residual might only inactivate the indicator organisms, and the negative coliform tests observed in such situations may give rise to a misleading feeling of safety. Furthermore, the disinfectant residual decreases with increasing residence time as a result of reactions with pipe materials, sediments and water components. Consequently, a disinfectant residual does not protect against the recontamination of the distribution system with polluted water or soil, or with micro-organisms attached to particles.

Balancing effects

Balancing the beneficial and detrimental effects of a disinfectant residual on water quality in the distribution system is becoming an issue of increasing importance, both in Europe and the USA. A disinfectant residual may help in conserving the microbial quality of drinking water, but the formation of toxic by-products and taste and odour compounds is the price to pay for water quality. Consumer complaints about drinking water quality, e.g. taste, odour, colour, turbidity or hardness, are serious signals from the client in an increasingly market-orientated society. In addition, the water supply companies, which in most cases operate as monopolies, feel the need to demonstrate that customer satisfaction is their main objective. Customer satisfaction is an essential precondition to enable the company to increase the water charges to the consumer, resulting from the application of enhanced treatments that are needed because of a deteriorating quality of source water. Against this background the water supply companies face the need to: (i) ensure a microbiologically safe drinking water, (ii) minimise the concentration of toxic by-products, (iii) achieve a high aesthetic quality, and (iv) provide the consumer with drinking water at an acceptable cost. This paper evaluates the distribution of drinking water without the use of disinfectant residuals, based on the situation in the Netherlands.

WATER SUPPLY IN THE NETHERLANDS

Overview

In the Netherlands there are at present about 20 water supply companies with a total of 250 treatment facilities and an annual production of 1.3×10^9 m^3 for about 15.5 million people. A total of 18 surface water treatment plants produced about 485×10^6 m^3 of drinking water and 232 ground water treatment plants, including 15 supplies abstracting a mixture of ground water and river bank filtrate, produced 805×10^6 m^3/year. Surface water treatment has multiple barriers against micro-organisms. These barriers include combinations of storage in impoundment reservoirs, dune passage, coagulation/sedimentation, rapid filtration, granulated activated carbon (GAC) filtration and slow sand filtration. In nine of the surface water supplies, chemical disinfection is one of the barriers, in seven of them ozone is used and in two locations break-point chlorination is applied. Ground water supplies, including river bank filtrate supplies, do not apply chemical disinfection in treatment. Untreated ground water is free from faecal contamination as a result of soil passage over an extended period of time, sometimes exceeding more than 1000 years. In addition, river bank filtration, with a residence time for river water of months to years, is free from faecal contamination. The main chemical disinfection in surface water treatment does not result in a disinfectant residual in the water leaving the treatment facility. In 11 surface water supplies post-disinfection is applied, five using chlorine dioxide in residual concentrations ranging from $\leqslant 0.01$ mg/L (four supplies) to 0.07 mg/L, and six using chlorine with residual concentrations at the treatment plant ranging from 0.1 to 0.35 mg Cl_2/L. These surface water supplies represent 22% of the total volume of distributed drinking water. Post-disinfection is aiming at: (i) reducing the colony counts and numbers of coliforms coming from the sand filters and/or granular activated carbon (GAC) filter beds, and/or (ii) limiting regrowth in the distribution system.

The disinfectant residual concentration in drinking water is low and is further reduced during distribution. Consequently, the great majority of water supplies do not have an effective disinfectant residual in drinking water during distribution. Legislation does not prescribe a disinfectant residual.

Disinfection by-products

The discovery of disinfection by-products in drinking water [17] stimulated the water supply companies in the Netherlands to limit the use of disinfectants in water treatment and distribution. Significant reductions in the use of chlorine were achieved in the late 1970s by limiting transport chlorination and break-point chlorination [24]. As a result, trihalomethane (THM) concentrations dropped from values that were in a few cases above 100 μg/L to values mostly below 40 μg/L. In the 1980s, in 7 out of 16 supplies post-disinfection with chlorine was ceased.

Amsterdam Water Supply stopped applying post-chlorination (residual: 0.2 mg/L) to the slow sand filtrate of its two water treatment plants in 1983 [25]. Major reasons for this decision were: the formation of halogenated organic compounds, an increase of in the mutagenicity of the water (Ames test), and an increase in the concentration of easily assimilable organic carbon (AOC) due to chlorination. As a result of stopping chlorination, the average THM concentrations in the two supplies—which ranged from 15 to 20 μg/L—dropped to undetectable levels and the absorbable organohalogen concentration was reduced by 70% [25].

Present European legislation [26] requires that the concentration of haloforms should be 'as low as possible', giving a guideline value of 1 μg/L for each individual compound. The proposed revision defines a total concentration of 100 μg/L for trihalomethanes [27]. Dutch legislation related to drinking water quality (the Drinking Water Decree, 1984) [28] also gives a guideline value of 1 μg/L for halogenated compounds other than pesticides. For the revision of this Decree, a total maximum concentration of 21 μg/L for trihalomethanes has been proposed [29]. This concentration is derived from the relationship between cancer risk and the concentration of genotoxic carcinogens (e.g. bromodichloromethane) and the objective of aiming at a negligible excess cancer risk of 10^{-6} (life-time exposure). A recent study on THM concentrations in drinking water revealed that their concentrations are below values corresponding to a 10^{-6} cancer risk. When required to achieve sufficient inactivation of pathogens in water treatment, a concentration of disinfectant by-products corresponding with a risk of 10^{-5} is accepted. This applies for bromate, which is produced by ozonation when bromide is present. Hence, aiming at negligible risks for disinfection by-products limits the application of chemical disinfectants for conserving microbial quality in the distribution system.

Taste and odour problems related to disinfection

A consumer organisation in the Netherlands which was testing the taste of drinking water concluded that taste and odour problems were related to the chlorination of the water [30]. The use of a chlorine residual in drinking water during distribution was characterised as an inadequate and out-of-date measure to protect water quality. The experience in Amsterdam Water Supply of using post-chlorination in severe winters at one of the treatment plants clearly demonstrates the effect of chlorination on consumer complaints about taste. After extending water treatment with ozonation and GAC filtration, such post-chlorination was no longer applied. As a result, complaints about the taste of the water dropped from about 80 per year to less than 14 per year over about 150 000 house connections. Furthermore, in the consumer's organisation survey of drinking water quality, Amsterdam was judged the best-tasting drinking water that had been prepared from surface water. In this survey, ground water-derived tap water was generally appreciated better than commercially available mineral waters [30]. Consumer complaints about taste and odour in unchlorinated ground water supplies are typically about 10 per 100 000 connections per year. Unchlorinated river bank filtrate gave rise to taste complaints in the past due to the presence of taste-affecting compounds originating from the river water itself [31]. Granular activated carbon filtration has been installed in a number of locations to remove these substances.

Microbiological water quality criteria and problems

Drinking water leaving the treatment facility complies with the criteria for microbial quality as defined in the Drinking Water Decree (1984) [28]. These criteria are derived from the European Council Directive (1980) [26] but are more stringent, e.g. 300 mL volumes (instead of 100 mL) are examined for coliforms and *Escherichia coli*, and volumes of 100 mL (instead of 20 mL) are examined for spores of sulphite-reducing clostridia. The Drinking Water Decree (1984) [28] does not define criteria for HPC values in water leaving treatment plants. Within the distribution system, regrowth should be limited and the mean values of HPC values over a 1-year period should not exceed 10 CFU/mL (48 h at 37 °C) and 100 CFU/mL (72 h at 22 °C), respectively. Controlling HPC values is achieved by distributing biologically stable drinking water.

Recontamination

Two incidents of drinking water recontamination resulting in disease have been seen in the Netherlands since 1945. In 1962, sewage contamination occurred in Amsterdam resulting in six cases of typhus. In 1981 a total of 609 people became ill as result of contamination of the water distribution system of Rotterdam with waste water from a marine vessel [32]. In the absence of a disinfectant residual, monitoring for total coliforms effectively detects contamination and/or regrowth. Percentages of coliform-positive samples obtained from distribution systems are usually below 0.5% but in a few systems values of 1–2% have been seen. *Escherichia coli* has been detected in a fraction of these samples, and repeat samplings are negative for total coliforms in nearly all cases. Samples collected directly after repair or construction are typically coliform positive in 3–5% of cases. Adequate corrective measures (flushing or chlorination) are applied when needed.

Regrowth

The introduction of ozone into water treatment resulted in increased colony counts in drinking water during distribution in a number of supplies. Applying biological filtration after ozonation resulted in reduced colony counts. Presently, the 90-percentiles of the HPC values (spread plate at 22 °C, 3 days) in surface water supplies and in the unchlorinated ground water supplies are clearly below 100 CFU/mL. Regrowth problems, as experienced in the Netherlands, include the presence of *Legionella* in warm water supplies causing cases of legionellosis in hospitalised people [33]. In 1978 an outbreak of *Mycobacterium kansasii* infection was seen in one water supply area. The organism was found to multiply in water taps inside buildings [9]. In 1984 the presence of aeromonads in a water supply initiated much debate because literature reports suggested that *Aeromonas*-associated diarrhoea was due to the presence of aeromonads in the drinking water [34]. National surveys for the presence of this organism in water systems have been conducted, in combination with surveys of the incidence of *Aeromonas*-associated diarrhoea in the Netherlands [35,36]. Aeromonads were commonly present in most water supplies but were only isolated from 1.6% people with diarrhoea [37]. Epidemiological studies could not detect a relationship between the aeromonad concentration in drinking water and the prevalence of *Aeromonas*-associated diarrhoea. Furthermore, a detailed characterisation of the isolates from patients and drinking water showed very little overlap in types [37]. Based on these studies, a guideline value for *Aeromonas* in drinking water has been defined, which is that the 90-percentile value over a 1-year period should be less than 200 CFU/100 mL. This guideline aims to prevent exposure to the organism and to initiate further limitation of regrowth.

Due to incidental complaints about invertebrates in ground water supplies, a national survey has been conducted to assess the range of concentrations and the nature of such organisms in distribution systems. Water flushed from distribution pipes was found to contain invertebrates with average numbers for *Asellus* ranging from less than 1–200 per m^3. This organism formed about 80% of the invertebrate biomass in sediments [38].

Prevention of recontamination

The water supply companies have defined a series of measures as part of good engineering practice to prevent the recontamination of drinking water during distribution. These measures include:

- application of approved construction materials and appendages;
- maintaining a constantly high pressure (minimum about 2 bar) in the distribution system;
- installation of back siphonage-preventing valves in all house connections and break tanks in connections with hospitals and most industries;
- detailed instructions and supervision measures to prevent cross-connection;
- detailed instructions and supervision measures during mains construction, repair and other activities in the distribution system;
- only authorised persons are allowed to install and use fire hydrants; and
- optimised scheme for microbial water quality monitoring.

Knowledge about retention times and flow is another important factor supporting effective water quality control in drinking water during distribution. For this purpose, many water supply companies use a computer program allowing them to make residence time calculations. Detailed descriptions of each of these measures is beyond the scope of this paper.

Biologically stable drinking water

Regrowth is prevented by distributing biostable drinking water and installing biostable materials in contact with the drinking water. The methods used for assessing the biostability of drinking water include:

- assessment of the concentration of easily assimilable organic carbon (AOC) in a batch test procedure [39,40].
- assessment of the biofilm formation characteristics of drinking water in a flow-through system [41–44].

Extended databases about the levels of these parameters in a wide range of drinking water types and water types in various treatment stages have been produced. Furthermore, the relationships between these parameters and the degree of regrowth in distribution systems has been established.

In a study of 20 different types of drinking water, a statistically significantly correlation was observed between AOC concentrations in drinking water leaving the treatment facility and the level of HPC values in drinking water during distribution [40]. AOC concentrations decreased in drinking water during distribution at values above 10–15 μg C/L (Fig. 1). Based on these observations, it was concluded that AOC concentrations should be less than 10 μg C/L to limit increases in heterotrophic plate count. More recent observations have shown that in some supplies in which ozonation is used in water treatment, AOC uptake is limited when concentrations ranging from 15 to 20 μg C/L have been reached after GAC filtration.

In most ground water supplies, AOC values are below 10 μg

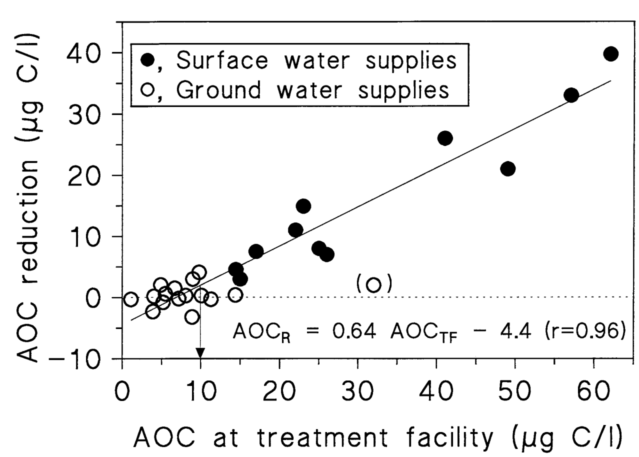

Fig. 1 The maximum decrease in AOC concentration (AOC concentration in water leaving the treatment facility – AOC concentration in water collected from the distribution system) as a function of the AOC concentration of drinking water leaving the treatment facilities. Adapted from ref. 40.

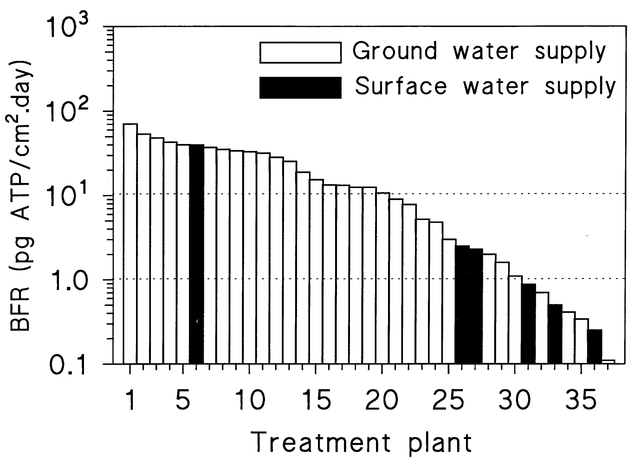

Fig. 2 Biofilm formation rate (BFR) values of drinking water at the treatment facility in a number of water supplies in the Netherlands. Numbers 31, 33 and 36 are slow sand filtrates.

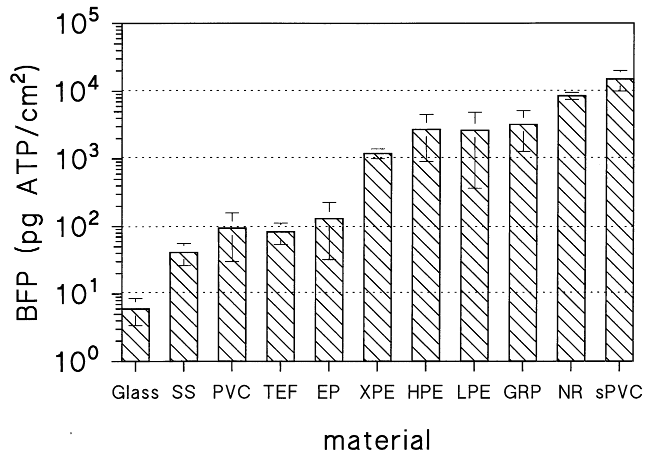

Fig. 3 Biofilm formation potential (BFP) values of synthetic materials. Glass = negative control; SS = stainless steel; PVC = unplasticised PVC; TEF = Teflon; EP = expoxy; XPE = cross-linked polyethylene; HPE = high density polyethylene; LPE = low-density polyethylene; GRP = glass-fibre reinforced polyester; NR = natural rubber; sPVC = soft PVC. Values represent averages of several materials tested.

C/L and the HPC levels remain low (< 100 CFU/mL). However, regrowth of aeromonads had been observed in a number of ground water supplies. Investigations using a biofilm monitor revealed distinct differences between the biofilm formation rates (Biofilm Formation Potential, (BFR), pg adenosinetriphosphate (ATP)/cm^2.day) of drinking water (Fig. 2) with values ranging from less than 1 pg ATP/cm^2.day to about 100 pg ATP/cm^2.day [41–44]. A highly significant relationship was observed between the *Aeromonas* densities and the BFR values in ground water supplies [44]. Based on this relationship, it was calculated that the risk of exceeding the guideline value for aeromonads (200 CFU/100 mL) was $\leqslant$ 20% at BFR values $\leqslant$ 10 pg ATP/cm^2.day [45]. Consequently, the definition for biostability is based on two parameters, *viz*. AOC and BFR.

Biostability of materials and unified-biofilm approach

Synthetic materials and coatings may release biodegradable compounds into the drinking water. For this reason methods have been developed to test the growth promoting properties of materials. In the UK, the MDOD (mean dissolved oxygen demand) test is used [46] and in Germany a test based on measuring slime production is employed [47]. In the Netherlands the Biofilm formation potential (BFP) test is applied. This test determines the biofilm density (pg ATP/cm^2) on the material as a function of time in a batch test in slow sand filtrate [48]. Typical BFP values are below 10 pg ATP/cm^2 for glass, and 20–50 pg ATP/cm^2 for PVC, whereas values between 500 and 3000 have been observed for polyethylene types (Fig. 3). Such BFP values can be directly compared with Biofilm Density values observed on the surface of pipe segments collected from the distribution system [44]. Furthermore, biofilm formation observed in the biofilm monitor also gives information about the biofilm density which can be achieved in contact with the water tested. In this way, a simple framework is obtained which enables the assessment and evaluation of the biostability of both water and materials with a consistent approach, the Unified Biofilm Approach. Collecting data about the biofilm densities on pipe walls and in biofilm monitors in relation to water quality problems will lead to a clear definition of biostability based on biofilm formation. Present research is aiming at connecting biofilm formation data with AOC concentrations in water.

HIGHEST ACHIEVEMENT

The quality of tap water depends on the effects of treatment on the raw water and the subsequent effects of transportation and distribution on this treated water. Consumers make high demands on tap water quality concerning health-related aspects and also aesthetic aspects. Consequently, the design of water treatment is determined by health-risk based criteria for toxic compounds and disease-causing micro-organisms and the criteria related to water quality aspects which are perceivable by the consumer, i.e. taste, odour, colour, turbidity and invertebrates. Maintaining the quality of drinking water during distribution is therefore an essential objective in water supply. Contamination with undesirable micro-organisms and toxic compounds must be prevented, and factors with a negative influence on the aesthetic quality of the water must be controlled. In the Netherlands, the quality of the drinking water during distribution is maintained by good engineering practices to prevent microbial and chemical recontamination in combination with distributing biostable drinking water and using biostable materials in contact with drinking water. Under these conditions, a disinfectant residual which results in the formation of toxic compounds and may affect the taste and odour of the water is not needed for the preservation of microbial water quality. Hence solving problems by taking away their causes is the real challenge for water supply engineers and ensuring the microbial quality of the drinking water in the way described above may be qualified as a great achievement.

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