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Mededeling 127

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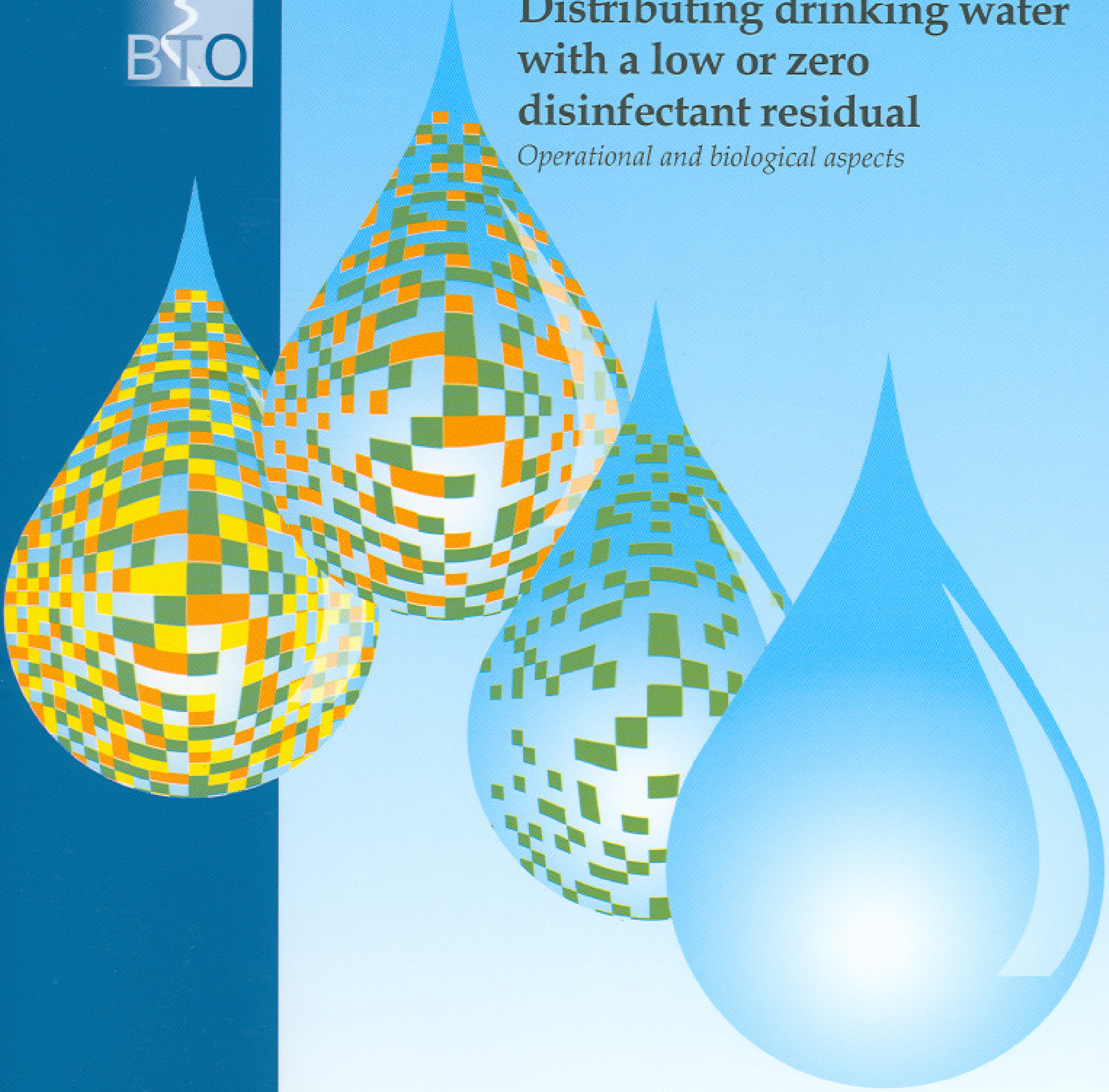
Distributing drinking water with a low or zero disinfectant residual

Operational and biological aspects



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UK Water Industry Research Limited provides a framework for a common research programme to undertake projects which are considered to be fundamental to water operators on 'one voice' issues. Its contributors are the water and sewerage companies and the water supply companies of England and Wales, Scottish Water and Northern Ireland's Water Service.

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UK WATER INDUSTRY RESEARCH LIMITED

DISTRIBUTING DRINKING WATER WITH LOW OR ZERO DISINFECTANT RESIDUAL

EXECUTIVE SUMMARY

Background and objective of study

Preventing deterioration of the microbiological quality of drinking water during distribution is a major concern for the water industry. In the United Kingdom, drinking water is distributed with a disinfectant residual, but in the Netherlands most supplies are distributed without a disinfectant residual. Drinking water quality standards in both countries are based on the European Community Drinking Water Directive. This report describes a study aimed at evaluating the operational aspects of distributing drinking water with or without a disinfectant residual. The undesirable effect of a chlorine residual on the taste of drinking water was an important motive for this study, because customer satisfaction has become increasingly important for the water industry. The study was conducted as a collaborative project in the United Kingdom Water Industry Research (UKWIR) programme and in the Joint Research Programme of the Netherlands Water Supply Companies. The study included (i) a limited review of the literature concerning the use of a disinfectant during distribution, (ii) a survey of water quality and operational practices in a number of representative water supplies in the Netherlands and in the UK, (iii) a comparison between the two countries and (iv) a workshop to exchange information between water supply companies in both countries.

Literature review

The disinfectant residual present in treated water entering the distribution system in many supplies originates from water treatment. Its presence is not always based on a separate decision to maintain such a residual, and in a number of cases originates from a time when knowledge about effects and side effects was much more limited than present knowledge. Chlorine is the most commonly applied disinfectant. Major drawbacks of the use of chlorine are: (i) formation of disinfection byproducts (DBP), some of which with carcinogenic properties; (ii) effects on taste and odour; (iii) limited effect on micro-organisms attached to particles and/or present in biofilms. Recent observations have also shown that protozoan (oo)cysts are much more resistant to chemical disinfection than bacteria and viruses. As a result, the absence of indicator bacteria (coliforms) as achieved by chemical disinfection in water treatment or in the distribution system may lead to erroneous conclusions regarding the microbial safety of water. The disinfectant decay is another factor limiting the effect of adding a disinfectant to drinking water prior to distribution. Pipe materials play an important role in this decay, especially in the case of corroding cast iron mains. In addition the concentration of organic compounds is influencing this decay. In many situations it is difficult to maintain a residual throughout the distribution system without booster disinfection.

Most of the drawbacks mentioned for chlorine also apply to monochloramine and chlorine dioxide. Decomposition of monochloramine results in the multiplication of nitrifying bacteria and nitrite formation. However, monochloramine has several advantages as compared to chlorine: (i) less DBP formation; (ii) less effect on taste and odour and (iii) the disinfectant is more stable than chlorine and relatively active against micro-organisms in biofilms. As a result many water supply companies in the USA are moving towards maintaining a monochloramine residual in the distribution system. In Europe, the use of this disinfectant is very limited.

An evaluation of the incidence of outbreaks of waterborne diseases as reported in the literature (USA and UK) shows that 15 to 30% of these outbreaks were due to distribution deficiencies. In most cases the causative agent could not be identified. Most of the systems were chlorinated. Studies conducted in Canada suggest that pathogens may be introduced in drinking water during distribution, despite a disinfectant residual. Hence a disinfectant residual is not an effective barrier against contamination during distribution. Effective good engineering practices are needed to ensure the safety of drinking water. In most countries the use of a disinfectant residual is intended for the reduction of regrowth within the distribution network.

Comparison of the situation in the Netherlands and in the UK

Water treatment and distribution

Water sources, water treatment and water distribution practices in the Netherlands and in the UK show a number of significant differences, which clearly affect the application and effects of a disinfectant residual in drinking water during distribution. Most drinking water (2/3) in the Netherlands is derived from groundwater sources. As a result of the geological situation in the Netherlands, soil passage effectively removes micro-organisms and disinfection is not used in groundwater treatment. Soil passage (dune passage or bank filtration) is also applied in about 50% of the surface water supplies. Surface-water treatment includes multiple barriers to remove micro-organisms, pollutants and the majority of naturally-occurring compounds which may stimulate regrowth in drinking water distribution systems. In most surface water treatment plants, ozonation in combination with GAC filtration is used to ensure proper removal of chemical contaminants.

Most supplies (60%) in the UK are surface water supplies with direct abstraction. Chemical disinfection is commonly applied in groundwater treatment in the UK and is also a major barrier in surface water treatment. Many surface water treatment systems have been upgraded by introducing GAC filtration, in some cases in combination with ozonation. However, soil passage is not included in surface water treatment and biological filtration is less commonly used than in the Netherlands. In a number of groundwater supplies derived from chalk regions, soil passage has a limited effect on the removal of micro-organisms.

Finally, the distribution system materials differ greatly. In the Netherlands, unplasticized polyvinylchloride (PVCu) is the most commonly used pipe material (41%), with asbestos cement (36%) and cast iron (14%) being used less frequently. In the UK however, cast iron is the main pipe material, with polyethylene (PE) as the main plastic pipe material. Leakage rates as reported in the Netherlands are usually less than 5%, but values as high as 30% have been reported in the UK.

Water quality standards and monitoring

Water quality standards in the Netherlands and in the UK are based on European standards and thus are very similar. However, national legislation has introduced a few differences. In the Netherlands, surface water derived drinking water leaving the treatment facility is tested daily for the presence of coliforms in 300-ml samples. Samples of 100 ml are collected weekly to examine the presence of spores of sulphite-reducing clostridia (SSRC) and fecal streptococci. The water supply companies in the Netherlands are also aiming at reducing the concentrations of pathogens below the levels related to a maximum infection risk of 10^{-4} for each microbial contaminant. This maximum infection risk level has been proposed for inclusion in national legislation, which presently is under revision. In the UK 100-ml samples of treated water are collected to assess for the presence of coliforms, but tests for SSRC and fecal streptococci are not prescribed. In the distribution systems, samples of 100 ml are collected and tested for the presence of coliforms in both countries. Heterotrophic plate counts (HPC, at 22°C) are monitored with low frequencies in both countries and a guideline value of 100 CFU/ml applies.

For the disinfection byproducts a guide level of 1μg /l for hydrocarbons, as stipulated in the EC Directive of 1980, applies in the Netherlands, but in practice higher THM concentrations are allowed. A value of 25 μg/l for the total THM concentration will be included in the revised Drinking Water Decree in the Netherlands. This level is based on the carcinogenicity of a few THM compounds and the national policy to strive for a negligible additional risk of 10^{-6} at life time exposure. In the recently adopted EC Directive, a total THM concentration of 100 μg/l is included which is similar to the value in present UK legislation. Consequently, water quality criteria are more stringent in the Netherlands than in the UK for some indicator bacteria and for disinfection byproducts.

Water quality during distribution

The quality of drinking water in both countries complies with the standards for hygienically-safe drinking water as defined in European and national legislation. Frequencies of coliform positive samples generally are very low in both countries. On a national basis the values were below 1 % (including first samples) in the UK and in the Netherlands, despite the differences in distribution practices, viz. disinfectant residual and different materials. Data collected in a number of representative water supplies revealed that in some cases coliform positive samples may attain a few percent. In these cases regrowth is the main cause of these occurrences. A statistical evaluation of the data derived from the representative supplies in the UK showed that coliform positive samples would have been higher in the absence of a disinfectant residual. HPC values in drinking water during distribution were low in both countries. Values were lower (usually <10 CFU/ml) in the representative supplies in the UK than in those in the Netherlands. Also here, indications were obtained that the disinfectant residual is limiting the HPC values and that reducing this residual would result in increased HPC values. Generally the DBP levels in the UK are clearly above those observed in the Netherlands, where no such compounds are observed in ground water supplies. Concentrations in surface water supplies in the Netherlands were below the level related to a negligible cancer risk.

Taste and odour

The number of complaints about taste and odour in the Netherlands is about 10 per year per 100.000 inhabitants in unchlorinated supplies, with clearly higher values in situations where chlorine is used. Termination of post-treatment chlorination caused a clear decline in the number of complaints about taste and odour. Consumer complaint frequencies about taste and odour in the UK are clearly higher and related to fluctuations in the chlorine concentration. In the past decade the level of such complaints has increased, probably as the result of: (i) an increase of public awareness of drinking water quality since privatisation and/or (ii) an increase of disinfectant residuals in large parts of the distribution systems as a result of extended treatment.

Prevention of microbial contamination

Water supply companies in both the United Kingdom and the Netherlands consider the presence of a disinfectant residual in the distribution of little or no importance in counteracting the effects of any microbial contamination that occurs during drinking water during distribution networks. In both countries good engineering practices are critical for the protection of water quality in the distribution system. Strict procedures for hygiene during mains construction and repair have been implemented in the past decades. Measures to prevent cross-connection and back-siphonage in buildings and houses have also been applied for many years. More recently, companies have focused on limiting the risks of ingress resulting from the improper use of fire hydrants.

Mains leaks and bursts remain a risk for contamination. The distribution system mains in the UK in many places consist of a larger percentage of cast iron and are older than those in the Netherlands. As a result higher leakage rates occur. Differences in altitude in the UK may increase the possibilities of temporary low pressure in the mains, even during normal operation. Therefore, the potential for microbial contamination of the drinking water during distribution may be higher in the UK than in the Netherlands.

Aiming at limiting the risks of contamination, the question remains whether or not a disinfectant residual contributes to increase the safety of drinking water. At present not enough knowledge is available to quantify the effect of a disinfectant in terms of risk prevention. Qualitatively, it may be stated that a residual will have some effect on some microbial contaminants (bacteria, viruses) provided that these organisms are present in low concentrations and are not attached to particles. Protozoan (oo)cysts most likely are not sufficiently inactivated. Furthermore, when chloramine is used the effect on viruses will also be very limited. Hence, the disinfectant residual might inactivate the indicator bacteria without inactivation of the pathogens and testing for indicator bacteria (coliforms) may not give reliable information about the safety of distribution in these situations.

Limiting regrowth

Data as obtained from the water supply companies in the UK demonstrate that the disinfectant residual limits regrowth of bacteria contributing to HPC values. The percentage of samples containing total coliforms has dropped nation-wide in the UK, probably due to a combination of optimised treatment and improved maintenance of disinfectant residuals. In the Netherlands the HPC values remain clearly below the guideline value (100 CFU/ml) by distributing drinking water with a high degree of biostability. Such biostability is the result of the use of multiple barriers including biological filtration in water treatment. The degree of biostability is assessed using AOC measurements and by determining the Biofilm Formation Rate (BFR) of treated water. Relationships established between these parameters and the extent of regrowth (HPC values, *Aeromonas* counts) have yielded reference values for biostability, viz. AOC < 10 μg C/l and BFR < 10 pg adenosinetriphosphate/cm^2.d, respectively. The methods used in the UK for determining the biostability of drinking water differ from those in the Netherlands. As a result it is not possible to compare the biostability data of drinking water types in the UK with those in the Netherlands. On the basis of source water quality and water treatment it may be expected that drinking water derived from ground water in the UK in a number of cases has a high degree of biostability. In these situations a disinfectant residual may not be needed for the prevention of regrowth. An uncertain factor in these cases however is the mains materials. Corroding cast iron may stimulate regrowth and prevention of corrosion or relining of these pipes may be needed. In the Netherlands the major materials are PVC and asbestos cement, which do not promote regrowth.

Conclusions

Drinking water quality complies with high standards in the Netherlands and in the UK. Good engineering practice is the principal factor in protecting the distribution system against contamination with pathogens. Risk analysis and risk assessment is needed to further improve the (suite of) measures aimed at preventing contamination. A disinfectant residual may slightly reduce the risk of microbial contamination, but quantitative data about its effect on risk prevention are not available. Data are also lacking about the significance of disinfectants in reducing the reliability of the use of indicator bacteria to assess microbial safety in drinking water during distribution. A chlorine residual appears to be a cheap way to reduce regrowth, but it increases the DBP concentrations and causes consumer complaints about taste and odour. Monochloramine, which has a limited effect on taste and odour, may be an alternative way to prevent regrowth, but the effect of this compound on indicator bacteria and pathogens in distribution systems needs more attention.

Distributing drinking water without a disinfectant residual requires the distribution of biologically stable water in a clean distribution system using biostable materials. This approach is common in the Netherlands and may also be feasible in the UK in a number of ground water supplies with raw water of a high hygienic quality. Most likely, many surface water supplies do not achieve biostability because biological filtration is not commonly used. Introducing such a treatment would increase the price for drinking water and thus requires the willingness of the customers to pay for the improvement of the taste and odour of drinking water.

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Foreword

Maintaining the hygienic safety of drinking water during transportation and distribution is an essential objective for water supply companies. Employing a chemical disinfectant in drinking water helps in conserving microbiological quality but results in the formation of disinfection byproducts and also impairs the taste and smell of water. Several disinfection byproducts have toxic properties and water supply companies aim to minimise their concentration. Water quality properties that are measurable by consumers, e.g. taste, smell, colour and also turbidity are becoming increasingly important in a customer-oriented society. For these reasons the issue of distributing drinking water with or without a chemical disinfectant is attracting much attention in many countries. Differences in water sources as well as differences in traditions in water treatment and distribution technology between the UK and the Netherlands have resulted in significant variations in water supply practices. In the UK most water supply companies treat and distribute drinking water with a disinfectant residual. In the Netherlands most supplies are distributed without a disinfectant residual.

The quality of drinking water in the UK and in the Netherlands must comply with European legislation. An evaluation of the advantages and disadvantages of applying chemical disinfectants for maintaining the microbial quality of drinking water during transportation and distribution is of interest for the water supply companies in both countries. This collaborative project between UKWIR and Kiwa was conducted to assess the role of chemical disinfection in water distribution. This report describes the advantages and limitations of the use of a disinfectant in drinking water during distribution, based on available scientific information and practical experiences in the Netherlands and in the UK. It also identifies areas for further research that will lead to improved drinking water quality.

International cooperation, enabling comparison of different approaches and practices, has proved invaluable in identifying the issues relating to maintaining water quality in distribution systems.

Abbreviations

AC	asbestos cement
AOC	assimilable organic carbon
ATA	attest toxicological aspects
ATP	adenosine triphosphate
BDOC	biodegradable dissolved organic carbon
BFR	biofilm formation rate
CFU	colony forming units
CI	cast iron
CT	concentration x time
DBP	disinfection by-products
DOC	dissolved organic carbon
EC	European Community
EPA	Environmental Protection Agency (USA)
FS	faecal streptococci
GAC	granular activated carbon
HPC	heterotrophic plate counts
MDOD	mean dissolved oxygen difference
MPN	most probable number
PAC	powdered activated carbon
PE	polyethylene
PVC	poly vinyl chloride
RSF	rapid sand filtration
SSF	slow sand filtration
SSRC	spores of sulphite-reducing clostridia
THM	trihalomethanes
TOC	total organic carbon
UK	United Kingdom
UKWIR	United Kingdom Water Industry Research Ltd.
UPVC	unplasticised PVC
UV	ultraviolet light
VEWIN	Netherlands Water Works Association
WHO	World Health Organisation

1 Introduction

The quality of drinking water available to consumers is determined by the quality of the water leaving the treatment facility and the changes during transport in the distribution system. Extensive research into water treatment processes has led to the introduction of new technologies to improve water quality e.g. application of oxidation and adsorption techniques for the removal of pesticides. Also, new approaches have been developed to define the microbiological safety of drinking water. These approaches are based on risk assessment and risk management using data about concentrations of pathogens in the water, the infection risk related with exposure and the effect of water treatment on concentrations of pathogens, respectively. Following the improvements in water treatment on concentrations of pathogens, the next step is to minimize water quality changes in drinking water during distribution. Water quality aspects as perceived by the consumer, especially taste and odour, play an important role in this approach. Consequently, a better understanding of the factors and interactions affecting water quality should result in a cost–effective operation and management of the system to minimise noncompliance and maximise customer satisfaction.

A critical issue for maintaining drinking water quality during distribution is the use of chemical disinfectants. Most of the water supply companies in the United Kingdom, in the United States of America and in many other countries distribute drinking water with a disinfectant residual with the aim:

- to limit multiplication (regrowth) of (micro-)organisms, which cause non compliance with legislation and/or are undesirable for aesthetic or technical reasons. Multiplication can occur when compounds serving as energy sources are present in drinking water, either in the water leaving the treatment plant, in the pipe materials or in the sediments built up in pipes;
- to monitor water quality changes by determining the disinfectant residual;
- to provide additional protection against recontamination during distribution with pathogenic micro-organisms. Recontamination can occur by pipe leakage, pipe damage, via hydrants, back siphonage, repair activities etc.

Distributing drinking water with a residual of chlorine or another disinfectant frequently causes customer complaints about the taste and odour of drinking water. Furthermore, disinfectants react with natural organic compounds present in drinking water, forming 'disinfection by-products' (DBP's), including trihalomethanes (THM's), trihaloacids etc. A number of these compounds have toxic properties and therefore maximum allowable concentrations for DBP's have been defined in national and international legislation, including the revised EC Drinking Water Directive (European Community, 1998).

In the Netherlands the water companies distribute drinking water without or with a low disinfectant residual concentration. Maintaining a residual concentration at the point-of-use (tap) is not an objective for these companies. Multiplication of micro-organisms is limited by achieving biologically-stable drinking water in water treatment and distributing this water in a clean and closed distribution system. Recontamination is prevented by good engineering practices and water quality is frequently monitored for the presence of faecal contaminants. A number of water supplies in Germany, Denmark and France, strive to operate in the same way, but in these and other countries many water supply companies are sceptical towards this approach.

Consumer complaints about the taste and the smell of drinking water are in many cases, related to the use of chlorine. The objective to limit taste and odor problems on the one hand and the option of maintaining the microbiological quality of drinking water without using a disinfectant residual in the distribution system have led to an increased interest of United Kingdom water supply companies in the approach of the Netherlands water supply companies. At the same time water supply companies in the Netherlands are interested in evaluating the effects of low concentrations of a disinfectant on water quality. Therefore a cooperative study has been conducted including an evaluation of the available literature and description of the experiences of a number of water supply companies in the Netherlands with distributing drinking water without or with a low disinfectant residual. These experiences form the basis of this report. The project is jointly funded by United Kingdom Water Industry Research Ltd. (UKWIR) and the Netherlands Water Works Association (VEWIN).

1.1 Objectives

The main objective of the study is:

- to evaluate the theoretical and practical knowledge available on operational aspects of distributing drinking water without or with a low disinfectant residual. These aspects especially concern the microbiological water quality. The information on data from practice in the Netherlands will enable the UK water industry to consider its policy with regard to the use of a disinfectant in drinking water during distribution. Conversely, the data about experiences in the UK will enable the water supply companies in the Netherlands to evaluate their situation with regard to distributing drinking water without or with a low initial disinfectant residual. Identification of aspects, which need further investigation is another aim of the study.

The project included the organisation of a workshop to present and discuss the results of the study with representatives of the water industries in the UK and in The Netherlands. This workshop is an important stage of the project enabling a direct exchange of information between water supply companies of the two countries.

1.2 Organisation of the report

A review of present knowledge on disinfectant residuals in distribution systems, mainly based on literature is given in Chapter 2. This chapter includes historical aspects, current practice of chemical disinfection of drinking water during distribution and its effects on water quality and policies to safeguard drinking water quality during distribution. Chapter 3 describes the microbiological quality of drinking water in the Netherlands as well as the means and methods used to achieve and maintain this quality in the distribution system. The approach followed in the Netherlands for assessing and defining the biological stability of drinking water has been described in Chapter 4. Chapter 5 presents information about the distribution of drinking water in the United Kingdom. Chapter 6 compares the practices in the Netherlands and in the UK. The strong and weak points of distributing drinking water without a disinfectant residual based on the presented data as discussed during a combined workshop between representatives of Water Supply Companies in the UK and the Netherlands are described in Chapter 7. The final conclusions of the study are compiled in Chapter 8.

2 Protection of drinking water quality in distribution systems

2.1 Historical developments in the application of disinfectants in drinking water supply

In the course of the 19th century the positive impact of a safe drinking water supply on public health became obvious and stimulated further efforts to improve water quality by enhancing water treatment and distribution. In these efforts the application of chlorine played an important role. After a series of incidental applications, continuous chlorination (initially as chloride of lime) was first applied in Belgium in 1902 (White, 1972). Chlorine and its derivatives were primarily applied for disinfection purposes in water treatment, in particular in water supplies which used surface water as a source. The presence of a disinfectant in drinking water during distribution is in many cases a consequence of its use in water treatment and is not based on a separate decision to add a disinfectant for protection of drinking water quality in the distribution system.

In 1908 the inactivation of microorganisms by a disinfectant was described as a first order reaction, thus confirming the efficacy of chlorine for the inactivation of micro-organisms (Chick, 1908; Watson 1908). However, when chlorine was introduced on a large scale, the side effects and chemical aspects such as the formation of byproducts and the health aspects were hardly known. Wolman and Enslow (1919) showed that chlorine was absorbed differently in various types of water affecting the effectiveness of the disinfectant and introduced the concept of chlorine consumption. When practical experience with using chlorine increased other beneficial effects such as improvement of taste was observed. Still in some cases chlorine introduced taste and odour problems. It was discovered that the chlorine taste could be diminished by adding small amounts of ammonia, resulting in the formation of chloramine. In 1939 breakpoint chlorination was introduced as a treatment process to remove ammonia from heavily polluted sources (White, 1972).

Initially the application of chlorine was directed at achieving a hygienically reliable water quality at the treatment plant. Later on chlorine was used to limit regrowth during transport and was regarded as an additional barrier against pathogens. The presence of chlorine at the consumer tap gave a feeling of safety and it has been argued that the absence of chlorine is a signal that the protection was insufficient. However, even at the beginning of the century multiplication of coliforms in distribution systems was observed despite the presence of a chlorine residual (Baylis, 1930). In more recent years coliform regrowth has been shown as a main cause of noncompliance in a number of water supply companies and has attracted much attention (Wieringa, 1985; Smith et al. 1990; LeChevallier, 1990)

The decision to apply chemical disinfection during water treatment is in many cases directly related to incidents of pollution of the water source. Contamination of drinking water sources is not restricted to surface waters. In some countries incidents of microbiological contamination are also reported in ground water sources (e.g. the Riverside incident in the USA and the Croydon outbreak in the UK). The outbreak at Croydon in 1937 was caused by contamination of the ground water source by *Salmonella typhimurium* (Galbraith et al. 1986). The Riverside incident in the USA in 1965 was also caused by *S. typhimurium* and was probably related to contamination of the ground water source (Ross et al. 1966; Greenberg and Ongerth, 1966). Although these incidents were most likely caused by contamination of the drinking water sources they resulted in a general policy to distribute drinking water with a disinfectant residual.

In the period 1940-1960 the effect of chlorine on the prevention of taste and odour complaints attracted much attention. Various methods of applying chlorine were investigated. The decrease of chlorine concentration in the distribution system became a subject of study and various options to achieve a measurable concentration at the tap were investigated. By adding ammonia, a residual of combined chlorine could be produced with a greater stability in the distribution system, so that the requirements of a measurable residual could be met.

In the period 1900-1960 surface water treatment was generally based on using chlorination in combination with physico-chemical techniques such as coagulation/sedimentation and/or filtration. In the period 1960-1980 treatment processes such as ozonation and granular activated carbon filtration were introduced. The use of ozone diminished the dominant role of chlorine as a disinfectant. The application of ozone during treatment enhanced microbial regrowth as a result of the formation of biodegradable compounds from organic compounds and pollutants.

This phenomenon resulted in a growing interest in the aspect of regrowth in the distribution system.

In the period after 1950 interest in standards and development of legal instruments to protect drinking water quality was increasing. In the first phase of the development of public drinking water supply, assessment of water quality was mainly focused on monitoring of coliforms as an indicator of faecal pollution. The increasing pollution of the drinking water sources attracted much attention to chemical pollutants and taste and odour problems. A set of standards was developed for a uniform assessment of drinking water quality and to protect the health of the consumer.

In the Netherlands the Drinking Water Decree of 1960 contained only standards for eight parameters, including those for microbiological quality. In the adapted Drinking Water Decree of 1984 this number had been increased to more than 60 (Drinking Water Decree, 1984). These developments, which were the result of scientific achievements and practical observations, followed the international development of drinking water quality standards by the World Health Organisation and the European Community (European Communities, 1980). The water quality criteria for chemical pollutants resulted in an increased effort to remove the pollutants at the treatment plant by introducing more advanced technologies such as ozonation and granular activated carbon filtration.

2.1.1 Developments after 1970

After 1970 new scientific discoveries and practical experiences further affected the approaches to ensure the quality of drinking water:

- reports of the formation of trihalomethanes as byproducts of chlorination had a major impact on the traditional design of water treatment (Rook, 1974; Bellar and Lichtenberg, 1974).
- application of a microbiological mutagenicity test (the Ames test) revealed that chlorination increased the concentration of mutagenic compounds in the water;
- pathogenic viruses were discovered which could contribute to the spread of disease through drinking water e.g. Rotavirus, Calicivirus, Astrovirus, and recently hepatitis-E virus (Skidmore et al. 1992, Ray et al. 1991, Grabow et al. 1996). Some of these viruses seemed to be more resistant to chlorine than the indicator for faecal pollution.
- microorganisms with opportunistic pathogenic properties and the ability to multiply in the distribution system and house installations (i.e. Legionella, Aeromonas, Pseudomonas, Mycobacteria, etc.) were detected (Tobin et al. 19981; McSwiggan and Collins, 1974; Engel et al. 1980; Fischeder et al. 1991; Fordham von Reyn et al. 1994; Schoenen et al. 1985);
- epidemiological data on infectious waterborne diseases showed that the normal practice of chlorination did not prevent the spread of certain infectious diseases (Giardia, Cryptosporidium) through drinking water because of the high resistance of these microorganisms to chlorine;
- knowledge about factors affecting regrowth of micro-organisms and the removal of growth-promoting substances led to new strategies for the prevention of regrowth and the formation of biofilms in the distribution system;
- good engineering practice to protect the distribution system against recontamination with microorganisms and chemicals were developed further and included in national legislation's and regulations;
- ozonation and granular activated carbon filtration processes were further developed for the removal of pesticides and taste and odour compounds;
- the technology of UV-light treatment of drinking water was further developed. This treatment was considered as an alternative for post disinfection in a few countries including Germany and the Netherlands;

- increasing awareness of the consumer on the quality of the drinking water led to a more critical attitude towards the taste and odour of drinking water;
- the increase of legal requirements, standards and measuring obligations led to a more stringent approach to drinking water quality. The health aspects of the by-products of chlorination necessitated the search for alternatives and the optimisation of strategies to minimize the formation of byproducts.

Summary/Conclusions

- In many cases the presence of a disinfectant residual in drinking water during distribution is a result of the application of chemical disinfection in water treatment;
- Decisions to treat and subsequently distribute drinking water with a disinfectant residual were taken in a period when knowledge about the effects of the disinfectant on various types of pathogens was limited and the formation of disinfection by-products could not yet be taken into account;
- the large amount of scientific information and practical experience which is now available about the effects of distribution on drinking water quality can be used to re-evaluate maintaining residual disinfectants in drinking water during distribution.

In this review disinfectants and processes which are relevant for the water quality during transportation and distribution will be considered.

2.2 Current practices on the application of disinfectants during distribution

2.2.1 Situation in the Netherlands

In the Netherlands two thirds of drinking water is produced from ground water, 21.2% directly from surface water and 14.3% from infiltrated surface water (dune and bank filtration). Ground water and surface water produced after soil passage are distributed without a chemical disinfectant. A disinfectant is added on a continuous basis to less than 21.2 % of the distributed drinking water in the Netherlands. Chemical disinfection is primarily used to treat water that is abstracted directly or indirectly (after storage in impoundment reservoirs) from rivers or lakes. Here a disinfectant is one of the essential barriers against pathogenic micro-organisms. In seven plants ozone is used whereas breakpoint chlorination is applied in three plants, one of which is producing water for industrial purposes. In 11 supplies a disinfectant is added to drinking water prior to distribution to achieve a reduction of the heterotrophic plate count (HPC) and/or coliforms originating from the filter beds (post-disinfection). Chlorine is used in 7 supplies with residual concentrations ranging from 0.1 to 0.35 mg/l and chlorine dioxide is used in 5 plants with residual concentrations ranging from less than 0.01 to more than 0.07 mg/l. These supplies represent 22% of the total volume of distributed drinking water. Presently chloramine is not applied in the Netherlands. More details about water treatment systems are given in Chapter 3.

The aquifers in the Netherlands are composed of layers of sand, clay and peat which effectively remove pathogens from the water. As a result abstracted ground water is normally free of pathogens and consequently drinking water produced from ground water is not disinfected. The hygienic quality of the abstracted water is further guaranteed by precautionary measures to protect the ground water source such as special protection zones. This protection is achieved through ownership of the land and through special legislation based on the Environmental Law, which restricts activities in the production zones. In other countries, where the upper layers consist of porous media with holes e.g. with chalk formations (karst), the hygienic reliability of ground water may be threatened. In the USA many incidents have been reported which were due to unreliable ground water sources. In a number of ground water sources viruses have been detected (Bitton et al. 1986; Abbaszadegan, 1995). In the Netherlands a few relatively vulnerable areas can be found where the subsoil consists of coarse sediments and gravel.

No incidents of ground water contamination have been observed for over 50 years and it was concluded that continuous chemical disinfection was not needed to achieve the required microbial quality of drinking water. Furthermore, the quality of drinking water at the consumers tap, as determined by regular microbiological monitoring, has given no reason to add a disinfectant. The discovery of disinfection byproducts (Rook, 1974) and increasing consumers complaints of taste and odour are reasons to limit the use of disinfectants in drinking water during distribution.

It was generally believed that ground water was more biologically-stable than surface water, but observations of aeromonads and invertebrates in ground water supplied systems in the period 1984-1990 have led to a new area of research (See Chapter 3). It should be noted that regrowth of *Aeromonas* was not detected with the traditional microbiological monitoring parameters (heterotrophic plate counts and coliforms) (Havelaar et al. 1987). A national survey revealed that methane and/or ammonia in ground water may be the indirect cause of the regrowth of *Aeromonas* in these systems (Van der Kooij, 1992). These compounds are transformed into biomass during the filtration processes and certain biomass components entering the distribution system may lead to regrowth of the aeromonads and invertebrates. Prevention or control of regrowth was achieved by modification of the treatment process (intensive aeration) and cleaning (flushing, pigging) of the distribution system. Following observations of relatively high numbers of *Aeromonas* bacteria in a few supplies, disinfectants were added on a timely basis (Van der Kooij, 1988). Further information about regrowth of aeromonads is given in Chapter 4.

Surface water treatment using soil passage does not include chemical disinfection or uses oxidants in very low doses. In a number of cases ozone is used for the oxidation of recalcitrant organic micropollutants (pesticides). Recontamination of water by birds after soil passage has also been a reason to add a disinfectant to the water after slow sand filtration (Schellart, 1986). Slow sand filters have a lower biological activity in the winter period and removal efficiencies are reduced. Hence, the reasons for applying a disinfectant in these cases is primarily based on water treatment and not intended for protecting drinking water quality during distribution.

Historically drinking water companies using surface water without soil passage depended on the use of disinfectants. After the discovery of disinfection byproducts (Rook, 1974) there have been considerable efforts to reduce the use of chlorine and to optimise the use of disinfectants (Kruithof, 1986). In 1983 the Water Supply Company of Amsterdam stopped the application of chlorine as a post-disinfection process after a long tradition of chlorination (Schellart, 1986). In a few supplies UV disinfection was installed to reduce the heterotrophic plate counts in GAC filtrates (Kruithof et al. 1992). UV effectively reduces HPC values without affecting the concentration of growth-promoting compounds (Van der Kooij, 1988; Hengesbach et al. 1993). A major factor limiting the use of chlorine (based disinfectants) in water treatment or distribution is the guideline (1 μg/l) for organohalogens as defined in the Revised Drinking Water Decree (1984). In practice concentrations exceeding this guideline value are allowed. In the latest revision of water quality criteria a THM concentration of 21 μg/l is proposed. This value is based on what is considered a negligible excess cancer risk of 10^{-6} (life time exposure) for genotoxic carcinogens, e.g. bromodichloromethane (Van Dijk-Looijaard, 1993).

The distribution of drinking water without or with a low concentration of a disinfectant in the Netherlands is described and evaluated in more detail in Chapter 3.

2.2.2 United Kingdom

In the United Kingdom chemical disinfection is generally the final stage of the treatment process. In most cases chlorine or hypochlorite is used, but in some cases chlorine dioxide is also applied (Breach, 1994). An important role in the policy on disinfection is the interpretation of the drinking water supply regulations. These regulations require that water undertakers should not supply water from any source that consists of, or includes, raw water unless the water has been disinfected. Disinfection has been described as "subjected to a process which removes or renders inactive pathogenic micro-organisms" (HMSO, 1989). The way in which the requirements have to be fulfilled have not been defined. In fact, the water supply company has the freedom to select the means to achieve the goals. Further information on the legal structure is given in a subsequent paragraph. Following chemical disinfection, the residual may be reduced prior to passage into the distribution system. Chlorine and chloramine residual in distribution generally range from 0 to 1 mg/l.

2.2.3 Germany

The majority (70%) of the drinking water supplied in Germany is produced from relatively small ground water sources. Continuous chemical disinfection is applied in 45% of the supplies according to a survey in 1992 (Haberer, 1994). The main reasons are to ensure the microbiological quality and to prevent regrowth. In 14 cases a disinfectant is added to prevent the growth of invertebrates. The supplies that did not use a disinfectant were mainly ground water supplies. In about 1200 (44%) ground water supplies however, a disinfectant is used. No disinfectant is used in 12 % of the 230 companies using surface water. Among these are 10 companies which apply artificial recharge and 13 companies using river bank filtrate.

The disinfectants used are mainly based on chlorine and chlorine dioxide. The use of chloramine is not allowed in Germany due to the potential for nitrite formation and the toxicity of monochloramine. Other methods of disinfection are used on a small scale, such as UV radiation, potassium permanganate, hydrogen peroxide, silver, ozone and combinations of these agents. In most cases the application is primarily a part of the treatment process. It is not easy to distinguish to what extent the application is only for distribution purposes.

A limit value of 10 µg/l for trihalomethanes is defined in the German Drinking water Act of 1986 (Trinkwasserverordnung, 1986). In 90 % of the supplies lower values are achieved (Haberer, 1994). The highest values are found in situations where chlorine is used. The lowest values were obtained with chlorine dioxide.

2.2.4 France

A total of 30-35% of the drinking water in France is produced from surface water and 68% is ground water derived (Premazzi et al. 1997). Ozone was used as a disinfectant in more than 700 facilities in 1990 (Langlais et al. 1991). Generally a disinfectant is added to drinking water prior to distribution, although the concentrations are usually low. The drinking water legislation sets a maximum for chlorine concentration to be applied during distribution of 0.1 mg/l. In exceptional cases and, in cases of contamination, a higher dose may be applied. If higher dosages have to be applied on a continuous basis authorization is needed. In some situations where there is a high chlorine consumption during distribution, chlorine is added at various locations along in the distribution system to maintain a chlorine residual (Levy et al., 1998). Chemical disinfection is not used in treatment of ground water abstracted from sources with a good and reliable quality, but is added to drinking water prior to distribution in 80% of the groundwater supplies (Wellstein et al. 1993). In situations with a long residence time, chlorine dioxide is also used.

In general the total concentration of trihalomethanes is lower than 5 µg/l (Premazzi et al. 1997). When a relatively high chlorine concentration is applied in water treatment reducing agents such as sulphur dioxide are added to lower the concentration for distribution. The chlorine concentration is also kept low by application of UV disinfection.

2.2.5 United States of America

Chlorination is common in water treatment in the USA although there is also widespread use of chloramines. The Surface Water Treatment Rule (EPA, 1989) prescribes the use of chlorination in combination with coagulation + sedimentation + filtration to obtain a sufficient removal of pathogens. In a number of supplies chlorine dioxide is used to limit the formation of THMs (Lykins et al. 1990). Initially EPA proposed that a chlorine residual of at least 0.2 mg/l was maintained in 95% of the samples collected from the distribution system, but this proposal has been revised. In the final rule either a detectable residual is required or HPC values below 500 CFU/ml (EPA, 1989). Consequently, a disinfectant residual is not prescribed to prevent recontamination, but to limit regrowth. Furthermore, EPA believes that monitoring chlorine residual can be used as a means to detect contamination from outside (e.g. cross-connection) of from inside (presence of organic or inorganic compounds). Recent developments show that chloramination is becoming increasingly popular in water treatment and in water distribution to limit DBP formation. It has been estimated that about 50% of the water supplies will be using a chloramine residual in the distribution systems at the beginning of the 21st century (Clement, 1998).

2.2.6 Summary/Conclusions

- Differences in current practices for maintaining a chemical disinfectant in drinking water during distribution are mainly due to differences in legal rules, in source and the quality of the raw water and the subsequent use of chemical disinfection in water treatment;
- Legislation on disinfection by-products restricts the use of chlorine and other oxidants in drinking water during distribution in several European countries viz. the Netherlands, Germany and France and stimulates a shift from chlorination toward chloramination in the USA;
- The main reasons for adding a disinfectant to drinking water prior to distribution are: (i) reduction of HPC numbers in water leaving the treatment facility (the Netherlands); (ii) control of regrowth in the distribution system (Germany, France, UK, the Netherlands);
- In the Netherlands treated ground water meeting all drinking water standards has been distributed without chemical disinfection for more than 50 years.

2.3 Epidemiological data on microbiological contamination during distribution and effects of disinfectants

2.3.1 Incidents of microbiological contamination of drinking water in the distribution system

Only a few countries have published epidemiological surveys which allow an assessment of the extent that contamination of drinking water in the distribution system contributes to the spread of waterborne disease. In the USA such data are published regularly, but the authors claim that registered and investigated incidents are only a small proportion of the real number of incidents (Safe Drinking Water Committee, 1981). In the USA 16% of the 502 reported outbreaks related to public water supply in the period 1971 to 1985 were due to distribution system deficiencies (Craun, 1988). From 1989 to 1992 13% of 60 reported outbreaks were related to distribution (Herwaldt et al. 1992, Moore et al. 1994). Most of these cases occurred in the large public supplies. The complexity of the distribution system in urban areas may be a factor that leads to higher contamination risks. Most cases are caused by indirect cross contamination by means of back-siphoning (see Table 2.1). Craun (1988) reported that in about 40% of the investigated incidents the cause of illness could not be identified. One incident in 1989 was caused by *E. coli* O157:H7, probably by insufficient decontamination and disinfection of the water mains after repair work, in another situation *Giardia* was observed (Moore et al. 1994). In a survey of water-borne diseases in the United Kingdom in the period 1937-1986, 7 out of 21 outbreaks caused by microbial contamination of public supplies were due to distribution deficiencies (Galbraith et al. 1992).

Table 2.1. Nature of distribution system deficiency in reported outbreaks involving municipal systems in the USA (1971-1978).

Deficiency	**Number**	**Percent**
Indirect cross connections	13	50
Direct cross connections	5	19
Contamination during construction	3	12
Leaching of copper from pipes	3	11
Contamination of open reservoirs	1	4
Unknown	1	1
Total	26	100

* From: Center for Disease Control, 1978

In the Netherlands two cases of contamination of the distribution system have been reported since 1960. Contamination of the distribution system in Amsterdam in 1962 resulted in 6 patients with typhoid fever. A second case occurred in Rotterdam in 1981 and was caused by an incorrect connection of the drinking water distribution system to the sewage outlet of a ship. After that incident an extensive epidemiological investigation was performed. A few days after the contamination a higher rate of gastroenteritis was observed, but specific infections caused by viruses and hepatitis were not found. Detailed investigations of infections with, amongst others, *Campylobacter*, *Giardia* and *Salmonella* suggested a higher incidence rate of these infections, but the effect was difficult to quantify against the normal frequency of laboratory isolation of these microorganisms (Huisman and Nobel, 1981). It should be noted that in this case the contamination might not have been representative of contamination with sewage from an urban sewage system.

Chemical contamination of the distribution system resulting in disease has also been observed (Craun, 1988; Galbraith et al. 1992). Such incidents demonstrate that good engineering practices to protect the distribution system from pathogens and other pollutants entering the system remain the first and most important measure for the protection of drinking water quality during distribution.

Data in the literature do not show if, and to what extent, a disinfectant residual in drinking water during distribution would have prevented disease outbreaks. A different situation exists when the contamination is caused by a failure of disinfection at the treatment plant. Craun (1988) reported that in most incidents with microbiological contamination, a lower level of the disinfectant at the water treatment plant was found. This observation could indicate that the presence of a higher level of disinfectant might have prevented the incidents, but the available data offer no proof that a higher level of disinfectant in distribution would prevent incidents. A conclusion on the significance of a disinfectant for the treatment system and consequences of failure cannot be extrapolated to the same effect during distribution. This is because both areas are different in that (i) the use of a disinfectant in water treatment is based on a dose that takes into account the chlorine consumption and the residual required at the end of the treatment process; (ii), at the treatment plant a certain contact time is being maintained before the water is distributed to the consumer and (iii), at the treatment plant suspended solids etc. are being removed.

The epidemiological surveys also show that in recent years a relatively high proportion of the incidents of water-borne disease could be traced to contamination with chlorine resistant microorganisms like *Giardia* and *Cryptosporidium* as demonstrated in a study over the years 1971-1985. Cryptosporidiosis has only recently been recognised as a waterborne disease. Most likely, maintaining a disinfectant residual during distribution would not have prevented the spread of these microorganisms through drinking water. A disinfectant residual present in drinking water during distribution might have some effect on pathogens that are more sensitive to disinfection, e.g. the Gram-negative enteric pathogens. The epidemiological data do not give information about the effect of disinfectants in drinking water during distribution on preventing the spread of water-borne diseases.

Table 2.2. *Etiology of reported outbreaks due to deficiencies in municipal distribution system or to other deficiencies.*

	Distribution system deficiency		Treatment deficiency	
Etiology	**Number**	**Percent**	**Number**	**Percent**
Unknown	13	50	17	40
Chemical	10	38	2	5
Bacterial diarrhoea (*Shigella, S. typhi*)	2	8	9	21
Hepatitis	1	4	4	10
Giardia lamblia	0	0	10	24
Total	26	100	42	100

* From Centers for Disease Control, 1978

2.3.2 Health effects of regrowth

Regrowth in the distribution system can lead to an increase of bacteria and other organisms which might have an impact on health. Recent epidemiological investigations (Payment et al. 1991; Payment et al. 1997) suggest that 14 to 30% of the cases of gastroenteritis may be attributed to drinking water that complies with microbiological water quality standards. Microorganisms surviving water treatment and/or multiplying in the distribution system might be responsible for this phenomenon.

In studies on virulence characteristics such as cytotoxicity, enzyme production etc. of bacteria isolated from tap water Edberg et al. (1997) concluded that the isolates did not possess significant virulence characteristics. Payment et al. (1994) however reported that in 57% of tap water samples, bacteria with cytolytic properties were present and 6% of the samples contained bacteria with one or more virulence factors (cytotoxicity, haemolysis, cell binding and invasivity).

In the Netherlands extensive epidemiological investigations have been performed with regard to the significance of *Aeromonas* in drinking water (Kuijper, 1989; Havelaar et al. 1992a). Most isolates of *Aeromonas* from patients did not correspond with the types detected in drinking water (Havelaar et al. 1992b). As a preventive measure however, standards have been proposed to limit excessive growth of *Aeromonas* in drinking water (Trouwborst, 1992).

A specific category of health problem relates to regrowth in drinking water systems and then the spread of infectious disease through the air following aerosolisation of bacteria from drinking water. A well-known example is Legionnaire's disease, caused by inhalation of aerosols from showers, splashing faucets and air humidifying installations and conditioners (Tobin et al. 1981; Wadowsky et al. 1982). *Legionella* can grow at increased water temperatures (tepid water) and in biofilms on growth promoting materials (Colbourne et al. 1984). Other bacteria like *Pseudomonas*, *Mycobacterium*, and moulds can also multiply in the distribution system and lead to infectious diseases in a similar way (McSwiggan and Collins, 1974; Engel et al. 1980;

Fischeder et al. 1991; Fordham von Reyn et al. 1994; Schoenen et al. 1985). To prevent the growth of such organisms, disinfection is very often not the method of choice. An approach based on eliminating the growth promoting factors (materials, high temperature to kill the bacteria) is generally more successful.

Within the framework of this study on disinfectant residuals the question is raised whether the addition of disinfectants is effective in reducing the possible health risk from regrowth. The question whether or not disinfection generally leads to lower heterotrophic plate counts when compared to situations without a disinfectant will be addressed based on a comparison of data from practical situations (Chapters 3 and 5).

2.3.3 Summary/conclusions

- Microbial contamination of drinking water during distribution contributes significantly (15 to 30 %) to reported outbreaks of waterborne disease from public water supplies.
- Preventing contamination of drinking water in the distribution system against chemicals and micro-organisms requires good engineering practices.
- The available epidemiological data do not demonstrate that maintaining a disinfectant residual in the distribution system is effective in preventing the spread of water-borne diseases.
- Regrowth in plumbing systems can pose a health threat.

2.4 Microbiological aspects of chemical disinfection

2.4.1 General

A disinfectant residual may have an effect on (i), micro-organisms contaminating drinking water during distribution and on (ii), micro-organisms multiplying in the distribution system.

To understand its effectiveness on microbiological contamination, the activity of the disinfectant under conditions determined by the composition of the contaminating fluid and the water quality should be ascertained. Also the relative inactivation rate in comparison to the indicator bacteria should be known to enable evaluation of the effectiveness of bacteriological monitoring. In analysing the potential of regrowth prevention special attention should be given to the effects of the disinfectant on biofilms and on micro-organisms suspended in the water. In both cases the effectiveness will greatly depend on the stability of the disinfectant in the distribution system.

Most of the disinfectants used in the distribution system are based on chlorine (chlorine gas, sodium and calcium hypochlorite), chlorine dioxide and chloramine. Properties of these disinfectants are described in Appendix 1. Properties of disinfectants.

2.4.2 Stability of the disinfectant during distribution

The stability of the disinfectant depends largely on its reactivity and composition of the water. Different water types can result in vast differences in stability. Chloramine has a relatively high stability in most waters. This is why it is favoured in situations where conservation and bacteriostatic action are the aim. Rook (1970) compared the application of chloramine in the treatment plant in Rotterdam. A concentration of 1.5-2 mg/l chlorine was added as chloramine to limit the development of invertebrates (oligochaetes). Routinely a chlorine dose of 0.2-0.3 mg/l free chlorine was added, but this was insufficient to prevent the development of invertebrates and addition of chloramine was necessary. Under normal operating conditions with free chlorine, 29% of the samples in the city and 39.5% of the samples in the periphery contained no detectable chlorine residual. With chloramine these percentages were 3.5% and 29%, respectively. It was concluded that even when operating with chloramine it was impossible to maintain a residual concentration at all points from a central disinfectant application.

The presence of a disinfectant is clearly affected by the residence time in the distribution system. Recently hydraulic models have been developed to calculate the residence time of the water in the distribution system. Subsequently the disinfectant concentration can be more accurately estimated (Chambers et al. 1995). It was found that the decay rate of free chlorine and total chlorine in the distribution system can be described with a pseudo-first order reaction and thus will have a logarithmic linear decay in time. The decay rates for free chlorine and total chlorine were about 0.29 and 0.17/h, corresponding with half-life times of 2.4 and 4.1 hours, respectively. In samples of the same water stored in flasks no decay of chlorine was found. Kiene et al (1998) reported that chlorine decay is strongly affected by the type of pipe material; the chlorine decay rate in old cast iron pipes was found to be 5 times greater than in cement-lined cast iron pipes. Other factors affecting chlorine decay include pipe diameter, water temperature and water composition, but the effect of biofilm was relatively small (Baribeau et al. 1998). Hence, chlorine decay in the distribution system was mainly caused by processes on the pipe walls. The decay rate has been shown to vary in different parts of the distribution system and it has been observed that chlorine consumption increases with turbidity (Montiel and Welté, 1990).

Clark et al. (1994) could not detect free chlorine after a residence time of 48 hours in a model distribution system. In the town of Metz only 12% of the samples in summer showed a chlorine concentration higher than 0.2 mg/l with a dose of 1 mg/l at the treatment plant (70-80% free chlorine). The residence time of the areas with lower chlorine residual was 1-3 days.

Similarly, with chlorine dioxide a rapid decay has been reported. In Toulouse (France) after a dose of 0.3 mg/l no chlorine dioxide could be detected after a residence time of 5 hours (Servais et al. 1995). Higher doses of chlorine dioxide cannot be applied because of toxicological aspects and taste problems. Similarly in the Netherlands, a relatively rapid decay of chlorine dioxide has been found in various types of water. In practice, no chlorine dioxide could be measured after a contact time of 5-30 minutes. The highest disappearance rate was found directly after the addition of chlorine dioxide. The disappearance rate decreased thereafter (Van Dijk-Looijaard and Wondergem, 1988; Nissing and Horsgen, 1987). The explanation is that easily oxidisable compounds like iron and manganese are oxidized in the first period and that consumption in the second phase depends on the type and concentration of organic matter present in the water.

The data show that the concentration of the disinfectant in drinking water decreases with the residence time. For chloramine however the decrease is slower than for free chlorine or chlorine dioxide, but also chloramine is subject to auto decomposition. The superior stability of chloramine makes it a better candidate for the conservation of drinking water in the distribution system, than free chlorine (Beck and Jensen, 1988). However, decomposing chloramine results in the formation of ammonia which can be utilised by nitrifying bacteria (Odell et al. 1996; Wilzak et al. 1996, Wolfe et al 1990, Lieu et al. 1993). Nitrification can result in increased heterotrophic plate counts and/or the formation of nitrite.

2.4.3 Effectiveness of the disinfectant to inactivate pathogenic organisms

The effectiveness of a disinfectant to inactivate organisms depends on many factors including the nature of the organism. Microorganisms with a protective cell wall, e.g. (oo)cysts of *Giardia, Cryptosporidium* and spores of bacteria, generally have a higher resistance to disinfectants than Gram-negative bacteria like coliforms and enteric bacterial pathogens. Also the degree of aggregation of the organism (present freely or attached to material) plays an important role, as the accessibility of aggregated particles are more difficult for disinfectants

(Grant, 1995). Particle removal therefore is an important step in water treatment. In practice contamination of the distribution system may be caused by microorganisms which are attached to particles. The pH of the water is also important (see above).

The rate of inactivation of micro-organisms by disinfectants is generally described with a formula known as a simplified version of the Chick-Watson law (Hoff, 1986; Haas and Karra, 1984a,b):

$$k_{99} = C^{n} \times T$$

where k_{99} = a constant for 99% (2 logs) inactivation. This constant has a typical value for each micro-organism and disinfectant under defined conditions.
C = residual concentration of disinfectant (mg/l);
n = coefficient of dilution; in most cases n = 1 is used;
T = time (min) to inactivate 99% of the organisms.

The formula is based on empirical observations and plays an important role when the required concentration of disinfectant must be calculated and for comparison of the effectiveness of the different disinfectants and relative resistance of the various microorganisms. Under specific conditions, deviations may occur (Haas and Karra, 1984a,b).

Table 2.3. *CT-values (mg.min/l) for 99% inactivation of various micro-organisms by disinfectants at 5°C.*

Organism	Free chlorine pH 6-7	Chloramine pH 8-9	ClO_2 pH 6-7	O_3 pH 6-7
E. coli	0.034-0.05	95-180	0.4-0.75	0.02
Poliovirus type I	1.1-2.5	768-3740	0.2-6.7	0.1-0.2
Hepatitis A virus	1.8	590	1.7	0.2-2.1
Rotavirus	0.01-0.05	3810-6480	0.2-2.1	0.006-0.06
Giardia lamblia (cysts)	47-140	-	-	0.5-0.6
Giardia muris cysts	30-630	-	7.2-18.5	1.8-2.0
Cryptosp. parvum oocysts	-	-	6.5-8.9	<3.3-6.4
Cryptosporidium oocysts (human faeces)	$8x10^{6}$	-		-

* From: WHO, 1993.

The data presented in Table 2.3 reveal that many pathogens are much less rapidly inactivated at a certain CT-value than the indicator for faecal pollution *E. coli.* These differences are more than a factor of 20 for poliovirus and more than a 1000 for *Giardia* cysts. Consequently, the absence of *E. coli* caused by chemical disinfection cannot guarantee that the pathogens of faecal origin have also been removed. Therefore it is important to ensure that the correct dose and contact time have been achieved to remove the pathogens.

Chloramine is a less powerful disinfectant than free chlorine, but due to its lower decay rate it can exert its action along a greater time. In some situations chloramine can be more effective than chlorine because of its ability to penetrate deeper into the protecting layers. This can be important in biofilms and aggregated particles (LeChevallier et al. 1990).

Chlorine dioxide has a lower efficacy for *E.coli* and rotavirus than chlorine, but it is more effective against *Giardia*. The formation of the toxic disintegration product chlorite and the taste of chlorine dioxide are factors that limit the use this agent on a larger scale. Investigations to remove *Aeromonas* from distribution systems using chlorine dioxide showed that in the water types tested the stability of the agent was insufficient to effectively suppress the growth of aeromonads. The decay product chlorite had no bacteriostatic effect (Medema et al. 1991). Monochloramine showed a rate of inactivation for various *Aeromonas* strains comparable to that for *E. coli* (Knochel, 1991).

In most cases, the effect of disinfectants has been investigated under laboratory conditions. In environmental conditions, microorganisms will usually be present as aggregates and bound to organic material shielding them against the disinfectant (Scarpino, 1984; Hoff, 1978; Hoff and Geldreich, 1981). Such protection has clearly been demonstrated for attached and freely suspended coliforms, explaining the presence of these organisms in chlorinated supplies (Baylis, 1930; Wierenga, 1985; LeChevallier et al. 1990). The higher resistance of some pathogens to disinfectants, compared to *E. coli*, can explain the occurrence of viruses in a few situations where the indicator for faecal pollution was absent. Rose et al. (1986) reported the isolation of viruses in the presence of 0.2 mg/l chlorine from drinking water free from coliforms or *E. coli.*

The relatively high sensitivity of the major indicator of fecal contamination to chlorine raises the question whether other, more suitable indicators should be used. For example spores of clostridia, which also have a higher resistance to disinfectants. This subject however, needs further investigation.

The inactivation potential of disinfectants where recontamination of the distribution system occurs has been studied by introducing sewage to model systems and measuring the rate of microbial inactivation. Only a few studies of these types have been performed. Snead et al. (1980) found that a residual chlorine concentration of 0.2 mg/l was ineffective in wastewater concentrations of higher than 0.01%. Free chlorine however, was effective against bacterial contamination introduced with 0.1% sewage; but less effective against poliovirus.

In 1953 the National Academy of Sciences and the National Research Council in the USA studied the significance of residual chlorine as a protective measure. In this report the following conclusion was drawn:

"Residual chlorine in the concentrations routinely employed in water utility practice will not ordinarily disinfect any significant amount of contaminating material entering the systems, though this will depend on the amount of dilution occurring at the point of contamination, on the type and concentration of residual chlorine and on the time-of-flow interval between the point of contamination and the nearest consumer. It is the opinion of the NAS-NRC that the establishment of a universal standard for maintaining residual chlorine in the water in distribution systems is not desirable. The NAS-NRC does not consider maintenance of a residual a satisfactory substitute for good design, construction and supervision of a water distribution system, nor does it feel that the presence of a residual in the system constitutes a guarantee of water potability".

This statement does not ignore that free chlorine in higher concentrations might give some protection but it underlines that a chlorine residual will not exert a sufficiently protective effect against contaminants. Other preventive measure, viz. good engineering practice, cross connection prevention program etc. are essential to provide sufficient protection against contamination of drinking water in the distribution system.

2.4.4 Effect of disinfectants on biofilms and regrowth

Multiplication of microorganisms in drinking water distribution systems (regrowth) to a large extent occurs in the biofilm and probably also in sediments. Microorganisms are released from the biofilm into drinking water by means of shear forces and possibly also by the degradation of the adhesive molecules. To analyze the effect of a disinfectant on regrowth a distinction must be made between inactivation of microorganisms in the water phase and inactivation in the biofilm. The growth of bacteria in a biofilm can result in protective layers around the cells resulting in a higher resistance to disinfectants. Disinfectants might promote the release of microorganisms from the biofilm through disruption of the protecting and connecting material.

The occurrence of coliform bacteria in drinking water distribution systems is a major reason for noncompliance in a number of water supplies. Freely suspended coliform bacteria are rapidly inactivated by chlorine or monochloramine (c.f. Table 2.3). However, the occurrence of coliform bacteria in the presence of relatively high concentrations of free chlorine has been reported by many investigators (Baylis, 1930, Wierenga, 1985; Hudson et al. 1983; LeChevallier et al. 1988). Bailey et al. (1996) found an average total chlorine concentration of 0.22 mg/l (0.13 mg/l free chlorine) in samples that were positive for coliforms compared to 0.41 mg/l (0.29 mg/l free chlorine) for samples that were negative. Reilly and Kippin (1983) found that, even at a concentration of free chlorine of 1 mg/l, there was little reduction in the number of coliforms even when relatively high numbers were present in drinking water. LeChevallier et al. (1987) also observed that 1 mg/l free chlorine residual was insufficient to control coliform occurrences. Investigations have shown that coliforms can multiply in biofilms and sediments in distribution systems (Baylis, LeChevallier, 1990) and commonly applied free chlorine residuals do not usually prevent multiplication or inactivate coliforms present in the water phase. Obviously, attachment to surfaces and particles protects these coliforms from the effect of disinfectants. Similarly, coliforms are protected by carbon fines (Morin et al. 1996).

The effect of attachment of microorganisms to surfaces on the impact of disinfectants has also been studied in laboratory experiments. Free chlorine was found to be 150-3000 times less effective against bacteria grown on granular activated carbon, glass or metal coupons at pH 7 than against cells suspended in the water phase. This difference was much less with chloramine (a factor 2-100) (LeChevallier et al. 1988). These observations confirm that attachment has a stronger protective effect against chlorine than against monochloramine. The effect of attachment on the inactivation by chlorine dioxide was similar to that of free chlorine. The relatively superior effect of chloramine is explained by its lower reactivity resulting in greater penetration into the biofilm before losing its activity. The laboratory data on chloramine indicate that it might be the most active agent in suppressing the formation of a biofilm. Moreover, the superior stability of this agent has a positive effect in that the disinfectant penetrates further into the distribution system. This supposition is supported by some practical experience (Neden et al. 1995).

How effective a disinfectant is depends also on the type of pipe material. Many studies have shown that corroding iron strongly affects the impact of disinfectants (Martin et al. 1982; LeChevallier et al. 1990; LeChevallier et al. 1993). In PVC pipes, a 1 mg/l residual was found to be effective for biofilm disinfection, but in iron pipes even a dosage of 4 ppm (3 ppm residual was not effective (LeChevallier et al. 1990). However, a dosage of 4 mg/l of monochloramine was found to cause more than a 3-log inactivation of heterotrophic bacteria.

The effect of residual chlorine in systems with cast iron pipes can be improved by the prevention of corrosion e.g. by reducing the corrosion rate with inhibitors or by relining or replacing corroding pipes with non corroding materials. In this study it was also demonstrated that the disinfectant (free chlorine CT = 0.1) resistance of microorganisms, collected from the biofilm and subsequently suspended in water, was similar to that of unattached bacteria.

It is expected that the presence of a disinfectant will have a suppressing effect on the formation of a biofilm, but addition of a disinfectant does not prevent biofilm formation. In an experimental small scale drinking water system, Clark et al. (1994) found that concentrations of 1.5 mg/l chlorine or chloramine at the outlet of the treatment plant did not prevent biofilm formation or density after a residence time of 24 and 48 hours. However, an effect was found on the colony counts in the water phase at the two residence times. Matthieu et al. (1993) also found that biofilm formation occurred at concentrations of 0.4 - 1.6 mg/l chlorine and 1.0 to 1.6 mg/l chloramine.

The effect of a disinfectant on heterotrophic plate counts in water samples is the result of its effect on the biofilm, the release of bacteria from the biofilm and inactivation of bacteria in the water phase. Matthieu et al. (1993) concluded that biofilm formation in the first part of the distribution system largely depends on micro-organisms entering from the treatment plant which are deposited on the walls of the pipes. Even when low heterotrophic plate counts are measured the water still contains viable bacteria which can form a substantial part of the biofilm in this area (Matthieu et al. 1995). A disinfectant may affect heterotrophic plate counts and to a lesser extent delay biofilm formation in the first part of the distribution system. At a greater distance from the treatment works where there is generally a lower disinfectant residual, biofilm formation depends on the concentration of growth-promoting compounds. In this situation colony counts in the water may increase.

One of the negative effects of chlorination is the formation of disinfection byproducts which can serve as nutrients for microorganisms. These may enhance regrowth in parts of the distribution system where no effective residual exists. Van der Kooij (1984) reported 50 to 100 % increase of the AOC concentration following chlorination. Ransone et al. (1995) observed a similar increase. The use of chloramine also can enhance microbial activity (nitrification) resulting in the formation of nitrite and biomass (Wolfe et al. 1990; Lieu et al. 1993). These processes seem to occur more frequently then previously thought. The nitrification process is favoured by high temperatures. In combination with nitrification occurring in systems applying monochloramine increases of HPC values have been observed (Skadsen, 1993; Wilczak et al. 1996). Adding free chlorine to a system where nitrification occurred resulted in increased HPC values (Skadsen, 1993).

The information presented above leads to the overall conclusion that disinfectants have a suppressing role but that complete prevention of biofilm formation is difficult to achieve, especially in iron pipes. Removing the primary cause of the problem, available nutrients, prevents biofilm formation and regrowth more effectively. Distributing biologically stable water, i.e. water with a very low concentration of growth-promoting compounds and using biostable materials in contact with drinking water is described in Chapter 4.

2.4.5 Experiences with ceasing the use of a disinfectant residual

A few companies have stopped adding a chemical disinfectant to drinking water prior to distribution after practicing it for several decades. The water supply company of Amsterdam originally applied a chlorine dose of 0.4-0.8 mg/l chlorine with a residual free chlorine of 0.2 mg/l after 20 minutes contact time. Reasons for terminating the addition of this disinfectant were: (i), the drinking water met hygienic standards after the treatment process (dune passage and slow sand filtration); (ii), addition of chlorine resulted in an increase of organohalogen compounds and mutagenicity (determined with the Ames test) of the water, and (iii), the AOC concentration was increased after chlorination. After termination in 1984, the content of organohalogens decreased drastically (Schellart 1986). The colony counts increased in the first part of the distribution system, but were lower at longer residence times. This is explained by the lower AOC-content of the water.

The drinking water company of Zürich terminated disinfectant addition in 1993 after a continuous reduction in previous years (Klein and Forster, 1995). The average values for colony counts from the treatment plant gave only slight differences after the change; 0-3 CFU/ml before and 1-5 CFU/ml afterwards.

A major reason for post-disinfection in the Netherlands is to reduce the heterotrophic plate counts from the treatment works to values below those prescribed for drinking water collected from the distribution system. In a number of water supplies chemical disinfection has been replaced by UV-light to reduce heterotrophs whilst limiting the concentration of trihalomethanes and improving taste and odour of the water. UV-light irradiation does not (or only to a very limited extent) increase the AOC-concentration of water (Van der Kooij, 1988; Hengesbach et al. 1993).

2.4.6 Summary

- the effect of a chemical disinfectant on a micro-organism depends on the characteristics of the disinfectant and the organism, the contact time and the effective concentration;
- a number of pathogens are more resistant to chemical disinfection than E. coli and therefore, absence of E. coli in the presence of a disinfectant residual may lead to erroneous conclusions regarding safety of the water;
- attachment of micro-organisms to particles and biofilms and the presence of certain materials (in particular corroding iron) reduces the effect of disinfectants;
- disinfectant residuals as applied in practice are unable to effectively inactivate pathogens arising from contamination of the distribution system with contaminated water or sewage;
- monochloramine has a lower activity but a larger stability in distribution systems than chlorine;
- chlorination and chloramination result in an increased concentration of compounds that promote the growth of microorganisms;
- UV is an alternative post-disinfection treatment for reducing the heterotrophic plate count of water leaving the treatment facility.

2.5 Toxicological aspects of disinfection

Continuous chemical disinfection in drinking water distribution system results in the formation of disinfection byproducts (DBP), some of which have toxic properties. A short description of the formation of such products is given in Annex 1. The importance of the DBP is discussed below.

2.5.1 Health aspects of disinfectants

Chlorine

In short exposure experiments with chlorine, a value for the NOAEL (No Observed Adverse Effect Level) of 5.8 mg/kg body weight per day was established (Daniel, 1990). On the basis of effects of long-term exposure in rats, the WHO recommended a guideline value of 5 mg/l (WHO, 1996). This value is based on a conservative estimate because in that study, no adverse effects were found at the investigated doses. In some epidemiological studies a relationship has been found between certain types of cancer and the consumption of chlorinated drinking water, but the significance of these findings are still a matter of debate. The possibility exists that these effects - provided that these are causal - are not an effect from the agent itself but rather from the formed disinfection byproducts (see below).

Chloramines

Depending on the ratio of chlorine to ammonia different types of chloramines (viz. mono, di, or trichoramine) can be formed. For monochloramine a NOAEL-value of 9.4 mg/kg body weight has been determined in animal experiments. Bull and Kopfler (1991) reported a value of 8.3 mg/kg.d. Taking into account an uncertainty factor of 100 and an allocation of 100% of the TDI (tolerable daily intake) a guide value has been proposed of 3 mg/l (Daniel et al. 1990). In epidemiological studies no relationship has been found between bladder cancer and drinking water with chloramine (Zierler et al. 1988; Zierler et al. 1986). In animal experiments lasting two years with concentrations of up to 200 mg/l chloramine no evidence was found for a carcinogenic effect of chloramine (WHO, 1996). Chloramine-containing water used for haemodialysis can give acute haemolytic anaemia through lysis of the red blood cells. Therefore for these specific population groups precautions should be taken. Insufficient data is available for di- and trichloramine to define a toxicological guide level for these compounds (Daniel et al. 1990).

Chlorine dioxide

Chlorine dioxide is converted to chlorite and chlorate. The health aspects of these compounds should be taken into account when determining the health implications of chlorine dioxide. The degradation product, chlorite, can result in methaemoglobin formation. On the basis of a long-term study with rats and a short term study with human volunteers, the WHO has proposed a tentative guide value for chlorite of 0.2 mg/l (WHO,1996). Insufficient data are available for chlorate to propose a guide level. On the basis of the guide level for chlorite and taste and odour threshold values, a tentative guide value for chlorine dioxide has been proposed by the WHO of 0.2 mg/l (WHO, 1996).

A summary of the toxicological guideline values for disinfectants is given in Table 2.4.

Individual compounds

During the period following discovery of DBP's most attention was focused on the health aspects of the volatile compounds, mainly because these compounds were the first recognised DBP's. At a later stage the other identified substances also received attention, but the available information is still incomplete and a risk evaluation on the basis of the individual compounds is impossible. The lowest toxicological guide levels have been determined for carcinogenic substances, where the value is determined by extrapolation to an acceptable risk level. In the Netherlands a risk level of 10^{-8} (excess death rate) per year has been accepted as a negligible risk and 10^{-6} is the maximum allowable risk. These risks correspond with a "life-time " risk of 10^{-6} and 10^{-4} respectively.

Table 2.4 *Guideline levels for disinfectants and their main degradation products.*

Disinfectant	Guideline level	Comment
Chlorine	5 mg/l	determined from animal experiments
Chlorine dioxide	0.2 mg/l	on the basis of chlorite formation
Chlorite	0.2 mg/l	methaemoglobin formation
Chlorate	-	insufficient data available
Monochloramine	3 mg/l	on the basis of animal experiments
Dichloramine	-	no data available
Trichloramine	-	taste objections at >0.02 mg/l

2.5.2 Health aspects of disinfection byproducts (DBP)

Various categories of carcinogenicity are distinguished, depending on the mechanism of action and the degree of understanding (WHO, 1996):

Group I : the substance is a proven carcinogen to human beings
Group IIA : the substance is almost certain a human carcinogen
Group IIB : the substance is possibly a human carcinogen
Group III : the substance cannot be assigned to one of the other groups and insufficient indications are present for carcinogenicity in humans or insufficient or restricted evidence exists for carcinogenicity in animals.
Group IV : the substance is almost certainly not a human carcinogen.

For substances without a carcinogenic action the guide level is derived from the NOAL or TDI. The TDI is determined on the basis of long-term exposure and a known dose-effect relation. If insufficient data are available for establishing a TDI, use is made of the NOAL-value derived from short-term experiments and application of an additional uncertainty factor. If the data still contain uncertainties then the guideline level is presented as "tentative".

The guideline levels are mostly determined on the basis of oral uptake of substances. In the case of more volatile substances additional uptake can take place through inhalation and through the skin after evaporation of the compounds from water, for example during showering (Trouwborst, 1982; Brown et al. 1984; Little, 1992; Andelman, 1985). This route can give an increase of the total uptake with more than a factor of 2 compared to oral uptake.

Mixtures
No specific rules exist for determining the toxicity of mixtures. For substances with a comparable action and structural analogues the sum of the quotients of the concentration and the individual compounds multiplied by the corresponding guide level is often used as a model. This procedure has been proposed by the WHO for guidelines for haloforms (THM's). Specific investigations on mixtures are rare. Wester et al. (1985) investigated a mixture consisting of trichloromethane, tetrachloromethane, monobromochloromethane, trichloroethylene, tetrachloroethylene, 1,2-dichlorobenzene, 1,3-dichlorobenzene, 1,4-dichlorobenzene 1,2,3-trichlorobezene, 1,2,4-trichlorobenzene, and 1,3,5-trichlorobenzene. The concentrations applied were 0, 0.22, 2,2 and 22 mg/l mixture of equal quantities of the individual compounds. The exposition period was 2 years. Under these conditions no significant toxic or carcinogenic effects could be observed in the animals (rats) tested.

An overall impression of the mutagenic effects of disinfectants can be obtainable from tests using bacterial concentrates or other in-vitro tests. Investigations in the Netherlands showed that at concentrations of 1 mg/l there was no increase of mutagenic activity with chlorine dioxide (Kool et al. 1985), whereas a marked increase was found with chlorine. However, at higher concentrations of chlorine dioxide of 15 mg/l an increase was found. A considerable increase of mutagenic activity is found following chlorination of water containing humic acids, whereas only a slight increase was found with chlorine dioxide (Backlund et al. 1985). The in-vitro tests give an indication of possible mutagenic effects but cannot provide direct evidence for the possible effects on humans.

Epidemiological investigations
After the discovery of the formation of DBP's various epidemiological studies have been performed to discover the relationship between consumption of chlorinated drinking water and the incidence of certain cancer types. The types of cancer reported as having a higher frequency with consumption of chlorinated water are stomach, colon, bladder and rectal cancer (Cantor et al. 1987). Other studies however, do not confirm these findings so that no final conclusions can

be drawn. Interpretation of these studies is complicated by the presence of other factors which can interfere with the results. This includes the lack of well-designed control groups. In a comparative study in an area where water was distributed with chlorine and chloramine respectively the risk of bladder cancer among a group of patients receiving chlorinated water was 3 times higher compared to those receiving chloraminated water (Craun, 1993; Zierler et al. 1986; 1988). In a review of all epidemiological studies, Craun (1993) concluded that current epidemiological data do not allow conclusions on the relationship between chlorinated drinking water and colon cancer. A suggestion for a relationship remains for bladder cancer but there is insufficient proof of a causal relationship. In a meta-analysis carried out in 1992 (Morris et al. 1992) a small increase in the risk of bladder cancer, was found but no relationship with colon cancer was observed. However, the design of this study is controversial (Murphy, 1993) so that no final conclusion can be drawn. In recent studies a correlation was found between the consumption of cold chlorinated tap water and the rate of spontaneous abortion (Swan et al. 1998). The possible role of compounds related with chlorination was discussed but not proven.

2.5.3 Environmental impacts of applying disinfectants during distribution

The environmental impacts connected to the application of disinfectants during distribution involve the transport, preparation, handling and discharge of the both the disinfectant and the water containing the disinfectant. The transport of chlorine has risks due to the possibility of release of chlorine gas in transport accidents. Therefore the use of hypochlorite solution is often preferred. The application and preparation of chlorine dioxide requires special precautions because of its explosive nature. Chloramine and chlorine can be toxic to fish and shellfish (Scott et al. 1990; Hermanutz et al. 1990; Tsai et al. 1990). The surface water criterion in the USA is 11 µg/l total residual chlorine (TRC) as a four-days average and 19 µg/l as a 1-hour average. Indications have been found that these values are still too high in the case of the presence of ammonia (Hermanutz et al. 1990). Total death was found at 24 µg/l for fish in the presence of ammonia, whereas growth retardation was found to occur below 1 µg/l. These data correspond with practical experience of accidental discharges of drinking water containing chloramine causing acute death in fish (Neden et al. 1992). These data indicate a necessity to neutralise chloramine when discharges occur. The use of chlorine leads to the formation of halogenated compounds which generally have a more persistent nature and are subject to a more stringent regime for discharges as "black list substances". For environmental impact reasons the production of DBP's should also be minimised.

2.5.4 Summary/conclusions

- The use of a chemical disinfectant in drinking water during distribution can increase the concentration of DBP's. Chlorination results in the highest concentrations and the widest range of byproducts.
- The selection of a chemical disinfectant for use in drinking water during distribution depends on both water treatment and the chemical characteristics of the involved source water.
- Water quality criteria for disinfection byproducts, based on a negligible health risk, can limit the use of chemical disinfectants in drinking water during distribution;
- The application of chemical disinfectants in drinking water during distribution can have a negative impact on the environment.

2.6 Effect on taste and odour compounds

Application of chemical disinfection affects the taste and the smell of water. These effects are either due to the presence of the disinfectant itself and/or to the formation of byproducts. On the other hand, disinfectants can have of positive effect in oxidising taste and odour compounds present in the water. All these effects depend on water composition and the nature and concentration of the applied disinfectant.

Taste and odour problems are significant because they are often the primary cause of consumer complaints. In a survey in the USA on taste and odour problems 60% of the companies reported problems in this area. A total of 67% of these companies identify the distribution system as a source of the complaint, whereas chlorine was implicated as the most important cause. It is contradictory that the agent used to improve water quality at the same time becomes an important cause of problems. The chemicals involved in taste and odour problems in drinking water supply generally have a low threshold value (Zoeteman, 1978). A survey of threshold levels of known nuisance compounds is given in table 2.5.

Most people can taste chlorine and chloramines in concentrations below 5 mg/l and some even detect chlorine at levels below 0.3 mg/l (Bryan et al. 1973). The taste and odour threshold can be lower with lower pH (Mallevialle and Suffet, 1987). The taste and odour threshold values of di- and trichloramine are significantly lower than that of chlorine or chloramine. Taste and odour observations are subjective and can become acquired. The taste and odour values of mono-, di- and trichloramines are respectively 5.0, 0.8 and 0.02 mg/l (White, 1972). Trichloramine thus has a very low taste and odour threshold and the formation of this compound should be avoided as much as possible by selecting the appropriate process conditions. Chlorine dioxide has a low taste and odour threshold of 0.4 mg/l, but in practice complaints have been reported at concentrations higher than 0.07 mg/l. The guideline level for chlorine dioxide is to a great extent determined by the its low taste and odour threshold value.

The oxidative properties of the disinfectant can lead to both the formation and degradation of taste and odour compounds. A notorious example is the formation of chlorinated phenols (c.f. Table 2.6). An increasing chlorine/phenol ratio subsequently results in a reduction of the taste compounds produced at a lower ratio (Burtschell et al. 1959). In the years 1920-30 it was discovered that the bad taste could be removed by a high dose of chlorine and then successive removal of the chlorine taste by adding a neutralising agent. If chlorine is replaced by chloramine then the oxidation process can be insufficient to remove the original taste and odour compounds (Krassner et al. 1989).

It has been stated that application of a disinfectant suppresses the formation of taste and odour compounds in biofilms. Actinomycetes are an important cause of the formation of taste and odour compounds such as geosmin and methyl isoborneol. These compounds give a musty and earthy taste (Jensen et al. 1994; Mcrae et al. 1993) and can be formed in the distribution system, but can also be present in the source water. These substances are difficult to remove because of their high resistance to oxidative degradation. Good results have been reported with physical treatment (GAC filtration) combined with hydrogen peroxide and ozone (Peroxone) (Suffet et al. 1995).

Various algae can form substances with a low taste and odour threshold, such as *Anabaena, Synura, Asterionella* (White, 1972). The substances are released after lysis and degradation of the cells (Zoeteman, 1978) and the degradation can be accelerated by chlorine. The occurrence of taste and odour problems is therefore directly related to the quality of the source water and the applied treatment.

Table 2.5 *Substances in drinking water with a low odour threshold value (Zoeteman, 1978; Krassner et al. 1989, Zander and Pingert, 1997)*

Substance	Odour threshold level (μg/l)
Octene	0.5
Biphenyl	0.5
2-Methylisoborneol	0.02
Geosmin	0.02
Octanal	0.7
Decanal	0.1
_-Hexachlorocyclohexane	0.3
trans-2, cis-6-Nonadienal	0.002
2,3,6-Trichloroanisole	0.007
Dimethyltrisulfide	0.01

Taste and odour problems have also been reported as being caused by the presence of areas in reservoirs with a low oxygen content. Krassner et al. (1989) found in these cases, substances such as methylsulfides with a very low taste and odour value, but also other unknown compounds which contributed to the bad taste. Beyond the treatment plant, new taste and odour compounds can be produced by reaction to the remaining disinfectant (Jestin et al. 1987). These problems can be solved by dechlorination.

Table 2.6 *Comparison of odour threshold values for some chlorinated and non-chlorinated substances (Mallevialle and Suffet, 1987; Montiel et al. 1987).*

Compound	Threshold value (μg/l)
Phenol	>1000
4-Chlorophenol	>1000
2,4,-Dichlorophenol	8
Anisole	50
2,3,6-Trichloroanisole	0.003
2,4,6-Trichloroanisole	0.3

An illustrative example of the effect of chlorine on the production of taste and odour compounds is the formation of anisoles. These substances have a very low taste and odour threshold and are produced by actinomycetes from a chlorinated product: trichlorophenol (Jensen et al. 1994, Mallevialle and Suffet, 1987; Montiel et al. 1987). For comparison the taste and odour thresholds values for a number of chlorophenols are given in table 2.6. Chlorine dioxide does not form chlorophenols (Montiel and Welté, 1990). If the source contains concentrations of bromide and iodide of about 0.1 mg/l then chlorine can start to form brominated and iodated THM's, which have a taste and odour level of 0.02-10 μg/l (Mallevialle and Suffet, 1987). If di- and trichloramines are formed then these substances can contribute to the bad taste and odour after the application of chlorine. Taste problems caused by di- and trichloramine can be reduced by increasing the pH to a level of 7.5-8.5 (Neden et al. 1992). However, at these higher pH levels the disinfectant activity decreases.

To prevent taste and odour problems caused by regrowth, the effect of disinfectants on growth is an important aspect. CT values for 2 log reduction of actinomycetes are 0.5 mg/l (chlorine) and 70 mg/l (chloramine), respectively (Jensen et al. 1992; Ransome et al. 1995), but as described above, inactivation of these micro-organism in biofilms would require higher concentrations. Various moulds are inactivated in residual chlorine concentrations of 1-3 mg/l, but if iron tubercles are present, much higher concentrations are required.

A special and peculiar case has been reported about the formation of taste and odour compounds by chlorine dioxide with substances in the indoor air (Hoehn et al. 1990). Organic compounds from a carpet glue reacted with chlorine dioxide evaporating from the drinking water supply and gave a strong kerosine and feline urine smell.

No generally applicable method can be given to prevent taste and odour problems in drinking water during distribution. It is clear that effective removal of taste and odour compounds from the raw water and preventing formation of such compounds in water treatment is an essential precondition. The application of a disinfectant residual in the distribution system thus always has the risk of causing taste and odour problems. Furthermore, a residual disinfection is probably ineffective in preventing regrowth of the micro-organisms in biofilms (actinomycetes and fungi) that produce taste and odour compounds. Prevention of regrowth in the distribution system by limiting nutrients and avoiding zones with a low oxygen level is probably the most effective way to prevent taste and odour problems.

2.6.1 Summary/conclusions

- Low concentrations of chemical disinfectants impair the taste and smell of water;
- Chemical disinfectants may react with compounds present in drinking water in the distribution system resulting in the formation of taste and odour compounds;
- Micro-organisms such as actinomycetes and fungi, that can produce taste and odour compounds, grow in biofilms where chemical disinfection may not be effective.

2.7 Good engineering practices and regulatory measures to protect drinking water quality during distribution

2.7.1 General

The application of good engineering practices is one of the most important means of protecting the quality of drinking water during distribution. Methods to reduce the risks of microbial contamination such as adding a disinfectant have restrictions and cannot protect against chemical pollution. Therefore a policy to prevent entry of contaminants and maintaining the integrity of the system should be the first priority. The approach to protect the distribution system and household installations differs between countries. The important ones will be described in relation to the regulations which apply in the Netherlands. The international development in this area will also be dealt with.

The following aspects play a role in protection of the distribution system:

1. *Good engineering practices*:

    - maintenance of a sufficiently high pressure in the distribution system to prevent contaminants entering;
    - use of equipment to prevent back flow of water from installations;
    - use of break tanks before installations with a high contamination risk (e.g. hospitals);

2. *Organisation measures*:

- maintaining an organisation and structure for inspection of connected installations and training of sanitary personnel and installers;
- prohibit the use of materials which have negative effects on drinking water quality with regard to the release of growth promoting substances.
- a quality system including protocols for repair, cleaning and construction activities in the distribution system.

3. *Measures related with water quality*:

- chemical and bacteriological water quality monitoring;
- addition of a disinfectant for preventive reasons treatment of water to minimise regrowth and the spread of micro-organisms.

2.7.2 Regulations on engineering practice and organisation aspects for the protection of drinking water quality during distribution in the Netherlands

Statutory regulations
In the Drinking Water Act (Waterleidingwet, 1960) various regulations have been laid down which directly or indirectly deal with the engineering requirements for protecting the distribution system:

- The owner of the drinking water company is obliged to maintain a sufficiently high pressure in the distribution system (art. 4.1 of the Act);
- Additional rules can be given by decree on the professional quality of the personnel and their training in education on hygienic aspects;
- By decree requirements can be laid down on the inspection of the installations connected to the distribution system and the technical merits of the installations;
- The owner must take care that no personnel are taken into service who offer a high risk of contamination by carrying infectious diseases.

In the Drinking Water Decree of 1984 (Drinking Water Decree, 1984) regulations have been laid down on the quality requirements for drinking water and the control and the supervision of public water supply by the Public Health Inspectorate. The owner of the drinking water company is obliged to take care that (Art. 5; Drinking Water Decree, 1984):

- The water mains for abstraction, treatment, storage and distribution are managed in a way to prevent contamination of the drinking water;
- The distribution system is designed in a way that repair work can be done with minimal interruption of the supply. Drawings and design data must be available;
- The mains for transport and distribution must be disinfected after repair work so that contaminants are removed and inactivated.

Security of the connected installations
In addition to these rules regulations have been laid down which give the drinking water company the power and obligation to supervise the security of the connected installations with regard to protection of the distribution system:

- The owner of the drinking water company is obliged to take care that the installations directly or indirectly connected to the distribution system have no risk of contamination;

- The connected person is obliged to take care that the installation cannot contaminate the distribution system and must co-operate when the drinking water company wants to inspect the installation.

In the Drinking Water Act no detailed technical descriptions have been given with regard to drinking water installations. It is the responsibility of the drinking water companies to give the necessary technical prescriptions in the framework of their responsibility to protect the distribution system. The requirements of the drinking water companies are laid down in technical installation standards, certification requirements for sanitary workers, installers etc. and the recommendations of the Netherlands Water Supply Association (VEWIN).

An important aspect is the prescribed use of certified materials and equipment as described in NEN 1006 (NNI, 1981). If necessary more detailed prescriptions have been given in the work sheets published by VEWIN. A specific rule in standard 1006 is devoted to protection (Art. 3.8.2. of NEN 1006):

- The connection of an installation that can give a risk of contamination must contain equipment to prevent backflow. The degree of prevention depends on the degree of risk of the installation and the substances involved.

This requirement has been detailed in a working sheet (nr. 3.8) that is currently being revised (VEWIN, 1997). This working sheet describes the technical requirements depending on the risk category. The determination of the risk category has been described in a recommendation of VEWIN (VEWIN, 1991). The method of judgement is based on the matrix method of Mantout and is subject to a standard within CEN.

Supervision on drinking water supply and drinking water installations

The protection of drinking water during distribution is highly dependent on the degree of supervision which in the Netherlands primarily is a responsibility of the drinking water companies within the framework of their responsibility to protect the distribution system. Consequently, a decrease of intensity of supervision will result in a weaker chain to safeguard drinking water. Such weakening of the chain can only partly be replaced by an increase in the frequency of monitoring.

Supervision of the drinking water companies has been dedicated to the Environmental division of the Public Health Inspectorate. The Inspectorate is involved in development of the recommendations and regulations of the drinking water companies. In this manner these regulations get the formal support and approval of the Inspectorate. Materials and chemicals to be used in drinking water supply are subject to a guideline of the Inspectorate which contains criteria on the basis of which Kiwa can confer an Attest Toxicological Aspects (ATA) (VROM, 1994).

2.7.3 ***International rules***

The national regulations on certification and technical requirements are increasingly subject to international regulations of CEN, based on the EC construction products directive (89/106/EEC) (EC, 1989). This directive intends to regulate the harmonisation of national approval systems of construction products through mutual recognition of certified products. CEN standards serve as the basis of certification. For the protection of the distribution system a draft standard has been developed with safety criteria for installations (NEN-EN 1717) (CEN, 1994). The European drinking water companies unified in Eureau have already agreed on a system for risk categories and related measures to protect the distribution system.

2.7.4 Water quality regulations for protecting drinking water during distribution

Key information

The following key information provides an insight into the differences between European countries in their approach to protective measures for maintaining drinking water quality in distribution.

Statutory regulations in the fields of:

- microbiological water quality criteria
- monitoring frequency and requirements
- requirements with regard to disinfection
- standards on disinfection byproducts
- regulations to protect the distribution system

These protective measures will be summarised and compared with regard to the requirements of the EC drinking water directive (European Communities, 1980). Regulations for safeguarding distribution systems will also be briefly discussed.

Situation in the Netherlands (summary in Table 2.7)

Drinking water quality criteria have been laid down in the Drinking Water Decree (1984). For bacteriological quality the absence of total and thermotolerant coliforms applies in 300 ml of drinking water leaving the treatment facility. This requirement is more stringent than in the EC drinking water directive (absence in 100 ml). For the distribution system absence in 100 ml is prescribed. In practice the standard is considered to be exceeded if a repeat sample shows a positive result. In practice this situation is seldom found (c.f. Chapter 3). For coliforms a positive result may be caused by regrowth and therefore the presence of these organisms will be judged differently from the presence of *E. coli*/thermotolerant coliforms. If a repeat samples is positive, additional investigations must include: analysis for faecal streptococci and sulphite-reducing clostridia. For both these parameters absence in 100 ml is required. The criterion for clostridia is more stringent than in the EC drinking water directive (less than or equal to 1 per 20 ml). Experience in the Netherlands has shown that a more stringent standard at the treatment plant is achievable.

The heterotrophic plate count at 22 and 37 °C in drinking water during distribution should be less than 10 CFU/ml and 100 CFU/ml respectively, based on geometric year average value (guideline value). Following the European Drinking Water Directive, issued in 1998, the HPC conducted at 37 °C is no longer included in National Legislation (proposed).

In the Netherlands, there is no obligation to apply a chemical disinfectant. The selection of technology used to achieve hygienic drinking water is the responsibility of the drinking water companies, but these must be approved by the Public Health Inspector. If a disinfectant is applied continuously or daily, registration of the disinfectant concentration is obligatory.

A DBP standard of 1μg/l applies. This value may be exceeded if the treatment and the source of the water makes higher values unavoidable. If chlorination is applied THM's must be determined once a week.

Situation in the United Kingdom (summary table 2.8)

The requirements on drinking water quality in the UK have been laid down in the Water Supply Regulations of 1989 (HMSO, 1989). In these regulations a general rule applies that drinking water to be distributed must be disinfected (Art. 23.1). Disinfection has been defined as a process which removes or inactivates pathogenic micro-organisms. The regulations do not prescribe the method of removal, but the primary goal is to achieve the absence of pathogens. Criteria for microbiological water quality are based on faecal coliforms (absence in 100 ml) and total coliforms (absence in 95% of the samples; at works absence in 100%). HPC values are determined by incubation at 22 or 37 °C and no significant increase in numbers may be found as compared to normal counts.

Water quality criteria and monitoring at the treatment plant differ from those for the distribution system (at the consumer tap). At the tap for instance, monitoring for bacteriological parameters and residual chlorine content are prescribed. For faecal streptococci a criterion of absence in 100 ml applies and sulphite-reducing clostridia (SRC) should not be found in samples of 20 ml. This conforms to the EC directive. For faecal streptococci or SRC no monitoring frequency is prescribed.

For trihalomethanes a standard of 100µg/l averaged for 3 months applies; if less than 4 samples per year have been investigated than the value of 100 µg/l may not be exceeded.

The Water Act of 1945 By-laws (DWI, 1995) provide obligations to the owners of the installations and the installers to protect water in distribution against contamination from installations. The Water Supply Regulations contain rules for conditioning water and require that no materials and substances are used which are not approved according to the Law.

Situation in Germany (summary Table 2.8)

The requirements in Germany for the protection of the drinking water quality have been laid down in the 'Trinkwasserverordnung' (1990). The indicator for faecal pollution is *E. coli*, which must be absent in 100 ml. Additionally, a standard of absence in 100 ml for 95% of the samples applies for coliforms. Faecal streptococci must be absent in 100 ml. For heterotrophic plate counts at 20 and 36 °C a guide level of 100 per ml applies. If the water is disinfected a value for the colony counts at 20 °C at the end of the treatment process of 20/ml applies.

If a disinfectant is used during water treatment then a residual of at least 0.1 mg/l free chlorine or 0.05 mg/l chlorine dioxide must be present at the end of the process with a maximum value of 0.3 mg/l for chlorine and 0.2 mg/l for chlorine dioxide, respectively. A general limit has been set for chlorine of 1.2 mg/l and for chlorine dioxide of 0.4 mg/l. Chloramine has not been approved as a disinfectant. For total THM's a maximum concentration of 10 µg/l applies.

There is no differentiation in monitoring requirements for distribution and water treatment. The basis for the frequency of monitoring is the volume of distributed water (15.000 m^3). The parameters to be investigated at that frequency are odour (qualitative), turbidity, conductivity, chlorine or chlorine dioxide, *E. coli*, coliforms and heterotrophic plate counts. If a daily consumption of 200 l per person is assumed then this basis corresponds with the frequency in the Netherlands of 1 sample per week per 10,000 inhabitants. The authorities can change the prescribed control measurements if necessary. The treatment method applied must be approved by the authorities.

The drinking water company is obliged to ensure that the connected installations do not influence the water quality in a way that the drinking water standards are exceeded. A general obligation exists for the owner of the installations not to connect other fluid systems to a drinking water distribution system and other systems should be made distinguishable by colour marking.

Situation in France (summary in Table 2.9)
In France the regulations on drinking water quality have been laid down in the decree of 1989 (Décret, 1995). For microbiological characterisation of water, standards apply for thermotolerant bacteria of the coligroup (absent in 100 ml), coliforms (absent in 95% of samples of 100 ml), faecal streptococci, (absent in 100 ml), sulphite reducing clostridia (less than or equal to 1 per 20 ml), *Salmonella* (absent in 5 l), pathogenic staphylococci (absent in 50 ml), enterovirus (absent in 10 l), *Pseudomonas aeruginosa* (absent in 100 ml) and colony counts at 37 and 22 °C after 24 hours incubation (less than 20 in. 100 per ml). Stringent requirements apply for turbidity, which is used as a measure to prevent the occurrence of chlorine resistant microorganisms.

During distribution a maximum value of chlorine of 0.1 mg/l as residual applies. Above this value the authorities must be informed and give approval.

Monitoring requirements defined for distribution systems include the thermotolerant coliforms, faecal streptococci, and the heterotrophic plate counts at 22 and 37 °C, turbidity and qualitative measurements of odour, taste and colour.

For THM's a guide value of 1 µg/l has been defined. Most drinking water companies have a THM level lower than 5 µg/l for water leaving the treatment plant.

The drinking water decree requires the maintenance of a certain pressure in the distribution system and makes the owner responsible for the maintenance of installations. Pipes with non-potable water quality must be marked to avoid cross connections. The ministers responsible for Public Health and Construction issue regulations on the technical requirements for protecting the drinking water from domestic installations.

2.7.5 Summary/conclusions

- The described European countries do not have legal obligations for maintaining a defined disinfectant level at the tap or in the distribution system;
- Some countries have low guideline values for THM concentrations (Germany, France, the Netherlands), which encourage optimisation and/or minimisation of the application of a chemical disinfectant;
- Although the EC Drinking Water Directive provides general standards and requirements for monitoring, the practical application of these rules differs among the various member states. This situation hampers comparison of legislation and monitoring results. Some countries have monitoring obligations for THM's and disinfectants at the tap and in the distribution system (UK), other countries determine these parameters at the treatment plant (e.g. NL);
- No uniform standard method exists for the assessment of growth promoting potential of materials in contact with drinking water. In most countries the assessment of materials is a shared responsibility of different departments, public health organisations and the drinking water companies;
- Legally prescribed responsibilities and powers to prevent contamination of the distribution system are important (and probably the most important) measures to safeguard the drinking water quality. The responsibilities are generally shared by different departments (housing, health or environment, drinking water companies and owners of the drinking water installations).

Table 2.7 *Legislative requirements in The Netherlands on water quality monitoring and aspects concerning disinfection and protection of drinking water during distribution.*

Parameter	Requirement	Required monitoring distribution system per 10,000 inhabitants
Microbial contamination		
Total coliforms	absent in 100 ml	1x per 2 weeks
Thermotolerant coliforms/*E. coli*	absent in 100 ml	1x per 2 weeks
Colony count at 22°C	geometric average 100/ml	2x per year
Colony count at 37°C	geometric mean 10/ml	
Faecal streptococci	absent in 100 ml	only at suspect of contamination
Sulphite-reducing clostridia	absent in 100 ml	only at suspect of contamination
Chemical substances		
Application of disinfectants	no obligation	if applied then continuous monitoring at the pumping station; network: 1x in 2 weeks
Trihalomethanes	1 µg/l, guide level	weekly at treatment plant if chemical disinfection is applied
Safety requirements		
Requirements for the drinking water company	Supervision; education on hygienic principles; responsible for protection of the network	
Requirements for connected customers	cooperation with inspection responsible for measures to prevent contamination	

Table 2.8 Legislative requirements in Germany on water quality monitoring and aspects concerning disinfection and protection of drinking water in the distribution system.

Parameter	Requirements	Required monitoring/ obligations for distribution system
Microbial contamination		
Total coliforms	absent in 95% of samples of 100 ml	-[1]
E. coli	absent in 100 ml	-[1]
Colony count at 20°C/36°C	100/100 per ml	-[1]
Faecal streptococci	absent in 100 ml	-
Sulphite-reducing clostridia	absent in 20 ml as trigger for further investigations	-
Chemical substances		
Application of disinfectants	application not obliged	
When chlorine is applied:	max. dose: 1.2 mg/l; min. required: 0.1 mg/l	
	max. at distribution: 0.3 mg/l	-[1]
When chlorine dioxide is applied:	max. dose: 0.4 mg/l: min required: 0.05 mg/l	
	max. at distribution: 0.2 mg/l	-[1]
Trihalomethanes	10 μg/l	1x per year min.
Safety requirements		
Obligations for drinking water company	Supervision on drinking water installations	
Obligations for connected customers	pipe lines with non-drinking water quality may not be connected directly to drinking water system; non-drinking water pipe lines must be marked	

[1] No specific monitoring frequencies are prescribed for the distribution network. The minimum frequency is 1 sample per 15,000 m^3 distributed drinking water.

Table 2.9 *Legislative requirements in the United Kingdom on water quality parameters and aspects concerning disinfection and protection of drinking water during distribution.*

Parameter	Requirement	Monitoring frequency in distribution System per 10,000-20,000 inhabitants (samples per annum)
Microbial contamination		
Total coliforms	absent in 95% of the samples of 100 ml	48
Thermotolerant coliforms/*E. coli*	absent in 100 ml	48
Faecal streptococci	absent in 100 ml	If suspected
Sulphite-reducing clostridia	1 per 20 ml	If suspected
Colony counts at 22°C/37°C	no increase compared to normal values	48
Chemical substances		
Disinfectant	pathogens should be removed	48
Trihalomethanes	100 μg/l average concentration for 3 months	1 - 4
Safety requirements		
Obligations for drinking water company	Only approved materials may be used; Water should be treated to diminish risk at distribution;	
Obligations for connected customers	Precautions to prevent contamination	

Table 2.10 *Legislative requirements in France on water quality parameters and aspects concerning disinfection and protection of drinking water quality during distribution.*

Parameter	Requirements	Required monitoring in the distribution system per 10,000-20,000 inhabitants (number of samples per year)
Microbial contamination		
Bacteria of the coligroup	absent in 95% of the samples of 100 ml	
Thermotolerant coligroup bacteria	absent in 100 ml	24
Faecal streptococci	absent in 100 ml	24
Colony count at 22 / 37 °C	100 in. 20 per ml	24
Salmonella	absent in 5 l	
Pathogenic staphylococci	absent in 100 ml	
Faecal bacteriophages	absent in 50 ml	
Enterovirus	absent in 10 l	
Chemical substances		
Residual chlorine	less than 0.1 mg/l (guide level)	24
Organohalogens	1 µg/l (guide level)	
Security requirements		
Obligations for company	Technical requirements for disinfection and materials to be used should be met	
Obligations for connected customers	Drinking water installation should meet technical requirements	

3 The microbiological quality of drinking water in the Netherlands

This chapter focuses on drinking water quality in distribution systems in the Netherlands, especially on the bacteriological water quality in relation to the absence of a disinfectant residual in the major part of the distributed water.

Most water supply companies in the Netherlands are N.V. (= plc) business enterprises, with provinces and municipalities as shareholders. One city (Amsterdam) has a municipal water supply company and one small company is private. In January 1997 there were 32 water supply companies, a number that was reduced to 26 companies in January due to mergers. In Table 3.1 these companies are distinguished by type of supply area. In January 2000, the number of companies was reduced to 23.

Table 3.1 Number of water supply companies in 1998, type of supply area, major water source and annual supply (1995 supply data from VEWIN, 1996).

Type of supply area	Source water type	Number of companies	Annual production (x 1000 megalitres)
provincial, rural	ground	14	748
	surface	2	115
provincial, urban	surface	1	82
city	surface	2	242
small city	ground	3	34
	surface	2*	-
none	surface	2**	-
Total		26	1,219

* These companies do not produce, only distribute 5,000 megalitres drinking water.
** These companies only pretreat surface water.

In 1995 these companies produced 1,219,000 megalitres of drinking water with 250 treatment plants. An overview of the source waters for these plants is presented in Table 3.2.

Some of the treatment plants use disinfectants in the surface water treatment process. Among these are all treatment plants using surface water without soil passage (bank filtration, infiltration). A disinfectant is added to 22% of all drinking water leaving the treatment plants in the Netherlands. In all cases post-disinfection serves as a 'polishing' step, mostly to reduce heterotrophic colony counts. Maintaining a disinfectant residual in the distribution system is not an objective and within a few kilometres from the treatment plant, disinfectant concentrations are below or near to detection limits. The quality of the drinking water in the distribution system is maintained by (i) protecting the system to prevent contamination and (ii) producing drinking water with low concentrations of nutrients to limit bacterial growth. Nutrient concentrations are not low in all distribution systems (yet) and therefore a number of companies periodically flush sensitive parts of the distribution system where heterotrophic colony counts and the number of *Aeromonas* grow to higher levels than preferred. Flushing of parts of the distribution system is mainly used to control coloured water problems but also to control numbers of invertebrates. Flushing is a routine procedure after pipe laying and repairs.

Table 3.2 Source water for treatment plants (adapted from Versteegh, 1996)

Source type	**Number of plants**	**Annual production** (x 1000 megalitres)
Ground water	*233*	*803*
deep wells*	87	
shallow wells**	131	
bank infiltration	15	
Surface water	*17*	*416*
infiltrated + ground water	10	
- dune	9	
- ground	1	
direct treatment (after impoundment)&	7	
Total	*250*	*1,219*

* Deep wells: protected by impermeable layers of e.g. clay
** Shallow wells: a number of these produce oxygenous ground water
& Two treatment plants also use ground water

3.1 Structure of the distribution systems

The entire drinking water distribution system of the Netherlands consists of approx. 100,000 km of mains with a diameter of 50 mm and larger. Cast-iron was the first material used in the construction of distribution systems (the first treatment plant producted drinking water in 1854). After World War II asbestos-cement mains were used until the disadvantages of this material became clear several decades later. Since then mainly plastic mains have been used, especially unplasticiced polyvinylchloride (uPVC), and also some polyethene (PE). At present uPVC mains are the most common, followed by asbestos-cement (Figure 3.1).

There is a growing interest in the Netherlands in developing long term mains replacement programmes. The water supply companies do not want to be confronted with sudden and/or a continuing increase of mains failure rates due to simultaneous over-aging of different materials. In 1997 Kiwa started a project in the joint research programme of the water supply companies to enable the companies to predict aging and to develop cost-effective long term replacement programmes.

3.2 Contamination of the distribution system

Water quality may change due to ingress, possibly introducing pathogens or chemical hazards. Ingress may be the result of 3 types of events:
(i) mains breaks and leaks;
(ii) mains construction and repair;
(iii) back-siphonage via taps and hydrants.

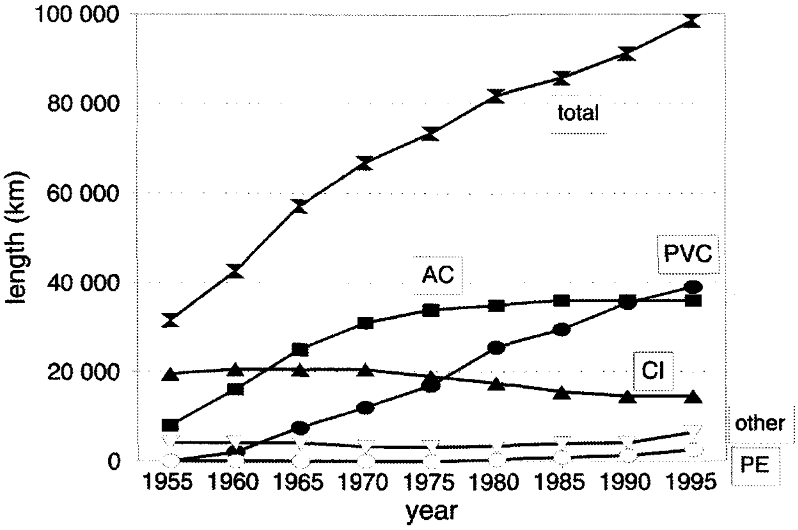


Figure 3.1 *Mains materials in distribution systems in the Netherlands (mains in operation, AC = asbestos cement, CI = cast iron)*

3.2.1 Mains leakage and breaks

Mains leakages could theoretically pose larger risks to drinking water quality than mains breaks. When a leaking main is put out of service temporarily, the surrounding soil may enter the main due to underpressure, but this may even occur while mains are in service (so called 'surges', Le Chevallier, 1998). The severity of the contamination depends of the quality and quantity of the surrounding soil or water entering the mains. Mains breaks are usually detected quickly and the rapid response of the water supply company, including intensified monitoring of drinking water quality, diminishes the risks of the contamination.

3.2.2 Mains construction and mains repair

New mains are not put into service before water quality is in compliance with legislation and in most cases the water supply company has additional criteria (e.g. presence of visual particles). In situations requiring mains repair, water supply companies are not legally expected to maintain regular water quality standards, they are however expected to prevent contamination of drinking water and completely remove any contamination from the mains after repair. Water supply companies are striving to prevent drinking water contamination during mains construction and repairs by following hygienic working procedures. Intensive cleaning of the mains after repair (flushing, pigging or air-scouring, when necessary including the use of a disinfectant) and intensive monitoring of the water quality are part of these procedures. The general policy is to advise the public to boil water from mains after repair when there is risk of faecal contamination due to the presence of faecally contaminated soil, surface water or even water from sewers in the immediate vicinity. Due to practical problems however, this policy in many water supply companies is not executed.

3.2.3 Back-siphonage via taps and hydrants

Back-siphonage from connected houses and industries can be prevented in many mechanical ways, e.g. by enforcing the application of one-way valves, break tanks and/or special taps. The complexity of mechanical devices used depend on the risks involved. Application of such mechanical devices is enforced by the water supply companies. For hydrants however, there are few or no procedures formulated to prevent back-siphonage. In the distribution systems of many water supply companies hydrants are used not only by trained company employees, but also by fire fighters during drills, by local government employees to fill mobile water tanks for irrigation of public parks and in some cases even by private companies to fill mobile water tanks for sewer cleaning. It is known that the relatively simple procedures to prevent back-siphonage when using hydrants are not always followed and this poses a risk of contamination of the distribution system. There is a growing concern within water supply companies about these risks and in many companies agreements with fire fighting departments and local government have been changed or are under review. The recommendations of a 1995 special committee report (Vreeburg & Poortema, 1995) that aims to improve the provision and use of fire fighting water connections, have been fully endorsed by the Inspectorate.

3.3 Monitoring drinking water quality and legislation

3.3.1 Monitoring

In the Netherlands, drinking water quality is monitored by 18 licensed laboratories that are either departments of water supply companies or separate companies established and owned by several water supply companies. These laboratories analyse raw water, process water, finished water and distributed drinking water. The laboratories of Kiwa and the National Institute of Public Health and the Environment (RIVM) are also licensed to monitor drinking water quality. Mandatory biological variables determined in finished water and drinking water are:

Indicators of contaminations
- coli37: coliform bacteria (membrane filtration (colony count) or MPN at 37 EC);
- coli44: thermotolerant coliform bacteria (colony count or MPN at 44 EC);
- FS: faecal streptococci;
- SSRC: spores of sulphite reducing clostridia.

Regrowth in the distribution system
- HPC22 heterotrophic bacteria (colony count, at 22 EC);
- HPC37 heterotrophic bacteria (colony count, at 37 EC);
- Aer30 *Aeromonas* bacteria (membrane filtration (colony count) at 30 EC).

Most laboratories incubate agar plates for determining coliforms at 37 EC and, using typical colonies from these plates, confirm coliform identity at 37 EC and thermotolerant coliform identity at 44 EC. Some use direct tests for thermotolerant coliforms at 44 EC, some use MPN-techniques.

3.3.2 Legislation and legal enforcement

Drinking water supply companies are responsible for the quality of the drinking water entering the premises of consumers. Service pipes and water meters (when present) are owned by the water supply companies. The owner of the premises owns the pipes and installations and presently are responsible for any impact on drinking water quality. Drinking water samples however are always collected from taps in premises. In Table

3.3. current legislation is presented regarding the monitoring frequency and the maximum allowable levels for microbiological drinking water quality. An overview of water quality data is reported yearly to the Inspectorate for Environmental Hygiene of the Department of Housing, Regional Development and the Environment, and more frequently to the Regional Inspectors. These Inspectors are informed about non-compliances and corrective measures taken by the water supply company. Maximum levels of *Aeromonas* bacteria have not been set legally, but in a special directive of the Inspectorate for Environmental Hygiene. In finished water the yearly 50-percentile should not exceed 20 CFU/100 ml, in the distribution system the yearly 90-percentile should not exceed 200 CFU/200 ml. *Aeromonas* colony counts higher than 1000 CFU/100 ml have to be reported to the Regional Inspector. In the draft revision of the Drinking Water Decree a maximum value for aeromonades of 1000 CFU/100 ml is included.

Table 3.3 Monitoring of drinking water and maximum allowable levels

Variable*	**Monitoring frequency** (samples per period)			**Maximum allowable levels** (per sample except HPC's)	
	TSW**	TGW**	DS**	TP*	DS*
coli36	day	week	2 weeks	< 1/300 ml	< 1/100 ml
coli44	day	week	2 weeks	< 1/300 ml	< 1/100 ml
FS**	week	-	-	< 1/100 ml	< 1/100 ml
SSRC**	week	-	-	< 1/100 ml	< 1/100 ml
HPC22***	12/yr$^{\&}$	12/yr$^{\&}$	6 months	-	GM < 100/ml$^{\#}$
HPC37***	12/yr$^{\&}$	12/yr$^{\&}$	6 months	-	GM < 10/ml$^{\#}$

* Abbreviations of variables are explained in paragraph 3.3.1.
** TSW = treatment plants (also) using surface water.
TGW = treatment plants using ground water exclusively.
DS = distribution systems: 1 sample per 10,000 inhabitants (minimum = 2).
TP = treatment plants.
*** When coliforms or thermotolerant coliforms are found in a sample, another sample has to be collected and the number of faecal streptococci and spores of sulphite-reducing clostrida in this sample have to be assessed as well.
& When disinfected: 1 sample per 10,000 m^3 daily produced or distributed drinking water or 1 sample per 50,000 inhabitants.
# GM = annual geometric mean.

\- No directive.

3.3.3 Water industry quality goals

Water supply companies in the Netherlands are organized in the Netherlands Water Works Association (VEWIN). In this organisation common water quality goals are set as 'VEWIN-Recommendations'. The recommendations for maximum allowable levels of bacteria are identical to government directives. There are provisional recommendations for levels of invertebrates in drinking water distribution systems supplied by surface water treatment plants. Most water supply companies have also created their own guidelines for water quality, in most cases striving for a higher water quality than legally required.

3.3.4 Source water quality

In the Netherlands all ground water sources, including bank infiltrated ground water, are protected from direct influence of pathogens present in surface water, due to compact soil structure and long residence times in the soil (minimum 3 weeks, usually much longer). Contamination of the soil and ground water is limited by laws prohibiting high-risk activities of residents in the capture zone, effecting a ground water protection zone. Treatment plants using natural and infiltrated surface water from the dunes are considered to be using surface water and water quality monitoring frequency and analysis programme is consistently more intensive. The use of surface water is legally limited to sources of adequate quality.

3.3.5 Non-compliance and corrective measures

Non-compliance with legal and Ispectorate directives is reported to the Regional Inspectors and reactive and/or proactive measures are discussed with them. There is a special directive from the Inspectorate concerning non-compliance with levels for indicators of recontamination: When (thermotolerant) coliforms, faecal streptococci and/or spores of sulphite-reducing clostridia are found in a water sample, a repeat sample is collected as soon as possible. When any of the indicators are found in the repeat sample this is reported to the Inspectorate, and further action is taken. In some cases local health authorities are also informed about the situation. When indicators are found in a sample from the distribution system, a repeat sample is usually collected from the adjacent property as well, although this is not required in the directive. When thermotolerant coliforms, streptococci or clostridia are found in the repeat sample(s), the drinking water is considered to be faecally contaminated and the presence of pathogens is presumed. In these cases reactive measures are consistent with the seriousness of the situation, usually including the application of disinfectants and instructing the public to boil drinking water before consumption.

When non-thermotolerant coliforms are found in the repeat sample(s), the drinking water is considered to be non-faecally contaminated. In some cases water supply companies react almost as if the water is faecally contaminated. In these cases they apply disinfectants and advise the public to boil drinking water before consumption. The general policy is however to prevent public concern about water quality and to limit the use of reactive measures that may arouse concern. Instructions to boil water or the use of disinfectants are not considered an immediately necessity in these cases, as public health is not endangered.

Reactive measures commonly taken to counter faecal and non-faecal contamination are intensive flushing of parts of the distribution system. Treatment plant (or parts thereof) are closed down when the contamination originates from the treatment plant provided the remaining production capacity is sufficient. Determining the source and cause of the contamination and keeping the Regional Inspector adequately informed are also part of the working procedure.

Non-compliance with directives (annual geometric means) on heterotrophic colony counts and *Aeromonas* bacteria are not of immediate concern to public health and formally do not require immediate corrective measures. Many water supply companies however periodically flush mains where growth of heterotrophs and *Aeromonas* bacteria is enhanced. Flushing is also a common reactive measure when numbers of these organisms are found to be high in other mains, especially when *Aeromonas* numbers exceed 1000 CFU/100 ml, a situation that has to be reported to the Regional Inspector.

3.4 Quality of finished and distributed drinking water

This paragraph presents data on the microbiological drinking water quality in the Netherlands in 1993, 1994 and 1995 and some data on related variables. These data can be found in the following parts of the paragraph:

3.4.1 and 3.4.2	Collection of microbiological water quality data.
3.4.6	Overview of microbiological water quality.
3.4.7 and further	Water quality data per variable (see contents).

3.4.1 Collection of national data

Kiwa, on the authority of VEWIN, maintains a national database on drinking water quality in the Netherlands which enables water supply companies to report the required water quality data to the Inspectorate for Environmental Hygiene. The minimum, maximum and mean heterotrophic colony counts and colony counts of *Aeromonas* bacteria are entered into the programme per sampling location. For coliforms, faecal streptococci (FS) and spores of sulphite-reducing clostridia (SSRC) the number of samples per sampling location (treatment plants) or per group of sampling locations (distribution systems) is entered, as well as the number of positive repeat samples.

3.4.2 Collection of data on selected treatment plants and their distribution systems

For this project a total of 9 treatment plants from 5 water supply companies were selected to provide information on treatment methods, distribution variables and the quality of drinking water that is produced and distributed. Of the selected treatment plants, 4 use surface water without dune infiltration (D = direct treatment), 2 use surface water after dune infiltration (I), 3 use ground water. Two of the ground water treatment plants use anoxygenous ground water (A), including one that uses bank infiltrated river water. The other ground water treatment plant uses oxygenous ground water (O). The main characteristics of the treatment plants are presented in Table 3.4 and also in Annex 5.

The total annual production capacity of the 9 selected treatment plants is 321,000 megalitres (25% of total national production), 22,000 from ground water supplies (2.6% of total production from ground water), 299,000 from surface water supplies (66% of total production from surface water). The selected plants represent the different types of treatment plants, but not the major raw water type. The distribution system of most water supply companies is only partly divided into specific zones, if at all. Therefore mixing of drinking water from two or more treatment plants is common. In these systems it is difficult to link certain water quality aspects to a specific treatment plant. Specific information about the 9 selected treatment plants and their distribution systems is presented in Annex 2.

Data on the quality of drinking water from these treatment plants and their distribution systems were obtained from the water supply companies cooperating in this project. These data were provided in more detail than available in the national database. For heterotrophic colony counts and *Aeromonas* bacteria the actual numbers of colony forming units (CFU) per sample were supplied, enabling presentation of more detailed statistics, differences between years and differences between seasons. For coliforms, FS and SSRC most companies only presented the percentage of samples that contained these bacteria, including the number of samples analysed. Note the difference with the national data where only the incidence of positive repeat samples is presented. Some companies provided the actual numbers of coliforms, FS and SSRC, enabling differences between years and seasons to be presented.

Table 3.4 Characteristics of the selected water supply systems

ID	**Source**	**Treatment***		**System**	**Annual production**
code	type	type	train	type	(x 1000 megalitres)
D1	lake	direct**	res/Cl_2/coag/RSF/GAC/GAC/**ClO_2**	rural	20
D2	river	direct	res/floc/O_3/RSF/GAC/**Cl_2**	urban/rural	41
D3	river	direct	res/floc/GAC/**NaClO**	urban/rural	102
D4	lake	direct	coag/res/RSF/O_3/GAC/SSF	urban	24
I1	river	dune	coag/RSF/dune/open/RSF/O_3/ GAC/GAC/SSF	urban	60
I2	river	dune	res/RSF/dune/open/PAC/RSF/SSF##	urban/rural	51
A1	river	anoxyg#.	RSF/RSF/GAC	rural/urban	12
A2	ground	anoxyg.	degas/RSF/RSF/RSF	rural	5
O1	ground	oxyg#.	aeration and pH-adjustment	rural	5

* main characteristics and treatment steps are mentioned; for details see annex 1.
res = impoundment reservoir; coag = coagulation/sedimentation;
RSF = rapid sand filtration; floc = flocculation and floc-removal;
SSF = slow sand filtration; dune = dune infiltration and passage;
open = open collection; PAC = powdered activated carbon dosage;
GAC = granular activated carbon filtration; degas = degassing.
** surface water treatment without infiltration always includes impoundment reservoirs.
\# oxyg. = oxygenous; anoxyg. = anoxygenous.
\## temporary chlorination with NaClO since 1995 until dune water collection is covered.

3.4.3 Disinfectants

In 3 of the 9 representative treatment plants (D1, D2 and D3) the finished waters are continuously disinfected (13 treatment plants in the Netherlands). Three types of disinfectants are used: chlorine (gas), hypochlorite and chlorine dioxide. Chloramine is not used in the Netherlands. In treatment plant I1 the finished water was disinfected during cold periods until ozonation and GAC filtration was implemented in 1995. In Figure 3.2 the total chlorine concentration in the finished water of treatment plant I1 is shown. In treatment plant I2 the finished water has been chlorinated continuously since the start of 1995 (0.04 mg/l after the contact tank, no residual), awaiting the covering of dune water collection canals. The finished water of D4 has not been disinfected since 1983, the finished waters of the ground water treatment plants (A1, A2 and O1) have never been disinfected.

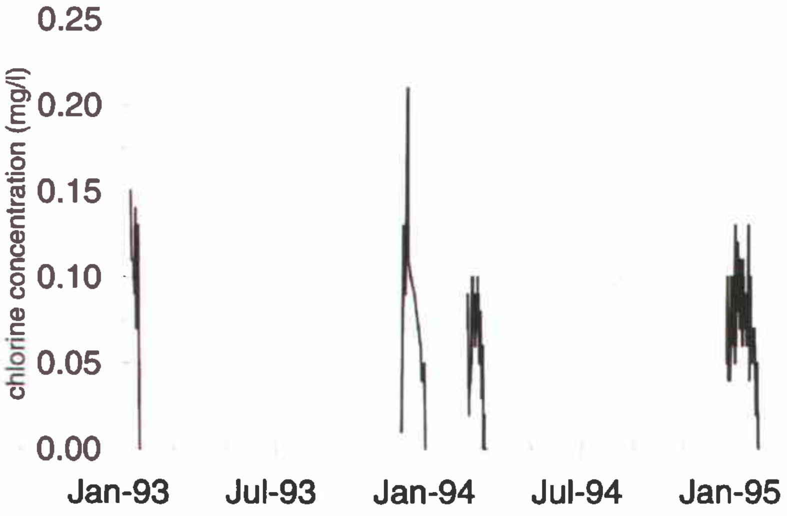


Figure 3.2 *Periodical chlorination of finished water of plant I1*

In Figure 3.3 the total chlorine concentrations in the drinking water are shown for the 3 treatment plants that continuously disinfect the finished water (D1, D2 and D3).

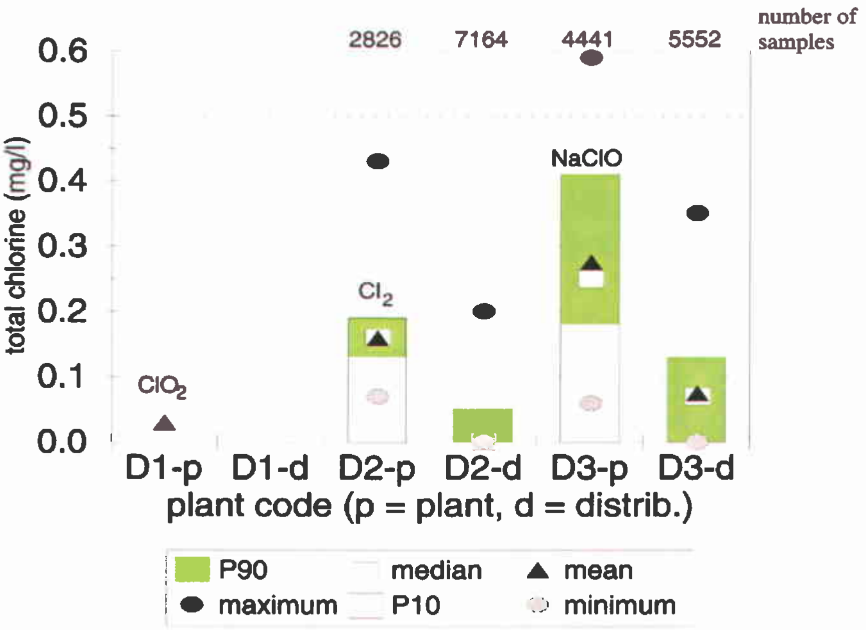


Figure 3.3 *Total chlorine in the finished water asnd the distributed water of plants D1 to D3 (1993-1995)*

3.4.4 Disinfection by-products

Water supply companies in the Netherlands periodically determine concentrations of disinfection by-products in drinking water. The information presented here is obtained from a recent report presenting an overview of the situation in the Netherlands (Van Genderen, 1998).

Total trihalomethane (THM) concentrations in the finished water water of the three surface water treatment plants that continuously disinfect finished water are presented in

Figure 3.4. THM concentrations are also shown for treatment plant I1 and I2 that temporarily disinfect(ed) the finished water (see paragraph 3.4.3). In the finished water of treatment plant I2 the total THM concentration is normally 0.8 :g/l due to chlorination of the raw water before transport when the water temperature is over 12 EC. Since starting temporary chlorination of the finished water the THM concentration has increased to levels that normally do not exceed 3 :g/l. In Annex 4 the concentrations of the seperate THM's and other DBP's are presented.

Concentrations of DBP's are low in the finished water of the treatment plants that use disinfectants in treatment or disinfect the finished water. These concentrations are well below those that are considered a negligable risk in the Netherlands (10^{-6} excess deaths during lifetime exposure). Concentrations of total trihalomethanes are always lower than 30 :g/l, those of trihaloacetate are lower than 3 :g/l, levels of tri- and dihaloacetonitrils are lower than 0.3 :g/l.

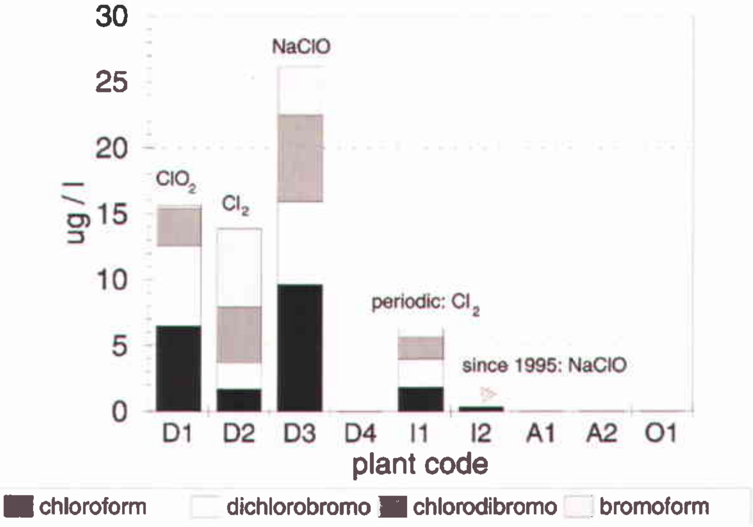


Figure 3.4 *Total THM's in finished water (1993-1995)*

The concentrations of DBP's change little during distribution, due to the low chlorine-demand of the finished water. In the distribution system of treatment plant D2 and D3 levels of THM's are maximally 30% higher than in the finished water of these treatment plants.

3.4.5 Taste and odour

Information on taste and odour complaints is presented in the descriptions of the distribution systems of the selected distribution systems in Annex 2. The numbers of complaints received by 3 companies are given in Table 3.5. Changes in chlorine concentrations affect numbers of complaints dramatically. The increase in 1995 of the number of complaints received by company 2 can be attributed to a temporary change in a part of the distribution system to a supply with a chlorine residual. The drop in 1995 of the number of complaints received by company 3 was due to ceasing periodical chlorination during cold periods after application of ozone and GAC-filtration. In company 4 complaints are related to mixing zones. In company 5 (actual numbers of complaints not reported) complaints are limited and also usually associated with mixing zones. The source of water quality changes causing complaints is often unclear.

Table 3.5 Taste and odour complaints received by 3 companies

Company	**Connections** (x 1000)	**Inhabitants** (x 1000)	**Complaints per 100,000 inhabitants** 1993	1994	1995
2	707	1,439	6.7 (96)*	5.9 (85)	56.0 (806)
3	150	718	10.2 (73)	12.3 (88)	1.9 (14)
4	501	1,200	ND	ND	2.4 (29)

* Total number of taste/odour complaints between brackets.
ND No data.

3.4.6 Overview of microbiological water quality

In Table 3.6 an overview is presented of microbiological data for the three year period of 1993 to 1995. For comparison, this Table also presents the data on the drinking water of 9 selected treatment plants and their distribution systems. National data on percentages of samples that contain indicators of contamination are not available, because water companies only report positive repeat samples to the Inspectorate. Therefore percentages of positive repeat samples of 1994 are presented. Detailed information on water quality, both national and from the selected treatment plants, is presented in the subparagraphs.

3.4.7 Total coliforms 37 °C and thermotolerant coliforms 44 °C

Water companies periodically test finished water and distributed water for coli37 (see Table 3.3), but not for coli44 (see paragraph 3.3.1), because these cannot be present when coli37 are not found, which is the case for the majority of the samples. When coli37 are found, repeat samples are tested for both coli37 and coli44 as well as for faecal streptococci and spores of sulphite-reducing clostridia. In 1994, coli37 were only found in 15 repeat samples of finished water and in 10 repeat samples of distributed water. In the same year, only 4 repeat samples of finished water and only 1 repeat sample of distributed water contained coli44. As is explained in Table 3.6, the differences between companies in reporting sample numbers for coli44 account for the relatively high percentages of coli44-positive repeat samples. As coli44 are not present when coli37 are not present in samples, the sample numbers for coli44 must be at least equal to the sample numbers for coli37, rendering the percentages of coli44-positive repeat samples 0.03% (4 per 15,439) instead of 0.2% (4 per 2,220) for finished water and 0.003% (1 per 30,508) instead of 0.006% (1 per 15,939) for distributed water.

Data on selected treatment plants (Figure 3.5) show that the incidence of total coliforms (coli37) in finished water was higher in dune supplies (means up to 0.75%), probably due to contamination of the open dune water collection canals and reservoirs by bird droppings, especially in cold winter periods. Temporary chlorination kept coliform numbers low in the finished water of treatment plant I1 during the cold periods of 1993, but was less adequate in 1994. The start of ozonation and GAC-filtration early in 1995 proved to be an effective alternative to temporary chlorination. The start of continuous chlorination in treatment plant I2 (0.04 mg/l residual after contact tank) is used to limit the numbers of coliforms in the finished water until dune water collection canals are covered. The relatively high number of coli37 in the finished water from the oxygenous ground water treatment plant (O1) was caused by only 1 positive sample in 1995 (which is also clear from the high overall detection limit ('det.lim' in the graph)). Coliforms were not found in any of the other samples from the ground water treatment plants.

Table 3.6 Microbiological drinking water quality in 1993, 1994 and 1995

Indicators of contamination*	**Percentage of positive samples** (and no. of samples)			
	Treatment plants		Distribution systems	
	National**	Selection***	National**	Selection***
	1994	1993-1995	1994	1993-1995
coli37	0.10 (15439)	0.22 (19306)	0.03 (30508)	1.23 (26746)
coli44	0.18 (2220)#	0.11 (18516)	0.006(15939)#	0.15 (26727)
FS	0 (?)	0.42 (2284)	0.24 (837)	1.24 (1140)
SSRC	0 (?)	1.70 (935)	0 (?)	0 (26)

Regrowth parameters*	**50-percentile of the annual geometric means** (and 90-percentile)			
	Treatment plants		Distribution systems	
	National	Selection	National	Selection
	1993-1995	1993-1995	1993-1995	1993-1995
HPC22	7 (40)	1.5 (5)	10 (40)	6 (24)
HPC37	0.2 (2)	0.2 (0.4)	1 (3)	0.5 (0.7)
Aer30@	1 (30)	0.1 (4)	3 (90)	1 (66)

* Abbreviations are explained in paragraph 3.3.1.

** Positive repeat samples in 1994 (from Versteegh, 1996) (percentage of total sample number).

*** Positive first samples (sample no. is total of 3 years).

$ Percentages and 50-percentiles are averaged, unweighed for e.g. annual production.

\# Some companies only report the number of samples that were analysed on thermotolerant coliforms (coli44) seperately (e.g. repeat samples), others correctly presume that coli44 are not present in samples that do not contain total coliforms (coli37). This accounts for the differences in sample numbers, affecting percentages.

@ For colony counts of *Aeromonas* bacteria the arithmetic mean in presented.

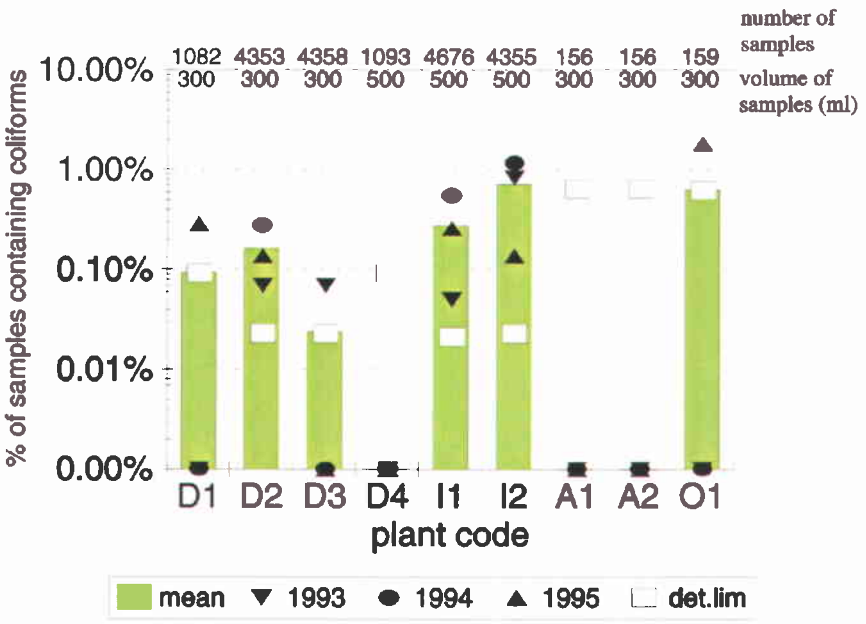


Figure 3.5 *Total coliforms in finished water in the selected supplies*

The percentage of coli37-positive samples in the selected distribution systems (Figure 3.6) was always higher than in the finished water. In the distribution systems of some treatment plants the mean percentages were relatively high (approx. 2 %). This may be an indication of a high frequency of small and temporary non-faecal contamination. Regrowth of coliforms in the distribution system however cannot be ruled out, as has been shown in the U.S. (Wieringa, 1985; Smith et al. 1990; Le Chevallier, 1990). The low percentage of positive samples in the distribution system of treatment plants D2 and D3 may be an effect of the suppression of regrowth due to the presence of a very low chlorine residual (0.05 mg/l) in large parts of the distribution system, especially in the distribution system of plant D3 (see figure 3.3). Large and/or persistent contamination very seldomly occurred, considering the low percentage of positive repeat samples (see Table 3.6: 0.03% of all (national) samples in 1994 = 10 samples).

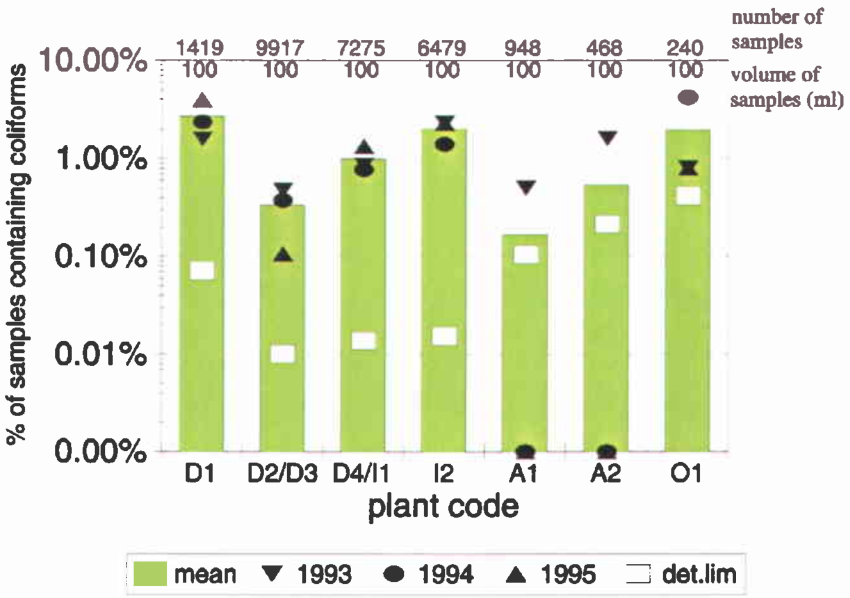


Figure 3.6 *Total coliforms in the distributed water in the selected supplies*

The incidence of thermotolerant coliforms (coli44) is shown in Figure 3.7. Highest values were observed in the finished water of the two dune water treatment plants. The figure also shows a clear decline from 1994 to 1995; percentages dropped below detection limits in both treatment plants (due to control measures described in paragraph 3.4.7). Treatment plant D3 was the only other treatment plant were coli44 were found in the finished water, however only in 1 sample (in 1994).

Coli44 have not been found in the finished water of the three ground water treatment plants (A1, A2 and O1) (as would be expected from treatment plants that use sources free from contamination). The sample frequency required (see Table 3.3) accounts for the high detection limits (1.9% per annum, 0.6% over a three year period). As is shown in Figure 3.8, coli44 were also not found in the distributed water, whereas these organisms were present in 0.06 to 0.4% of the samples from the distribution systems of the 6 surface water treatment plants. Due to the relatively low number of distribution systems that are evaluated in this study, these differences may be only coincidental.

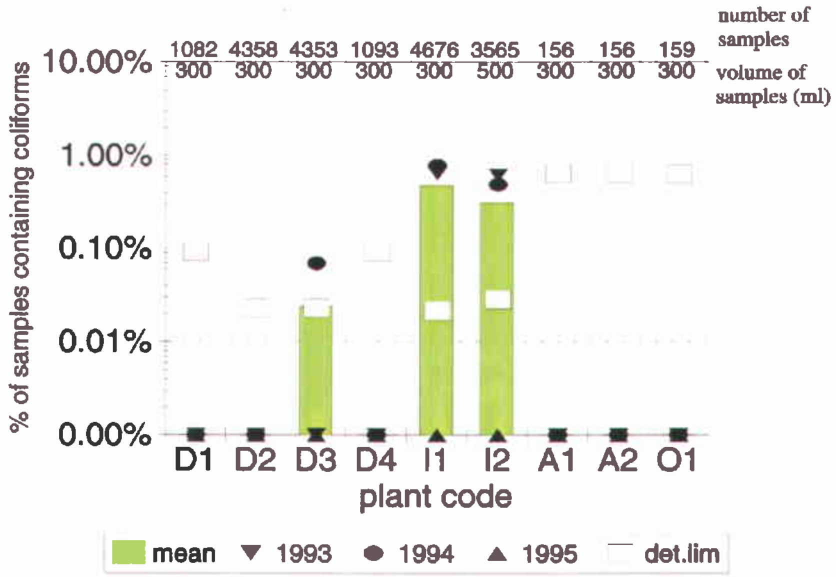


Figure 3.7 *Thermotolerant coliforms in finished water in the selected supplies*

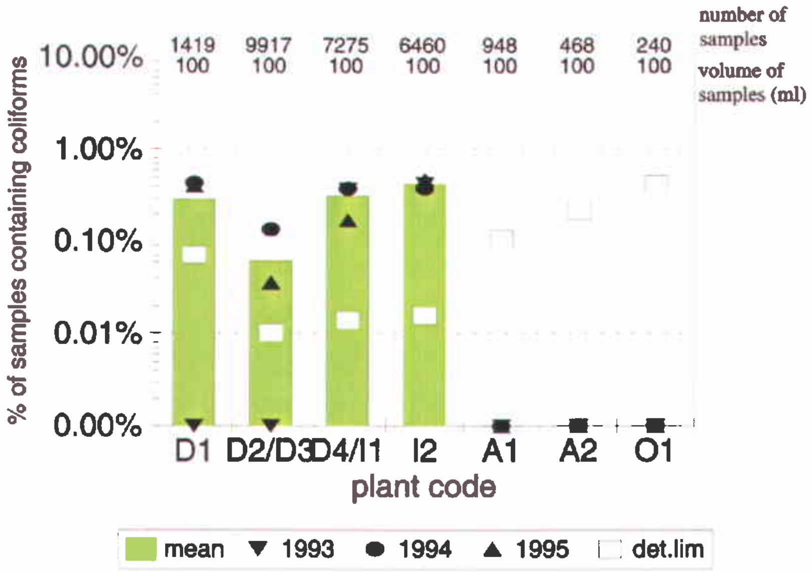


Figure 3.8 *Thermotolerant coliforms in the distributed water in the selected supplies*

These data may however also suggest that coli44 in the distributed water originate mainly from the treatment plants. Considering the low percentages of coli44 in the finished water of the direct treatment plants (D1-D4) this suggestion would imply that the organisms, for reasons yet unknown, are not well detected in the finished water.

One of the water supply companies participating in the project provided the actual numbers of coliforms found in all samples during the period 1993-1995. These data are shown in Figures 3.9 to 3.12.

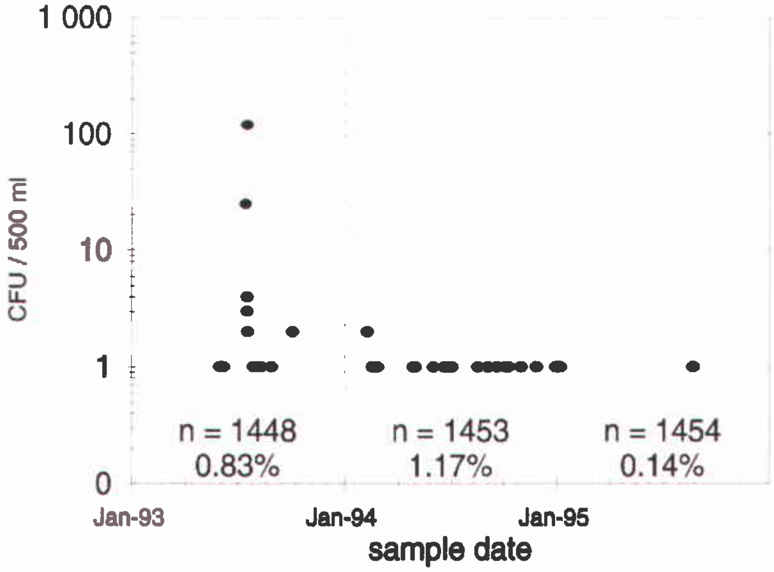


Figure 3.9 *Total coliforms in finished water in plant I2*

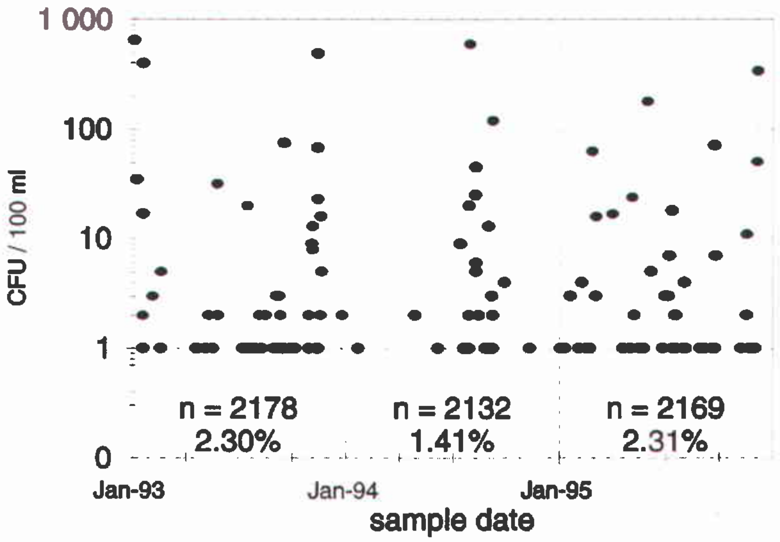


Figure 3.10 *Total coliforms indistributed water in plant I2*

Clearly, most of the positive samples (500 ml) of finished water contained only 1 and in some cases 2 CFU. In July 1993 there was a peak of greater than 110 CFU/500 ml, but none of these were thermotolerant (Figure 3.11). Since the start of polishing chlorination of the finished water in January 1995, the number of coli37 dropped and no coli44 have been found in the finished water. This chlorination does not seem to have any effect on coliform numbers in the distributed water (cf. Fig. 3.10), as would be expected for a free chlorine concentration after the contact tank of only 0.04 mg/l.

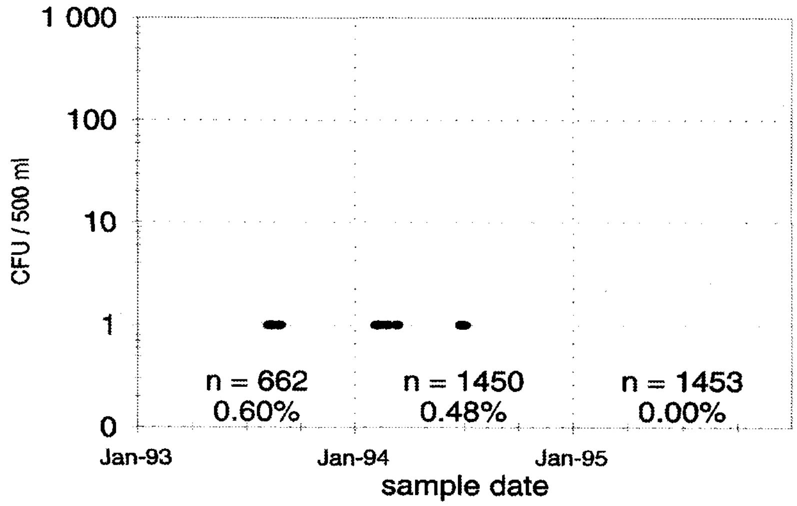


Figure 3.11 *Thermotolerant coliforms in finished water of plant I2*

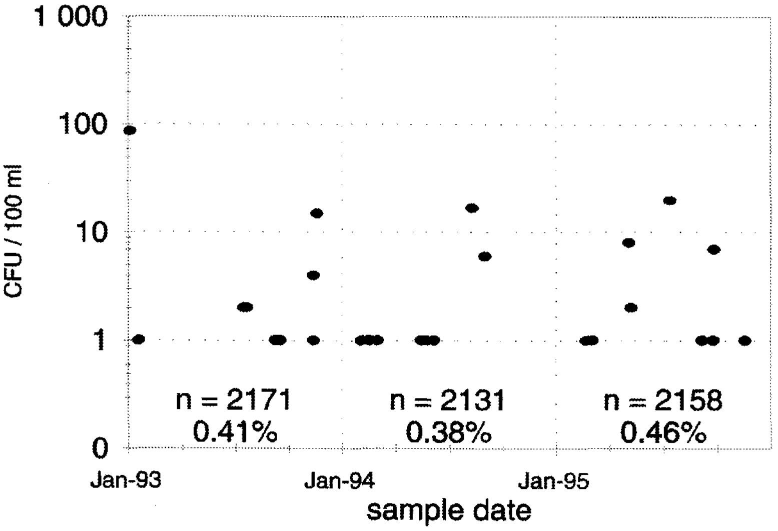


Figure 3.12 *Thermotolerant coliforms in ditributed water of plant I2*

There is no clear relationship between the seasons and the number of coliforms in the distributed water; peaks of high coli37 numbers (> 100 CFU/100 ml) occur in January 1993, November 1993, August/September 1994, June 1995 and December 1995. These peaks however do coincide with peaks of high coli44 numbers (> 10 CFU/100 ml) in three of these periods; January 1993, November 1993 and August/September 1994. Although the high numbers of coli44 and the coinciding occurence of high numbers of coli37 clearly indicate faecal contamination of the drinking water, numbers of coliform-positive repeat samples were very low, indicating that in most cases only small contamination events occurred. Furthermore, it has been standard procedure for the company to flush sample taps with only 250 ml of water before sampling. Contamination of taps and in-house plumbing will be detected using this method, implying that the mains may have been contaminated less frequently than coliform incidence indicates.

Procedures have now been adapted to the national procedure of flushing the tap until the sample water originates from the mains outside the building.

In Table 3.7 the frequency of bacterial species found on coliform plates by two water companies is shown. Species of other coliforms reported by water companies in the Netherlands are: *Enterobacter adecarboxylata*, other *Enterobacter* spp. and *Serratia* spp.. This table shows that *Enterobacter cloacae* and *Klebsiella oxytoca* were the predominant species in drinking water derived from surface water and *Citrobacter freundii* in drinking water derived from ground water. Because the bacteria are derived from colonies on plates before confirmation of identity at 37 or 44 EC, the non-coliform bacterium species *Aeromonas* is listed as well.

Table 3.7 Frequency of bacterial species identified from yellow colonies on plates for detecting total coliforms in drinking water (before confirmation of identity at 37 or 44 EC). From Van Lieverloo & Van der Kooij (1995b).

Organism		**Frequency of identified organisms**	
Genus name	Species name	2 surface water treatment plants total of 148 colonies 1977 - 1982	21 ground water treatment plants total of 91 colonies 1991-1993
Escherichia	*coli*	8%	11%
Citrobacter	*freundii*	8%	33%
Enterobacter	*cloacae*	27%	10%
	sakazakii	5%	8%
	agglomerans	5%	3%
	amnigenus	-	4%
	fergusoni	-	1%
Klebsiella	*pneumoniae*	11%	4%
	oxytoca	26%	3%
Proteus	*mirabilis*	-	1%
Serratia	*fonticola*	-	1%
	liquefaciens	0.7%	-
Kluyvera	spp.	-	1%
Aeromonas	spp.	10%	3%
Acinetobacter	spp.	-	4%

3.4.8 Faecal streptococci and spores of sulphite-reducing clostridia

Legislation requires low sample frequencies for faecal streptococci (FS) and spores of sulphite-reducing clostridia (SSRC) in finished water, resulting in relatively high detection limits (1.9% per year and 0.6% for the three year period, see Table 3.3).

In 1994, FS and SSRC were not found in repeat samples of finished water of treatment plants in the Netherlands and were found in only 2 repeat samples of distributed water FS (see Table 3.6).

Graphs of the percentage incidence therefore do not present a clear image of water quality. Data for surface water supplies are shown in Tables 3.8 and 3.9. In finished ground water supplies FS are not included in routine monitoring and have not been found in repeat samples of finished and distributed water of treatment plant A1, A2 and O2 during the three year period.

Table 3.8 Faecal streptococci in finished and distributed water (1993-1995)

Finished water			**Distributed water**		
Plant code	**Total no. samples**	**Incidence (%)**	**Plant code**	**Total no. samples**	**Incidence (%)**
D1	159	1 (0.63%)	D1	?	0
D2	156	0	D2/D3	854*	1 (0.12%)
D3	192	2 (1.0%)			
D4	162	0	D4/I1	90	3 (3.3%)
I1	522	2 (0.38%)**			
I2	1093	5 (0.46%)#	I2	196	3 (1.5%)

* Including samples collected after mains construction and mains repair.
** Not found in 1995 after the start of ozonation and GAC-filtration.
\# Not found in 1995 after start of chlorination (0.04 mg/l).

Table 3.9 Spores of sulphite-reducing clostridia in finished water (1993-1995)

Plant code	**Total no. samples**	**Incidence (%)**	**1993**	**1994**	**1995**
D1	159	0			
D2	168	13 (7.7%)		4	9
D3	162	3 (1.9%)	1	1	1
D4	117	0			
I1	171	0			
I2	158	1 (0.63%)			1

The incidence of SSRC in the finished water of treatment plant D2 is relatively high and is currently being investigated by the water company in cooperation with Kiwa. The incidence of FS is probably overestimated due to erroneous confirmation of identitity in the analysis method.

3.4.9 Heterotrophic colony counts 22°C and 37°C

The annual geometric means of HPC in finished water and distributed water are low compared to legal directives. Graphs with the cumulative frequency distribution of annual geometric means of 3 years (1993-1995) are presented in Annex 3 (national data). These graphs show that annual geometric means both for heterotrophic colony counts at 22 EC (HPC22) and for heterotrophic colony counts at 37 EC (HPC37) only exceed the maximum allowable levels of 100 CFU/ml and 10 CFU/ml respectively (see fold-out in Annex 5) in 2% to 3% of the treatment plants and distribution systems. Data presented in Figure 3.13 to 3.16 (from selected treatment plants) show more details on the variation of the HPC values. In these graphs data of the 3 years (1993-1995) are aggregated. Although maximum HPC values may exceed 1000 CFU/ml, geometric means in the distribution system in most cases were about 10-fold lower than maximum allowable levels. HPC22 values are highest in finished as well as in distributed water of ground water treatment plants A2 and O1 and lowest in three surface water treatment plants that disinfect finished water (D1 to D3), except for water of treatment plant D4.

HPC37 values are lowest in finished and distributed water of treatment plants A1 and O1, although neither of these chemically disinfect the finished water. Maxima of both HPC22 and HPC37 values are lowest in the finished and distributed water of treatment plant D1, disinfecting the finished water with ClO_2.

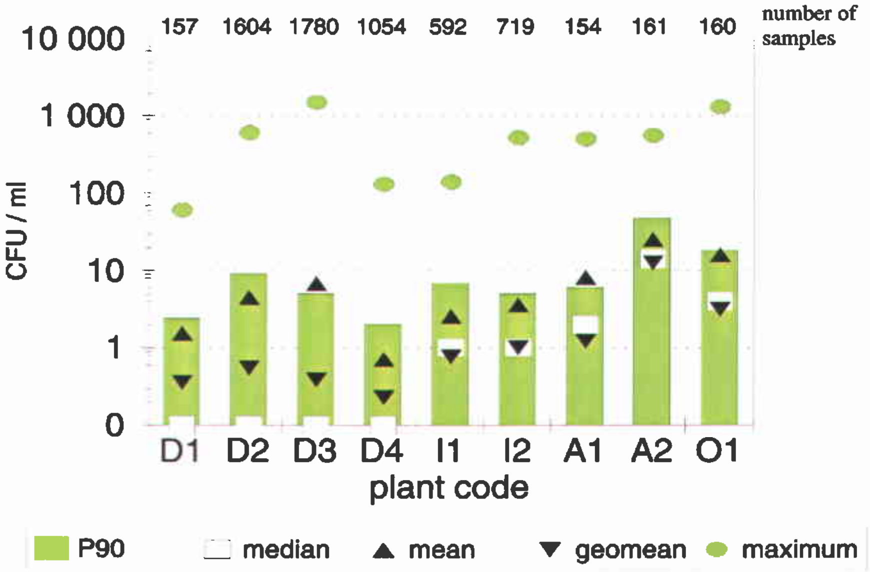


Figure 3.13 *HPC22 in finished water (1993-1995)*

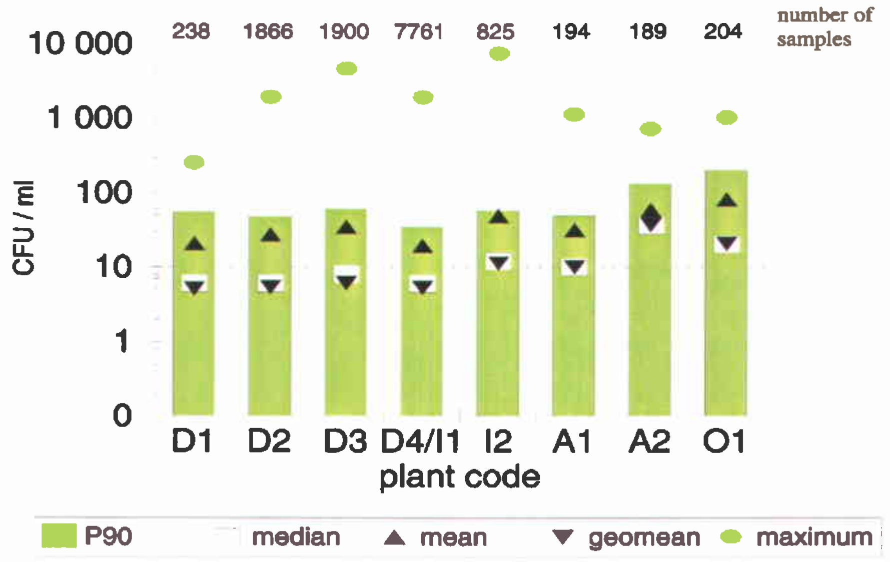


Figure 3.14 *HPC22 in distributed water (1993-1995)*

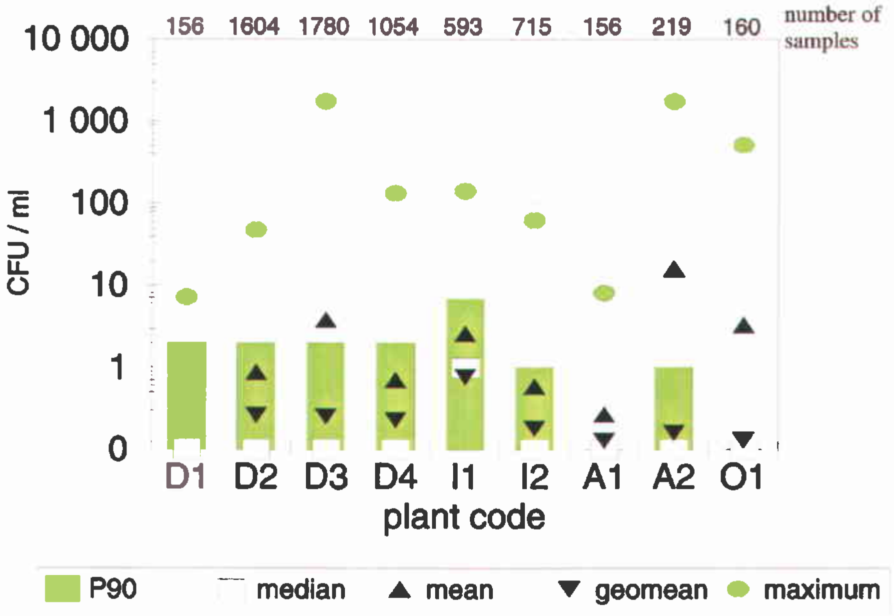


Figure 3.15 *HPC37 in finished water (1993-1995)*

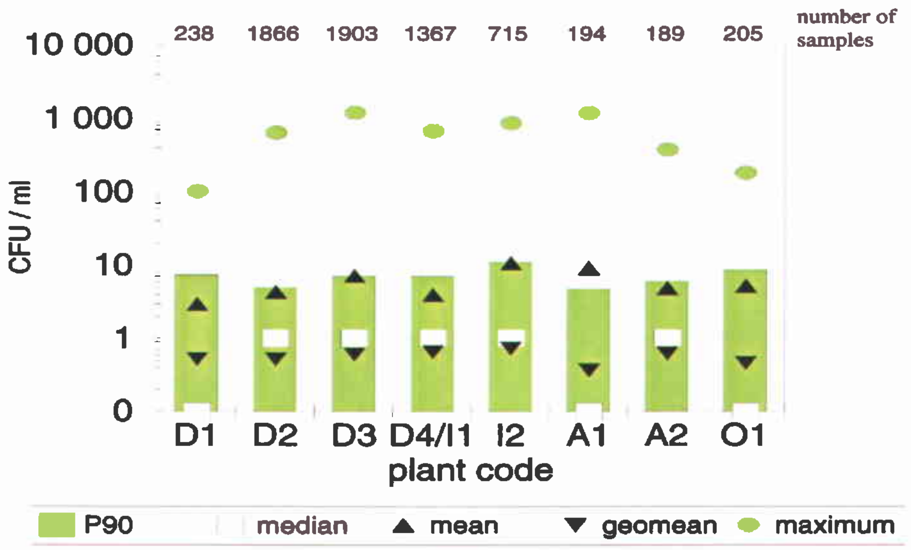


Figure 3.16 *HPC37 in distributed water (1993-1995)*

3.4.10 Aeromonas colony count 30 °C

A national survey in 1989 revealed the presence of high numbers of *Aeromonas* bacteria in drinking water (see paragraph 4.2.2.) and maximum allowable numbers were set in Inspectorate directives. Annual median numbers in finished water from treatment plants should not exceed 20 per 100 ml, the annual 90-percentile in the distribution system should not exceed 200 per 100 ml. Data from the selected treatment plants (Figure 3.17) show that *Aeromonas* counts in the finished water did not exceed guideline values in 1993-1995 (data aggregated). Counts were relatively high in the finished water of the treatment plants using slow sand filters (D4, I1 and I2). *Aeromonas* bacteria probably grow on the remains of dead bacteria and invertebrates in old biofilm (in filters) and in sediments (in the distribution system).

Observations have shown that aeromonads multiply on biomass accumulated in the effluent side (support layers and drains) of slow sand filter systems. Flushing of the drains resulted in lower Aeromonas numbers in the effluent (Kors, 1992). Numbers are very low in treatment plants D1 and O1. Treatment plant O1 uses aerobic ground water that only needs a pH adjustment (lime stone filtration) and aeration and therefore biofilm growth in the treatment plant is very limited. In the surface water treatment plant D1 rapid sand filtration is followed by two GAC-filters, providing enough surface for biofilm formation. Disinfection with ClO_2 however proves to be effective in controlling the numbers of aeromonads in the effluent of these filters.

As shown in Figure 3.18, the 90-percentiles in the distribution systems of treatment plant D1, D4/I1 and A2 exceed the guideline value of 200 per 100 ml. This clearly is due to extensive regrowth in the distribution systems of supplies D1 and A2. In the distribution system of treatment plants D4/I1, regrowth is only partially contributing to these numbers, considering the numbers of *Aeromonas* in the finished water. The numbers in finished water of these treatment plants have decreased considerably in the past years, due to application of ozonation and GAC filtration prior to slow sand filtration (in plant D4 in 1992, in plant I1 in 1995).

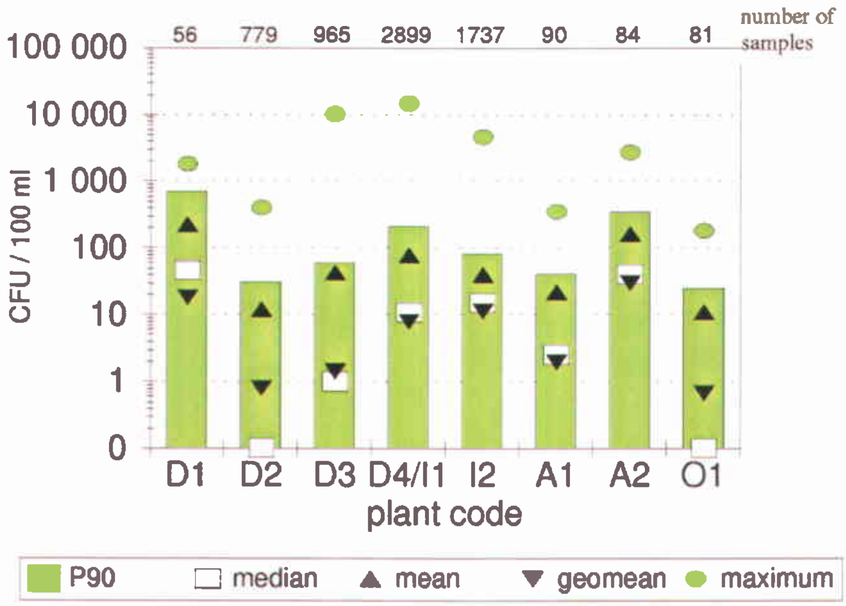


Figure 3.17 *Aeromonas in finished water of the selected supplies (1993-1995)*

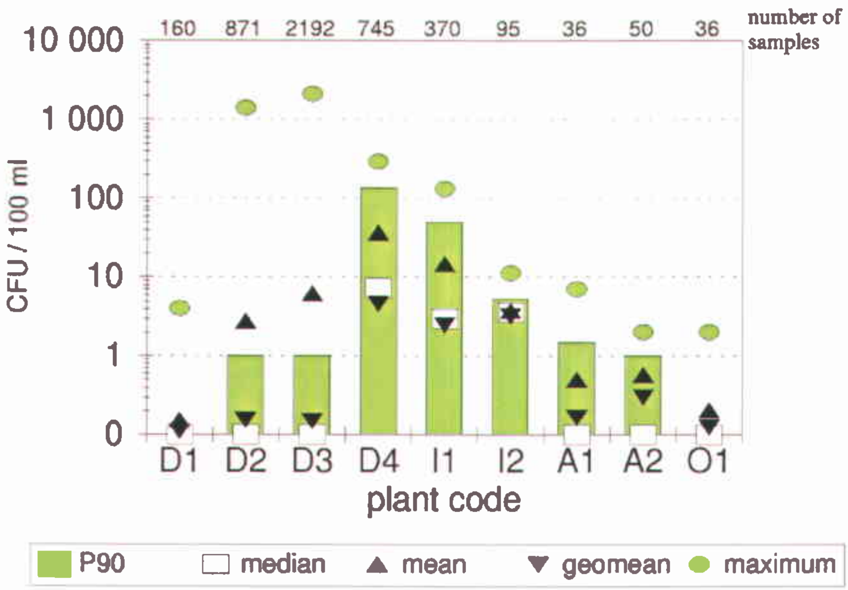


Figure 3.18 *Aeromonas in distributed water of the selected supplies(1993-1995)*

Although the numbers of *Aeromonas* are sometimes relatively high, compared to the directives, it must be emphasized that water supply companies usually collect most of the samples at times and locations were the regrowth of these organisms is most pronounced.

In Figure 3.19 the seasonal effects on *Aeromonas* numbers in distributed water are clearly shown for a representative distribution system. Numbers are highest in late summer and early fall, when water temperatures are highest.

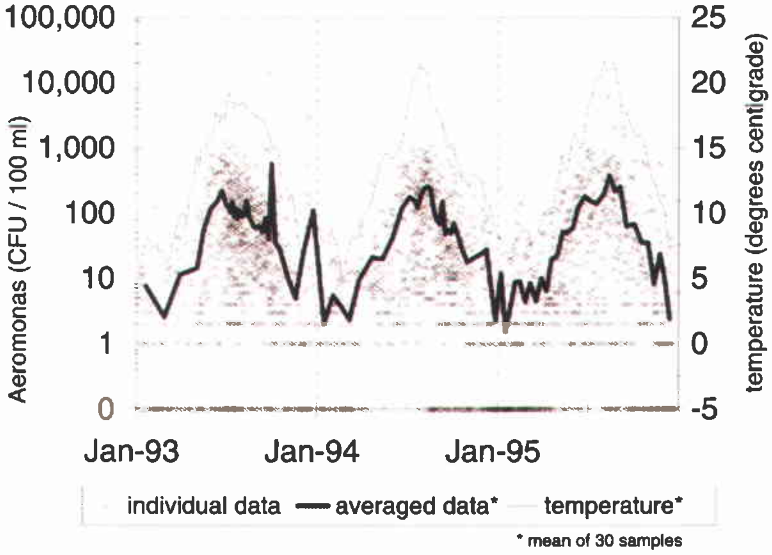


Figure 3.19 *Aeromonas in distributed water of plants D4 + I1*

In the national database for drinking water quality only the annual minimum, arithmetic mean and maximum counts of *Aeromonas* for a treatment plant or distribution area are entered (percentiles of the arithmetic means are shown in Table 3.6) These data cannot be directly compared to the Inspectorate Directives. However, the graphs of the selected treatment plants (Figure 3.17 and 3.18) indicate that the median is approx. 5 times lower than the mean (finished water) and that the 90-percentile is approx. 3 times higher than the mean (distributed water). Assuming that these factors also apply nationally, the maximum allowable mean in finished water would be 100 CFU per 100 ml, the maximum allowable mean in distributed water would be 70 per 100 ml. The graphs with cumulative frequency distributions of the national data in Annex 3 show that approx. 3% of all treatment plants and 12% of all distribution systems exceed these levels. Results of the national survey of *Aeromonas* in drinking water in 1980 show that the median values of the *Aeromonas* counts in treated water were higher than 20 CFU/100 ml (guideline value) in 17% of the plants. In 18% of the distribution systems the 90 percentile value was higher than the guideline value (200 CFU/100 ml) (Baggelaar et al 1992). The drop of the percentage of treatment plants with Aeromonas counts exceeding the guideline value suggests that finished water has improved since 1989. Comparison of the numbers in distributed water is complicated as a result of intensified monitoring in areas with regrowth of aeromonads. To enable detection of trends, results of random sampling for periodic water quality control and results of investigations in target areas should be reported and evaluated separately.

3.4.11 HPC values and Aeromonas in service reservoirs

Data on HPC22, HPC37 and *Aeromonas* for service reservoirs are shown in Figures 3.20 to 3.22. These numbers are between those in finished water and in distributed water, depending on the location in the distribution system.

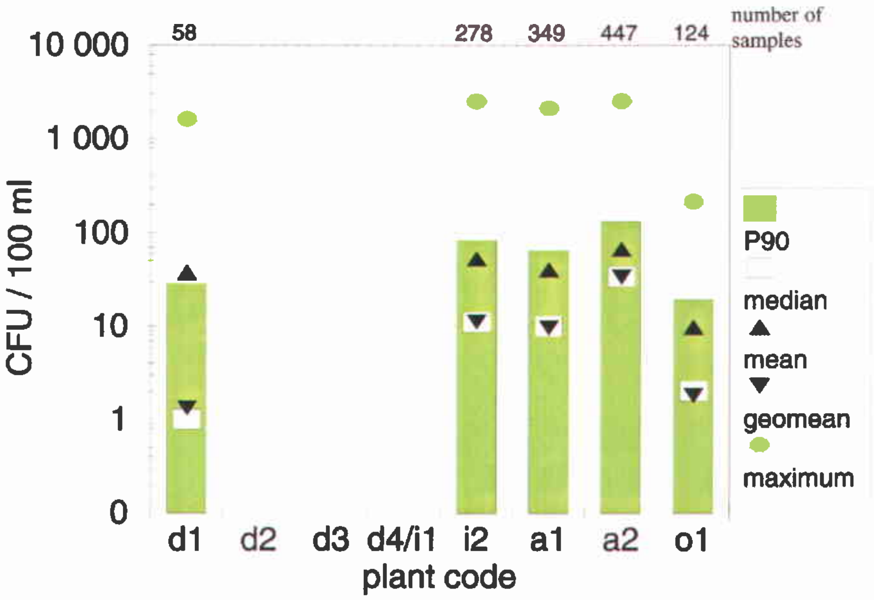


Figure 3.20 *HPC22 in distribution reservoirs of selected supplies (1993-1995)*

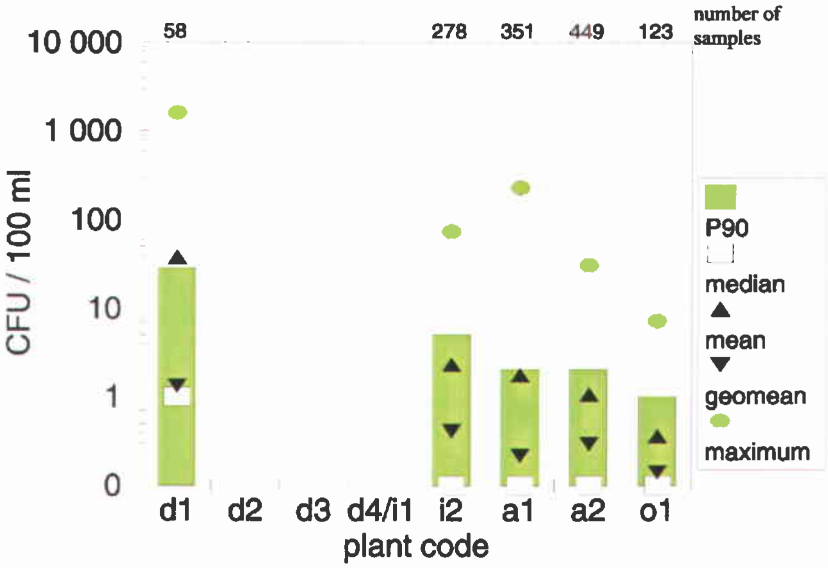


Figure 3.21 *HPC37 in distribution reservoirs of selected supplies (1993-1995)*

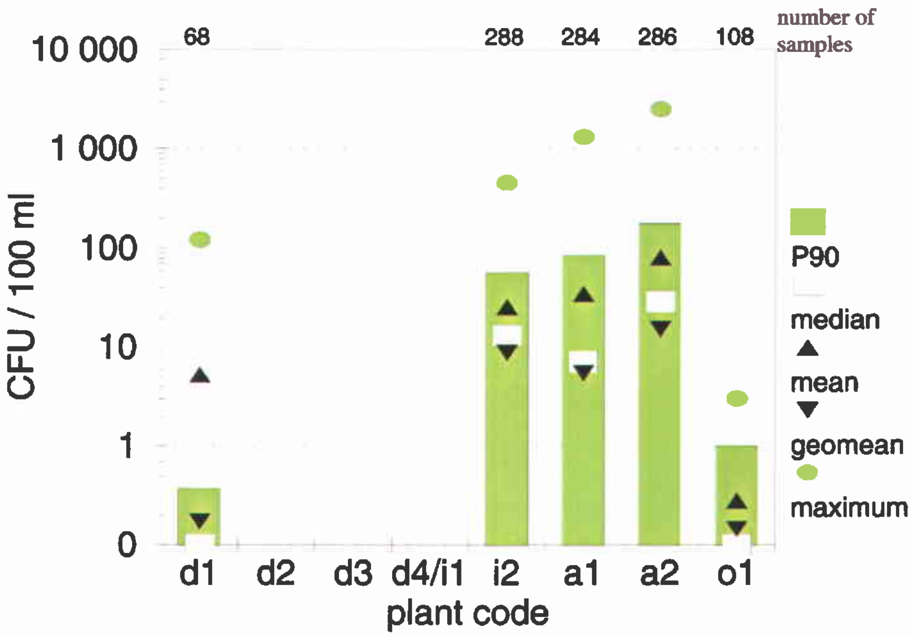


Figure 3.22 *Aeromonas in distribution reservoirs of selected supplies (1993-1995)*

3.4.12 Water quality after mains construction and repair

Water quality is intensively monitored after mains construction and mains repair (see paragraph 3.2.1 and paragraph 3.2.2). Bacteriological water quality is not in compliance with company directives in approx. 20% of the samples directly after mains activities. These directives are stringent and may differ between companies. An example of company directives is presented in Table 3.10.

Table 3.10 Company directives of 4 water supplies for drinking water quality after mains construction and mains repair (from Bakker, 1993)

Variable*	Company a	Company b	Company c	Company d
coli37	< 1/100 ml	< 1/100 ml	< 1/100 ml	< 1/100 ml
coli44	< 1/100 ml**	-	-	-
FS	< 1/100 ml**	< 1/100 ml**	-	-
SSRC	-	< 1/100 ml**	-	-
HPC22	< 250/ml	-	-	< 200/ml
HPC37	< 25/ml	< 50/ml	< 100/ml	-

* Abbreviations are explained in paragraph 3.3.1.
** Only determined in repeat samples.
\- Not determined.

The main failures following construction and repair are bacteriological, other failures are due to diminished aesthetic quality of the water (Table 3.11). Clearly, in only a few percent of cases, coliforms are found in drinking water after mains repair or mains construction. Indicators of faecal contamination are seldomly found, the bacteriological failures in most cases are due to high HPC values. Surprisingly, failure rates are found to be similar in companies with differing company directives. This phenomenon currently is an object of further research in the Netherlands.

Table 3.11 Failure to comply to company directives for water quality after mains construction and repair

Company and year		**Number of mains**		**Reasons for first failure***		
		Tested total	Instantly approved*	coli37 coli44 FS	HPC22 HPC37	other*
New mains						
2	1994	835	646 (77%)	7 (0.8%)	182 (21%)	-
	1995	912	707 (78%)	10 (1.1%)	195 (21%)	-
	1996	866	723 (83%)	1 (0.1%)	142 (16%)	-
3	1995	942	723 (77%)	38 (4.0%)	145 (20%)	36 (3.8%)
	1996	798	645 (81%)	25 (3.1%)	108 (14%)	20 (2.5%)
Repair						
2	1994	282	229 (81%)			
	1995	359	295 (72%)			
	1996	329	288 (88%)			
New mains and repair*						
5	1993	4563		182 (4.0%)	1597 (35%)	91 (2%)
	1994	3513		105 (3.0%)	386 (11%)	140 (4%)
	1995	3907		195 (5.0%)	547 (14%)	234 (6%)

* When 2 succesive samples (20 to 24 hour apart) comply, the mains are approved. Water samples are tested for (thermotolerant) coliforms, faecal streptococci, heterotrophic colony counts (22 and 37 EC) and usually also for visual particles and odours.

** For company 5 the number of samples tested are presented (not the number of mains) and the percentages of failures (repeat samples, not first failures).

3.4.13 Invertebrates

Asellids and oligochaete worms are invertebrates that can colonise distribution systems, in some systems abundantly. These organisms, which are visible to the naked eye, cause most of the consumer complaints about invertebrates. Although the number of complaints is low, in 1988 and 1989 they led to negative publicity about drinking water and even to questions in parliament. These incidents occurred in drinking water distribution systems supplied by groundwater treatment plants.

At the time there was little quantitative data available about invertebrates in this type of drinking water. From 1993 to 1995 a national survey was conducted with 17 water supply companies to assess the numbers and types of organisms in 36 distribution systems, 33 of which are supplied by groundwater-derived drinking water. Drinking water samples were collected by filtering 200 l from treatment plants and home-taps through a ι 47 mm 10 :m mesh plankton filter. Water was flushed out of distribution mains (ι 100 mm) via hydrants with a special top-piece, at a water flow in the mains of 1.0 m/s. The water (4000 l) was filtered through 100 :m and 500 :m mesh plankton filters. In Figure 3.23 an overview is shown of the numbers found (Van Lieverloo *et al.* 1995a, 1997a, 1997b).

Types and numbers of invertebrates in finished water and distribution systems as observed in the Netherlands resemble those reported in other countries. The numbers of nematodes in finished water are relatively low in the Netherlands, probably due to the multiple barrier treatment of surface water.

Drinking water

Protozoans and rotifers predominate in drinking water from treatment plants and homes (P90's of 150 to 400/m^3, the numbers in home-samples being slightly higher. The mean number of protozoans is relatively high due to some samples containing extreme numbers (> 100,000/m^3). Nematodes and copepods are also frequently found in drinking water (P90 of approx. 20/m^3). Asellids and snails were never found in drinking water samples, midge fly larvae only in 2 samples from home-taps. Mean invertebrate biomass concentrations varied from 0.003 to 5 mg/m^3 (based on the estimated mean biomass per organism).

Flushing water

The water flushed from the distribution mains undoubtedly contained high numbers of protozoans and rotifers, but these organisms were not retained in the 100 :m filters and therefore were not enumerated. Due to the high flow in the mains, larger organisms were abundantly found in the hydrant samples, cladocerans and copepods dominating the numbers (P90's of 600 to 750/m^3). Oligochaete worms, water mites and asellids were also found in high numbers (P90's of 100 to 250/m^3). Turbellarians and nematodes were frequently found. Midge fly larvae were found in a number of distribution systems, but their numbers are underestimated because they glue their sediment cocoons to the mains wall and are only partly flushed out at 1.0 m/s. Although asellids were less dominant in numbers (P90 of 100/m^3, max. 1,500/m^3) on average they formed 86% of the biomass (= 365 mg/m^3 w.w.) in the samples, oligochaete worms forming most of the remaining biomass (12%). Mean invertebrate biomass concentrations varied from 1 to over 2000 mg/m^3.

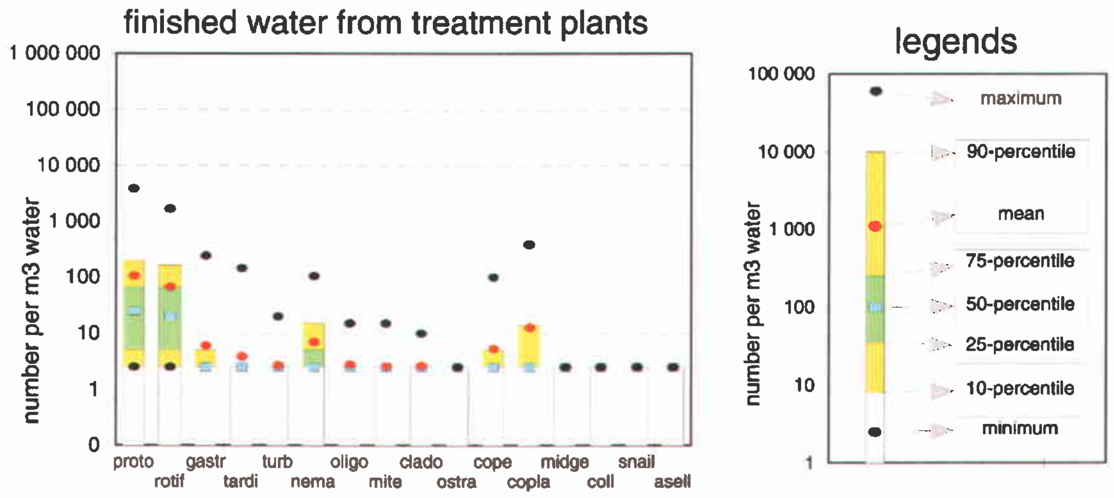
3.5 Conclusions

Disinfectants, taste and odour and disinfection by-products

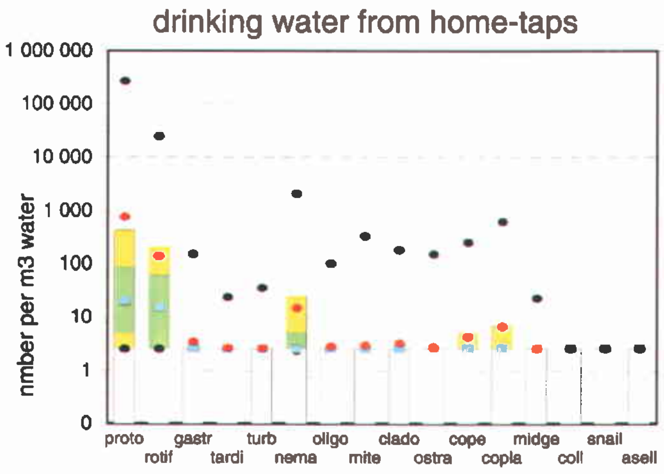
In the Netherlands a disinfectant is added to only 22% of the finished water prior to distribution. Disinfectant residuals are absent in most of these distribution systems and low in some (# 0.05 mg/l). Numbers of taste and odour complaints usually range from 2 to 12 per 100,000 inhabitants per annum. Disinfection by-products are absent in most types of drinking water and their concentrations are below levels of negligible risk (10^{-6}, lifetime exposure) when finished water is disinfected.

Contamination of drinking water

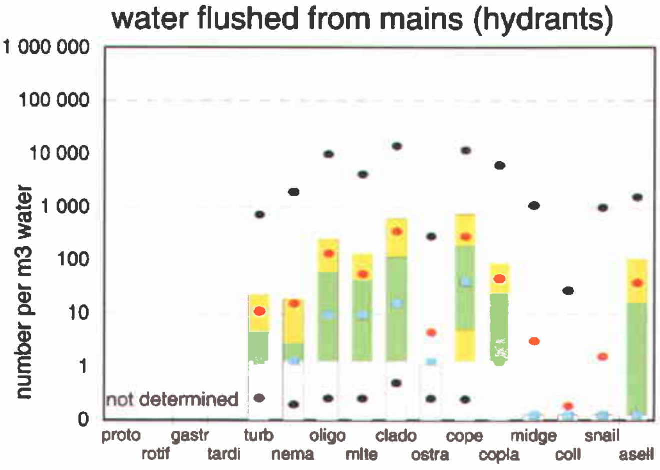
Thermotolerant coliforms are found in 0.11 % of finished water samples and in 0.15% of distributed drinking water samples (data from 9 selected treatment plants). The number of positive repeat samples is very low (0.03% in finished water, 0.003% in distributed water, national data). Incidence of total coliforms is higher, but positive repeat samples are also low (0.10% in finished water, 0.03% in distributed water).


finished water from treatment plants

legends


drinking water from home-taps

proto = protozoans (Protista)
rotif = rotiferans (Rotifera)
gastr = gastrotrichans (Gastrotricha)
tardi = tardigradans (Tardigrada)
nema = nematodes (Nematoda)
oligo = oligochaetes (Oligochaeta)
mite = water mites (Actinedida)
clado = cladocerans (Cladocera)
ostra = ostracods (Ostracoda)
cope = copepods (Copepoda)
copla = copepod larvae
midge = midge fly larvae (Chironomidae)
coll = collembolans (Collembola)
snail = snails (Gastropoda)
asell = asellids (Asellidae, Isopoda)


water flushed from mains (hydrants)

sample numbers

finished water:	261
tap water:	1297
flushing water:	1302

Figure 3.23 *Invertebrates in drinking water (det. Limit = 5/m^3) and flushing water (det. Limit =0.25/m^3 for midges, collembolla, snails and asellids,2.5/m^3 for others)*

Incidents of microbiological contamination are effectively prevented by (i), using multiple barriers for surface water sources, by (ii) preventing the contamination of boreholes for ground water sources and by (iii) preventing recontamination in the distribution system by good engineering practices. An intensive monitoring programme aims to detect contamination as soon as possible. In the past decades and the past 10 years especially, hygienic procedures for construction and repair of mains have been introduced and implemented. A relatively new topic is the prevention of backflow via hydrants, although some water supply companies have long enforced very strict procedures for the use of these for fire fighting drills and municipal irrigation.

Regrowth

Regrowth of heterotrophs is limited and guideline values for annual geometric means of HPC22 (100 CFU/ml) and HPC37 (10 CFU/ml) are exceeded in only 2% to 3% of the 310 distribution area's of the 249 treatment plants in the period of 1993-1995. Numbers of *Aeromonas* bacteria exceed the guideline values (annual median 20 CFU/100 ml) in 3% of treatment plants. The guideline values for numbers of *Aeromonas* bacteria in distributed water (annual 90-percentile 200 CFU/100 ml) are exceded in 12% of all distribution area's. Compared to HPC22 and HPC37, numbers of *Aeromonas* bacteria in distributed water however are low, numbers rarely exceding 1000 CFU/100 ml = 10 CFU/ml.

Drinking water from the tap usually contains small invertebrates invisible to the naked eye in numbers that are fairly comparable to those reported in other countries (means of 200 to 1000 per m^3). Large invertebrates (usually > 2 mm) like asellids (mean $35/m^3$) and oligochaete worms ($135/m^3$) are present in water flushed from the mains in numbers that also are comparable to those in other countries.

4 Biological stability

4.1 Multiplication of micro-organisms in distribution systems

4.1.1 Disadvantages of regrowth

Treated water entering the distribution system is not sterile and always contains compounds that may serve as sources of carbon and/or energy for micro-organisms. Depending of the concentration and nature of such compounds, and the conditions in the distribution system (viz. water temperature, disinfectant residual, residence time), multiplication of micro-organisms may occur in drinking water during transportation, storage and distribution. Such multiplication (regrowth) may have a negative impact on water quality. The main disadvantages potentially include:

- increase of the concentration of opportunistic pathogens, e.g. *Aeromonas, Pseudomonas, Flavobacterium, Mycobacterium and Legionella*. Such bacteria may infect immuno-compromised persons or other people with a reduced resistance to infectious micro-organisms. *Legionella* and *Mycobacterium* spp. can multiply in warm water plumbing systems and are transmitted via aerosols of water containing these organisms (Tobin et al. 1980; Von Reyn et al. 1994);
- increase of numbers of coliforms resulting in non compliance with water quality criteria (Geldreich, 1987; LeChevallier, 1990);
- increase of heterotrophic plate count (HPC) values;
- formation of taste and odour compounds by certain types of micro-organisms. Actinomycetes may produce compounds like geosmin and/or isoborneol. At low

oxygen levels methylsulfides can be produced from accumulating biomass (Krasner et al. 1989);

- the development of a population of invertebrates, some of which are visible to the naked eye, e.g. *Asellus aquaticus* (Levy et al. 1986; Van Lieverloo et al. 1994);
- degradation of pipe materials. Degradation of polyisoprene rubber sealing rings in pipe connections can result in leakage (Leeflang, 1968). Microbial processes can also enhance corrosion of cast iron and steel pipes (Lee et al. 1995), resulting in red water problems (Lee et al. 1980) and increased friction resistance;
- fouling of water meters, increasing the maintenance frequency.

Experiences in the Netherlands with a few of these aspects will be described in some more detail below.

4.1.2 Biofilm formation

Oligotrophic bacteria present in the aquatic environment can utilise trace amounts of compounds serving as a source of energy. Heterotrophic bacteria isolated from tap water have substrate saturation constants (K_s, concentration at which the growth rate is half of the maximum growth rate) as low as a few µg C/l. Mixtures of organic compounds with individual substrate concentrations below 0.1 µg C/l stimulate the growth of these micro-organisms (Van der Kooij et al. 1982, 1988). Bacteria suspended in drinking water are washed out of the system, but those growing attached to the walls of pipes and reservoirs remain present causing the formation of biofilms. Bacteria multiplying in biofilms are released into the water phase resulting in increased colony counts. Sloughing of biofilm material may contribute to sediment accumulation.

The total number of bacteria on the pipe wall typically ranges from 10^6 to 10^8 cells/cm^2 (Pedersen, 1990). Total cell numbers in treated water range from 10^4 to 5 x 10^5 cells/ml (Sibille et al. 1997; Prévost et al. 1998), but values as high as 10^6/ml have been reported (Brazos and O'Connor, 1996). Numbers of culturable bacteria on pipe surfaces generally are considerably lower than the total cell counts, ranging from 100 to 10^7 CFU/cm^2 depending on material type, disinfectant residual but also cultivation method (Nagy and Olson, 1985; Paquin et al. 1992; LeChevallier et al. 1990). HPC values (R2A medium) on the surface of PVC pipes in unchlorinated supplies in the Netherlands were between 500 and 5 x 10^4 CFU/cm^2. ATP concentrations on these pipe segments were 50 to 5000 pg/cm^2, from which it can be estimated that the total numbers of active cells were between 3 x 10^6 and 3 x 10^8 cells/cm^2 (unpublished results).

Invertebrates and other organisms feed on the biomass on the pipe wall and in sediments. Therefore a relationship is expected between the level of bacterial regrowth and invertebrates. The concentration of protozoa was found to increase at bacterial densities greater than 5 x 10^7 cells/l (Servais et al. 1995).

Biofilm formation in distribution systems is affected by the nature of the materials in contact with drinking water during distribution. Pederson (1990) did not observe any difference in biofilm formation between PVC and stainless steel pipes, respectively. However, corroding cast iron appears to enhance biofilm formation both by protecting the micro-organisms from disinfectants, and by providing additional food sources for bacteria (LeChevallier et al, 1993; Camper et al. 1999). Certain plastic materials and also natural materials such as wood and rubber release growth-promoting substances that can stimulate biofilm formation (Colbourne and Brown, 1979; Schoenen and Schöler, 1983; Kerr et al. 1999).

4.1.3 Prevention of regrowth

Maintaining a disinfectant residual during distribution is the most common measure used to control regrowth. The disadvantages and limitations have been discussed in Chapter 2. Bacteria present in biofilms are considerably less susceptible to disinfectants than bacteria in the water phase (LeChevallier et al. 1988). Consequently prevention of regrowth with a chlorine residual is difficult to achieve. However, the use of monochloramine appears to be more effective, because this disinfectant, with its lesser reactivity with pipe materials and organic compounds present in water, penetrates further into biofilms (LeChevallier et al. 1988). Disinfectants are relatively ineffective against invertebrates. Rook (1970) found only a slight effect for suppression of oligochaetes at concentrations of 0.3 mg/l free chlorine, but 2 mg/l monochloramine seemed to be effective. At present, monochloramine is not used in the Netherlands.

An alternative approach for limiting regrowth is the removal of biodegradable compounds from water during treatment, viz. the distribution of biologically stable drinking water. Achieving biostable drinking water requires the use of biological processes in water treatment for nutrient removal, i.e. sand filtration or granular activated carbon filtration (Rittmann and Snoeyink, 1984). Membrane filtration techniques also are effective in removing biodegradable compounds from the water (Sibille et al. 1997).

Measures applied in the distribution system to reduce the effects of regrowth, such as colony count reduction and removal of sediments and invertebrates, include flushing and/or pigging of the pipes. These techniques can have some local effects during a short period of time, but are labour intensive and may cause inconvenience to the consumer (LeChevallier et al. 1987; Hiemstra, 1992; Van Lieverloo et al. 1997). Selection of distribution system materials that do not enhance regrowth and prevention of sediment accumulation are important for controlling regrowth.

4.1.4 Assessment of biostability

Methods for assessing the potential of water to promote microbial growth are needed in order to evaluate how growth substrates are removed during water treatment processes. Chemical methods are available for determining the concentration of (groups of) organic compounds in drinking water. Also the total concentration of dissolved organic compounds (DOC) can be measured accurately. However, chemical methods are still not suitable for determining the growth potential of water for heterotrophic microorganisms, because: (i), it is difficult to identify and subsequently quantify all types of organic compounds present in drinking water and (ii), it is not possible to predict the impact of certain compounds on microbial growth. Therefore, the use of a bioassay is needed to assess the growth-promoting properties of water. In the past two decades a series of methods has become available, which can be divided into two groups based on different main principles:

I: methods determining the reduction of the concentration of organic compounds in water under defined test conditions;
II: methods based on assessing the formation of biomass under defined test conditions.

For both types of methods static (batch) tests and dynamic (flow-through column) test have been developed. The most frequently applied methods are listed in Table 4.1, which also includes reference values for biostability related to these methods. Huck (1990) has reviewed a number of these methods. The methods developed and applied in the Netherlands are described in more detail in the following paragraphs.

Table 4.1 includes reference values for biostability, based on the involved parameter. However, biostability is difficult to define quantitatively. The rate of substrate utilisation not only depends on the concentration but also on the nature of the nutrients. Furthermore, regrowth is affected by factors such as temperature, residence time, flow regime and also the type and residual concentration of the disinfectant. The supply of compounds potentially serving as sources of energy for micro-organisms is regarded as one of the most critical factors for regrowth.

Materials may release growth substrates into drinking water and therefore testing methods are used in various countries to assess the growth-promoting properties of materials to be used in contact with drinking water. These methods are based on different principles, for instance oxygen consumption (Mean Dissolved Oxygen Difference, MDOD) as used in the UK (Colbourne and Brown, 1979), slime production (Germany) (Schoenen and Schöler, 1983) and the biofilm formation potential (Van der Kooij et al. 1994). The various methods will be compared in an international investigation financially supported by the European Union.

4.2 Regrowth problems

4.2.1 Water supply in the Netherlands: no disinfectant residual

Two thirds of drinking water in the Netherlands originates from ground water and is treated and distributed without a chemical disinfectant. One third originates from surface water (SW). In these SW supplies multiple barriers are used to remove undesirable micro-organisms and other contaminants. Water from rivers and lakes is either treated after storage in open reservoirs or after soil passage (dune filtration, river-bank filtration). Treatment of water after storage in open reservoirs consists of oxidation/disinfection, coagulation/sedimentation and one or more filtration stages, usually including GAC filtration. A low concentration of a disinfectant (chlorine or chlorine dioxide) is added to this water to reduce the HPC values of bacteria originating from GAC filter beds. This low disinfectant residual disappears during distribution. Treatment of surface water after soil passage usually includes rapid sand filtration, in a few cases followed by slow sand filtration. This water type is distributed without disinfectant residual. Hence, biological processes play an essential role in water treatment in the Netherlands and most water supplies have a long history of distributing drinking water without a disinfectant residual.

Table 4.1 *Methods for determining the regrowth potential of drinking water*

Method	Principle	Reference value for biostability	Reference
Assimilable Organic Carbon (AOC)	Two selected bacterial strains are grown simultaneously in samples of pasteurized water at 15°C. AOC values are calculated from the maximum colony counts using the yield values of the strains for acetate	AOC $\leq$ 10 μg C/l. For details see main text.	Van der Kooij et al. 1982; Van der Kooij, 1992
Regrowth potential	Growth of indigenous bacteria is assessed with turbidity measurements (12° forward scattering) in reinoculated samples after membrane filtration. Incubation at room temperature.	Growth rate $\leq$ 0.1 h^{-1} and growth factor $\leq$ 5	Werner, 1985 Hambsch et al. 1992

Biodegradable organic carbon (BDOC)	The decrease in concentration of dissolved organic carbon (DOC) is determined in a water sample incubated with sand and attached micro-organisms. A variation of the method is based on prolonged (30 days) incubation of the samples without sand at 20°C	BDOC ≤ 0.1 to 0.2 mg/l. Based on BDOC decrease in distribution systems	Joret et Levy, 1986; Servais et al.1987
AOC-ATP	The growth of indigenous bacteria in a sample is assessed with ATP measurements	No value defined	Stanfield and Jago, 1987
Rapid BDOC	Water flows through a column containing sintered porous glass beads	BDOC ≤ 0.1-0.2 mg/l	Lucena et al. 1990
Rapid AOC	Growth of the strains used in the AOC test is assessed with ATP measurements	AOC ≤ 50 µg C/l to prevent regrowth of coliforms	LeChevallier et al. 1991; 1993
Biofilm Formation Rate (BFR)	Water is flowing through a column and the biomass accumulation is assessed as a function of time using ATP analysis	Limited regrowth of aeromonads when BFR < 10 pg ATP/cm^2.d. See main text for details	Van der Kooij et al. 1993; Van der Kooij et al. 1995, 1999

In the period between 1970 and 1990, surface water treatment was extended with ozonation and granular activated carbon (GAC) filtration as a response to the increasing pollution of river water with chemical contaminants. Ozonation was introduced to more effectively remove taste and odour compounds, colour and micropollutants. However, experimental observations and practice revealed that ozonation resulted in increased heterotrophic plate counts (Buydens, 1972; Snoek, 1970; Dietlicher, 1970), which was explained by the formation of easily biodegradable low molecular weight compounds from the recalcitrant humic and fulvic acids. The introduction of GAC filtration also gave increased colony counts, particularly in GAC effluents. Furthermore, observations on the formation of disinfection by-products by chlorination (Rook, 1974) stimulated measures to reduce the use of chlorine as much as possible in water treatment and distribution. These developments increased the need for a method to assess the effect of water treatment on the concentration of biodegradable compounds, aiming at a drinking water quality with a very limited microbiological growth potential. This type of water has been described as biologically stable drinking water (Rittmann and Snoeyink, 1984). This chapter summarizes the approach developed in the Netherlands to define biological stability and the tools which are used to assess concentrations of nutrients in drinking water: (i), as present in the water leaving the treatment facility and (ii), originating from the materials in contact with drinking water during distribution. Techniques for determining the biostability of drinking water have also been developed in other countries (see Table 4.1), but these methods will not be reviewed in this chapter.

4.2.2 Regrowth problems

Regrowth problems observed in the Netherlands include incidents with increased heterotrophic plate counts in distribution systems, e.g. following the introduction of ozonation in water treatment (Snoek, 1970). Coliform positive samples due to regrowth do not reach problematic levels as have been reported for the USA (LeChevallier, 1996), France (Gatel, 1998) and other countries.

Multiplication of opportunistic pathogens, especially *Mycobacterium kansasii* and *Legionella pneumophila,* has been observed in plumbing systems (Engel et al. 1980; Meenhorst et al. 1983; National Heath Council, 1986). Controlling *Legionella* in plumbing systems recently has become an important objective for the government, and a maximum colony count of 50 CFU/l has been proposed for this organism in recent legislation (VROM, 1999).

Aeromonads

In 1984 regrowth of aeromonads in drinking water attracted much attention in the Netherlands. The main reason was the detection of these bacteria in a number of water supplies (Van der Kooij, 1988), at the same time as international reports showing correlation between the presence of such bacteria in drinking water and the incidence of *Aeromonas*-associated diarrhoea (Burke et al. 1984). Surveys revealed that aeromonads were a common component of the microbial population of drinking water (Havelaar et al. 1990; Baggelaar et al. 1992), but the colony counts of aeromonads were usually only a small fraction (< 0.1%) of the heterotrophic plate counts on diluted broth agar medium. Aeromonads were observed in a low percentage (1.6 %) of fecal samples of people with diarrhoea in the Netherlands, but no evidence was found that these bacteria originated from tap water (Havelaar et al. 1992). Still, it was concluded that regrowth of aeromonads in drinking water supply systems should be limited to reduce the exposure of young children and immunocompromised persons to aeromonads. A national survey for the presence of aeromonads in drinking water supplies including a total of 230 distribution systems revealed that aeromonads were detected in samples (100 ml) collected over a period of one year from 95% of these water supplies. The colony counts ranged from less than 1 CFU/100 ml to more 27000/100 ml (maximum value). The highest colony counts were observed in ground water supplies using anaerobic ground water (Baggelaar et al. 1992). Based on these observations it was concluded that 90-percentile (P-90) values for *Aeromonas* counts in drinking water during distribution above 200 CFU/100 ml were indicative of situations in which corrective measures were needed. Effective corrective measures include: (i), improved methane removal by intensive aeration; (ii), improved backwashing of filter beds and (iii), renewal of filter bed material (Hijnen et al. 1992).

Invertebrates

Ever since the introduction of water supply systems in the 19th century occasional incidents with invertebrates, mostly *Asellus aquaticus,* resulting in consumer complaints have occurred in the Netherlands. In 1988 a complaint of a fish breeder about invertebrates in water samples resulted in negative publicity and gained political attention. A few years later complaints about *Asellus* in a ground water supply forced the involved water supply company to clean the system at high costs. The finding of aeromonads multiplying in ground water supplies further indicated that the biological activity in some of these systems was greater than previously expected. A national survey for invertebrates in ground water supplies was organised to determine the types and number of organism present in these water types and to elucidate the factors causing multiplication of invertebrates. Details about background, organisation and results of this survey have been described elsewhere (Van Lieverloo et al., 1994, 1997) and in Chapter 3 of this report.

4.3 Assessment of the biostability of drinking water

4.3.1 Easily assimilable organic carbon (AOC)

At the end of the 19th century attempts were made to assess the growth-promoting properties of drinking water by determining the growth curve of micro-organisms in a sample of water incubated in a glass container. However, large numbers of bacteria developed in most types of water and this method was not found suitable to differentiate between water types (Frankland and Frankland, 1894). Early in the 20th century a technique was developed in the Netherlands based on filtration of water through a sand column, followed by determining the reduction of the potassium permanganate demand of the water (Heymann, 1928). This method was only used for a short period in a few water supply companies. Following the deterioration of river water quality and subsequent changes in water treatment it was concluded in the early 1970's that a method was needed to assess the microbial growth potential of treated water. Determining the growth curve of micro-organisms in water in principle is a simple laboratory test and has the advantage of enabling the study of the behaviour of various types of bacteria. Therefore it was decided to make such growth measurements applicable for the assessment of the concentration of biodegradable organic compounds in (drinking) water. The following conditions have been introduced to obtain a reliable method:

1. Use of thoroughly cleaned Erlenmeyer flasks (1 liter) provided with a glass stopper both for sampling and testing to limit external contamination. Initially, Erlenmeyer flasks were cleaned with an acid treatment, at present acid treatment has been replaced by a heat treatment (3 h at 550°C);

2. Samples with a relatively large volume (600 ml) are used to limit the impact of external contamination with biodegradable compounds during sampling, transportation and handling;

3. The use of thoroughly cleaned glass pipettes coming into contact with the water sample. These pipettes are treated with acid washing followed by rinsing with tap water as described in earlier reports;

4. Selected pure cultures of bacteria are used for determining the growth potential instead of the indigenous heterotrophic bacteria. Growth measurements with pure cultures require that the indigenous bacteria are either removed or inactivated. Pasteurisation of the samples (30 minutes at 60°C) in the flasks in which the samples have been collected was found to be effective for this purpose.

5. The selected strains were:

- *Pseudomonas fluorescens* strain P17. This organism had been isolated from drinking water. Representatives of the species *P. fluorescens* are able to utilise a wide range of organic compounds. Simple N-sources are used (nitrate, ammonia) and growth factors are not needed. Furthermore the organism grows rapidly on solid media and is easy to handle in the laboratory. Details of the organism have been described in previous reports (Van der Kooij et al. 1982);
- *Spirillum* sp. strain NOX. This organism had been isolated from slow sand filtrate enriched with a low concentration of oxalic acid (Van der Kooij and Hijnen,

1984). Oxalic and other carboxylic acids have been reported as ozonation byproducts (Kuo et al. 1978). However, this compound is not utilised by strain P17 and therefore strain NOX was isolated for inclusion in the AOC test. Growth substrates and growth kinetics of the organism are described in a previous publication (cf. Fig. 4.1).

- *Flavobacterium* sp. A yellow-pigmented bacterium has been isolated which is specialised in utilising maltose and starch-like compounds at very low concentrations (Van der Kooij and Hijnen, 1985). This strain is not normally included in the AOC test.

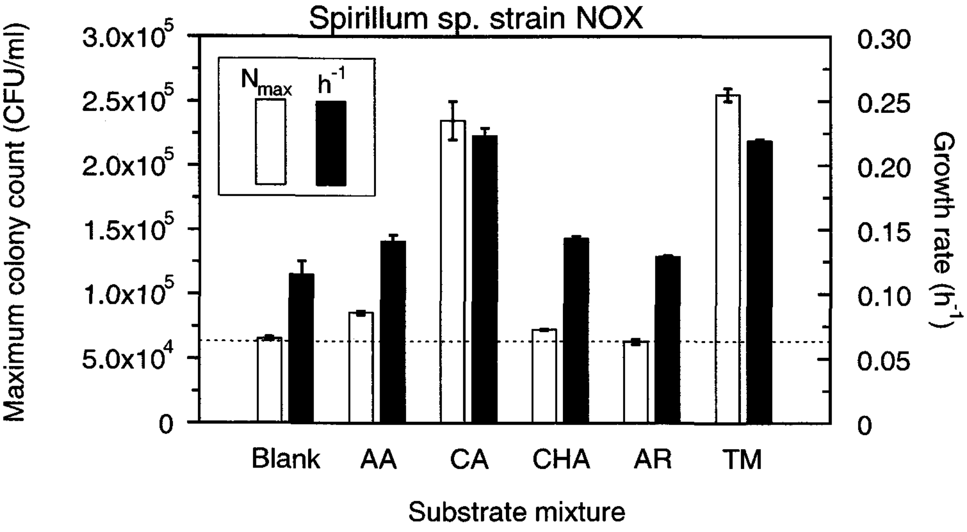


Figure 4.1 Maximum colony counts and growth rates of Spirillum sp. strain NOX in the presence of mixtures of compounds at an individual substrate concentration of 1 μg C/l. Blank: tap water (prepared from ground water) without added substrate; AA, 19 amino acids; CA, carboxylic acids; CHA, 6 carbohydrates; AR, 7 aromatic acids; TM, total mixture (46 μg C/l). Error bars indicate duplicate measurements. Data (adapted) from: Van der Kooij and Hijnen, 1984.

6. The growth test is conducted under strictly defined conditions, i.e. in the dark at 15 ± 1°C, without shaking. Flasks are incubated in a separate incubator to prevent the presence of biodegradable compounds in the incubator atmosphere. Colony counts are conducted in triplicate at regular intervals, usually every other day for a period up to 2 weeks, until the maximum growth is reached and confirmed. Water with a high degree of biostability, e.g. slow sand filtrate may require an incubation period up to one month.

7. The AOC concentration is calculated from the maximum colony counts of strain P17 and strain NOX as attained in the sample. The yield values of the organisms are calculated from their growth on acetate-C. Consequently, the AOC concentrations are expressed as acetate-C equivalents/l. The original concentration of organic carbon available for growth remains unknown. The contribution of the two strains to the obtained AOC concentration gives some information about the major groups of growth-promoting compounds, viz. the contribution of strain NOX reflects the concentration of available carboxylic acids. The yield values of the two strains are given below (Table 4.1). Yield value determinations have been repeated on a regular basis as part of the laboratory quality system. The obtained results are in agreement with the initially reported values.

A relevant aspect regarding yield values is demonstrated by the fact that oxalate carbon has a much lower growth yield than acetate. Consequently, there is no clear relationship between the concentration of biodegradable compounds and biomass production (growth potential). Biomass production is the critical parameter and therefore growth measurements in which biomass is used for calculating the growth potential are essential.

Table 4.2. *Yield factors (CFU/μg C) for the test strains P. fluorescens strain P17 and Spirillum sp. strain NOX at 15°C.*

Organisms	Acetate	Oxalate
Strain P17	4.1×10^6	not utilized
Strain NOX	1.2×10^7	2.9×10^6

The AOC test is usually conducted with duplicate samples. The relative standard deviation is less than 10% in 50% of the samples and less than 35% in 90% of the samples. Presently, AOC tests are conducted in 5 different water supply laboratories in the Netherlands.

4.3.2 Biofilm Formation Rate

A biofilm monitor has been developed for determining the biofilm formation rate (BFR) of drinking water (Van der Kooij et al. 1993, 1995). This system consists of a vertical glass column containing glass cylinders on top of each other. The water to be investigated flows downward through the column at a rate of 0.2 m/s (empty column). The formation of biofilm on the surface of the glass cylinders is measured as a function of time by sampling these cylinders at regular intervals. These cylinders are sonicated in sterile tap water and the concentration of active biomass is determined as adenosine triphosphate (ATP). Subsequently, the ATP concentration on the surface of the cylinders is calculated (pg ATP/cm^2) and the Biofilm Formation Rate (BFR) value (pg ATP/cm^2.d) is obtained as the increase of ATP as a function of the exposure time. In addition to ATP other biomass parameters (total microscopic cell counts, heterotrophic plate counts, aeromonads etc.) and chemical parameters (iron, manganese) can be measured in the suspension obtained after sonication of the sampled cylinders. From the iron and manganese analysis, the Iron Accumulation Rate (FeAR) and the Manganese Accumulation Rate (MnAR), both in mg/m^2.d, can be obtained.

For determining the relationship between Biofilm Formation Rate value and substrate concentration, experiments with acetate added to the water supplied to the monitor have been conducted. A concentration of 10 μg acetate-C/l gave a BFR value of about 360 pg ATP/cm^2.d (Van der Kooij et al. 1995). Additional observations revealed that a linear relationship exists between the acetate-C concentration and the BFR value. Consequently, the BFR can also be expressed in acetate-C equivalents/l, with an acetate-C concentration of 1 μg C/l corresponding with a BFR value of 35 pg ATP/cm^2.d

4.3.3 Relationship between regrowth and growth potential parameters

AOC and regrowth

In 1986 and 1987 a series of investigations were conducted to determine the relationship between AOC concentration of drinking water leaving the treatment facility and the level of regrowth (increase of heterotrophic plate counts) in drinking water during distribution. A total of 20 different water types were included in the investigation which has been reported in detail (van der Kooij, 1992). Two series of about 10 samples of drinking water were collected at different distances from the treatment plants and HPC-values were determined on Plate Count Agar medium (pour plate, 3 days at 22 °C) and on diluted broth agar (streak plate, 10 days at 25°C). AOC concentrations were determined in water leaving the treatment facilities and in samples collected from a few selected locations in each distribution system.

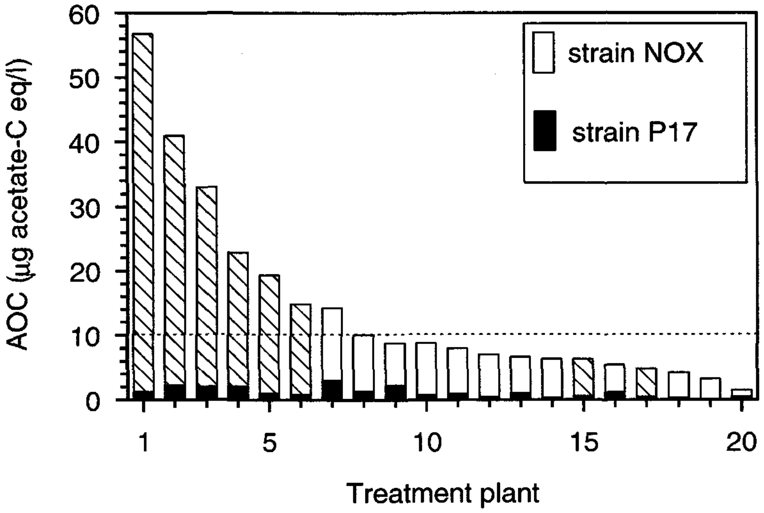


Figure 4.2 *AOC concentrations in 20 types of drinking water leaving the treatment facility. Hatched bars indicate surface-water supplies. Numbers 15 and 17 are slow sand filtrates.*

The AOC concentrations of the various types of drinking water ranged from about 60 μg C/l (treatment including ozonation) to 2 μg C/l (aerobic ground water), cf. Figure 4.2. In all except one the AOC concentration of the ground water supplies was less than 10 μg C/l. This low concentration was also observed in two surface water supplies using slow sand filtration as the final treatment step. The AOC-fraction utilised by strain P17 in the presence of strain NOX was ≤ 2 μg C/l in all water types, indicating that the concentrations of amino acids, carbohydrates and other compounds which can be utilised by this organism, but not by strain NOX, were very low.

Figure 4.3 shows examples of observed decreases of AOC concentrations in water during distribution. The rate and extent of the decrease depend on the initial concentration. At concentrations below 10 μg C/l no decrease or a very limited decrease was observed. The AOC decrease can be described by the following equation:

$$AOC_L = AOC_A . e^{-kL} + AOC_R$$

where: AOC_L = AOC concentration (μg C/l) at distance L (km) from the treatment facility; AOC_A = fraction of AOC available for uptake in the distribution system; and AOC_R = fraction of AOC not available for uptake in the distribution system. For the parameter k values of 0.07 to 0.2 have been calculated. This parameter is not a real constant and depends on many factors including the nature of AOC, water temperature, flow velocity and pipe diameter (Van der Kooij, 1999).

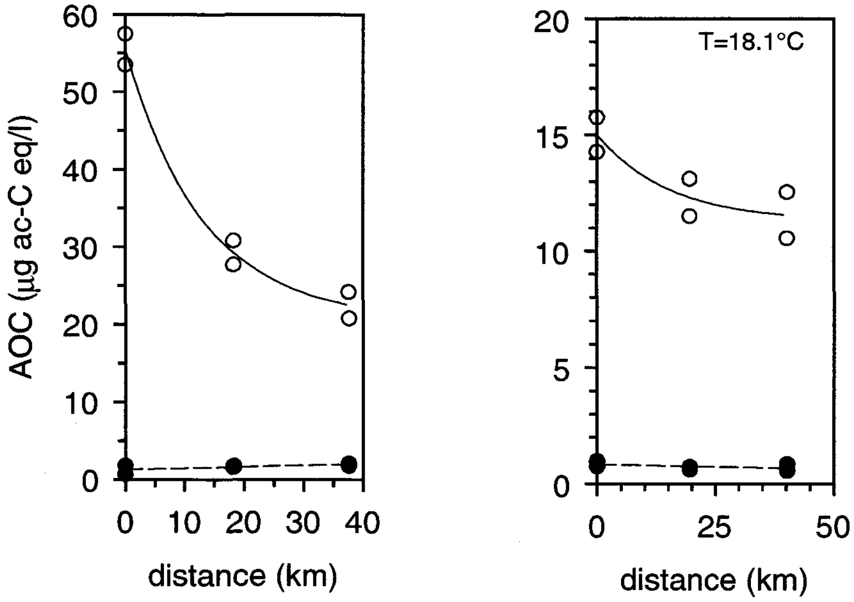


Figure 4.3 *Decline of the AOC concentration in drinking water during distribution in two surface water supplies. Symbols: O, AOC-P17/NOX; ●, AOC fraction utilised by strain P17.*

The AOC decreases observed in the distribution systems included in the investigation and in a few other supplies are presented in Figure 4.4. This figure shows that the observed maximum AOC decrease in drinking water during distribution depends on the initial AOC concentration. The observed maximum AOC decrease may not represent the real maximum decrease occurring in the system involved. Hence the calculated line may have a steeper slope. The obtained relationship suggests that there is no AOC decline at concentrations below an initial AOC concentration of 6.7 µg C/l but in reality this value may be close to zero. On average about two thirds of the AOC is utilised during distribution. Based on these observations it was concluded that AOC values below 10 µg C/l are indicative of a high degree of biostability.

Relationship between AOC and heterotrophic plate counts.

Statistically significant relationships were observed between the AOC concentrations in water leaving the treatment facility and the median (P-50) and 90-percentile (P-90) values of the heterotrophic plate counts (Plate Count Agar and Diluted Broth Agar) in samples collected from 20 different drinking water distribution systems in a summer period. Figure 4.5 depicts the relationships for the P-50 values. This figure demonstrates that the risk of the P-50 value (PCA medium) exceeding 100 CFU/ml was > 50 % at AOC values > 30 µg C/l. The 90-percentiles of the HPC values (PCA medium; 3 days at 22°C) had > 50 % risk of exceeding 100 CFU/ml at AOC values >10 µg C/l. In samples collected from a surface-water supply distributing drinking water with a low chlorine residual the plate counts remained below the calculated relationships, indicating that this residual hampered regrowth.

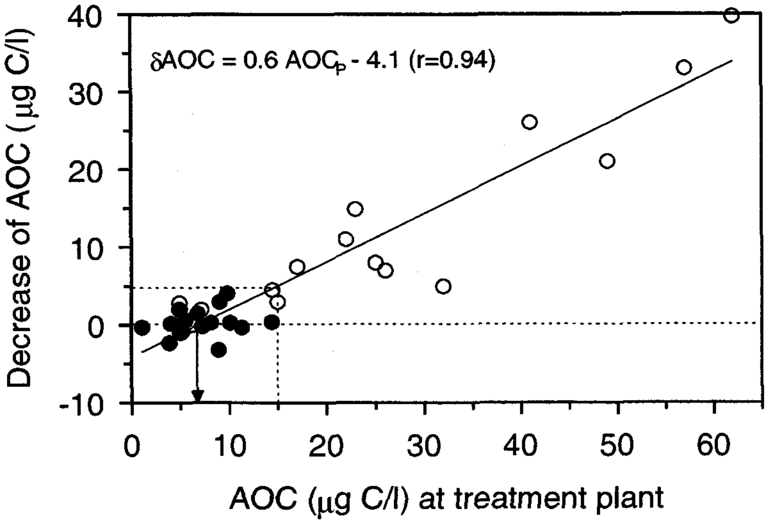


Figure 4.4 *The observed maximum AOC decrease in drinking water during distribution in a number of surface water supplies (O) and ground water supplies (●), respectively.*

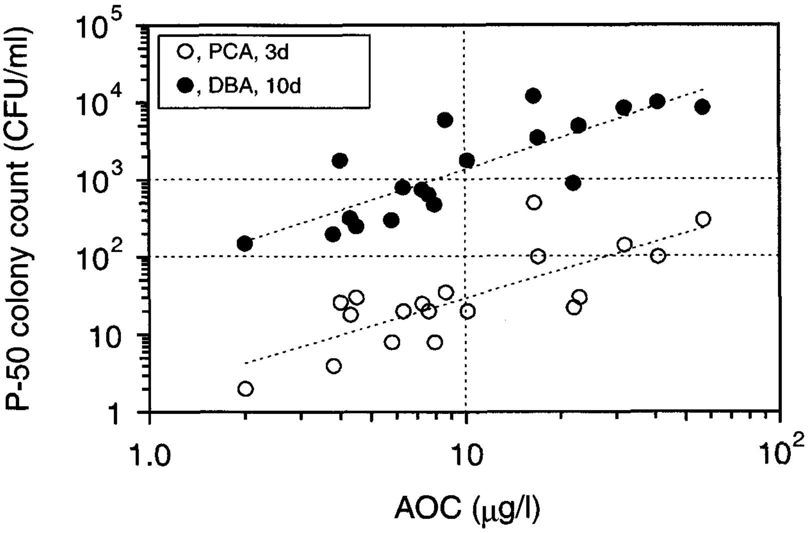


Figure 4.5 *Median values of heterotrophic plate counts of samples collected from 20 different distribution systems as a function of the AOC concentration in water leaving the involved treatment facilities (adapted from: van der Kooij 1992). PCA, Plate Count Agar medium; incubated at 22°C for 3 days. DBA, diluted broth agar medium. Incubated at 25°C for 10 days.*

Relationship between AOC and DOC of treated water

The AOC concentration in treated water usually is a small fraction of the total concentration of dissolved organic compounds (DOC). The highest AOC/DOC ratios (maximum: 1.7%) were found when water treatment included ozonation, which in all cases was followed by filtration. The lowest values were observed for ground water, approaching AOC = 0.001 DOC (1 µg AOC/mg DOC) (Figure 4.5). This ratio (0.1%) might be regarded as characteristic for biologically-stable organic carbon. DOC values in the distribution systems decreased in a few cases, but observations of DOC decrease were hampered by the precision of the DOC test (at best ± 0.1 mg/l; usually ± 0.2 mg/l) (data not presented).

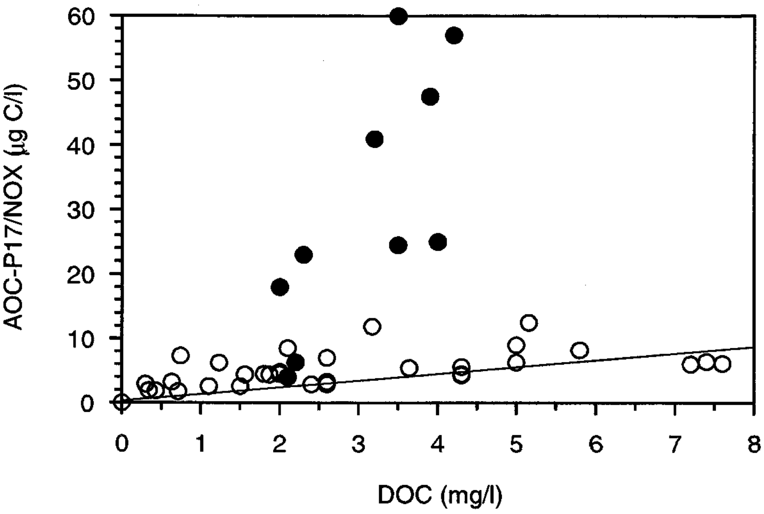


Figure 4.6 *The AOC concentrations of drinking water leaving the treatment plant in relation with the DOC concentration. Symbols: ●, surface water supplies; ○ , ground water supplies.*

AOC guideline value for biological stability

Based on the observations of the 1986-87 study it was concluded that drinking water with an AOC value ≤ 10 µg C/l is biologically stable, i.e. does not give rise to increased HPC values during distribution. Fig. 4.4 indicates that the AOC decrease is less than 4 µg C/l when AOC ≤ 10 µg C/l. AOC values ≤ 10 µg C/l are common in ground water supplies and in slow sand filtrate. In these water types the AOC/DOC value approaches 1 µg C/mg C. Observations conducted since 1987 have confirmed that AOC concentrations in ground water supplies in the Netherlands are < 10 µg C/l. However, in a number of these supplies regrowth of aeromonads was observed in a national survey conducted in 1989 (see above), despite low HPC values. Furthermore, AOC concentrations above 10 µg C/l do not cause regrowth in all situations. Application of ozonation in water treatment followed by two stages of biological filtration, e.g. rapid sand filtration and GAC filtration, may still give an AOC concentration between 15 and 20 µg C/l. Obviously, in such a water type a fraction of AOC is difficult to remove in biological treatment. Consequently, utilisation of this fraction is also slow in the distribution system and information about the rate of utilisation is needed in addition to the AOC concentration to define biological stability. Such information can be obtained by determining the Biofilm Formation Rate (BFR) of treated water.

Biofilm formation rate and regrowth of aeromonads

Investigations with aeromonads revealed that amino acids and long chain fatty acid can promote the growth of these bacteria at substrate concentrations below 1 µg C/l (Van der Kooij and Hijnen, 1988). These compounds are present in biomass and a relationship between microbial biomass accumulation and regrowth of aeromonads was expected. The AOC method may not be sufficiently sensitive to detect low concentrations of compounds promoting the growth of aeromonads, which in most cases do not exceed a density of 10 CFU/ml. Furthermore, the AOC test does not include ammonia and methane, which may be involved in biomass production. For these reasons the method for determining the biofilm formation characteristics of treated water using the biofilm monitor was developed.

Values for the biofilm formation rate (BFR, in pg ATP/cm^2.d), the biofilm formation potential (BFP, pg ATP/cm^2), the iron accumulation rate (FeAR, mg Fe/m^2.d) and the manganese accumulation rate (MnAR, mg Mn/m^2.d) have been measured for a large number of treated water types since the introduction of the technique (Van der Kooij et al. 1993; Van der Kooij et al. 1995).

A series of unchlorinated ground water supplies with a range of *Aeromonas* densities in the distribution system were selected and biofilm formation characteristics were determined in water leaving the treatment facility. BFR values ranging from about 0.2 pg ATP/cm^2.d. to values greater than 100 pg ATP/cm^2.d have been observed in treated water. The lowest values were observed in ground water supplies distributing aerobic ground water. Obviously, such water has a high degree of biostability as the result of the effects of aerobic biological processes during soil passage. Values below 1 pg ATP/cm^2.d were also found in slow sand filtrates. Values greater that 1000 pg ATP/cm^2.d have been observed with untreated river water.

A highly significant correlation was observed between the BFR values in treated ground water and the P-90 values of aeromonads in drinking water during distribution (Figure 4.7). This figure reveals that the guideline value of 200 CFU/100 ml is exceeded at BFR values greater that 20 pg ATP/cm^2.d. Based on this relationship it was calculated that the risk of exceeding the guideline value is ≥20 % at BFR values ≥10 pg ATP/cm^2.d and ≤10 % at BFR values ≤7 pg ATP/cm^2.d for the unchlorinated ground water supplies.

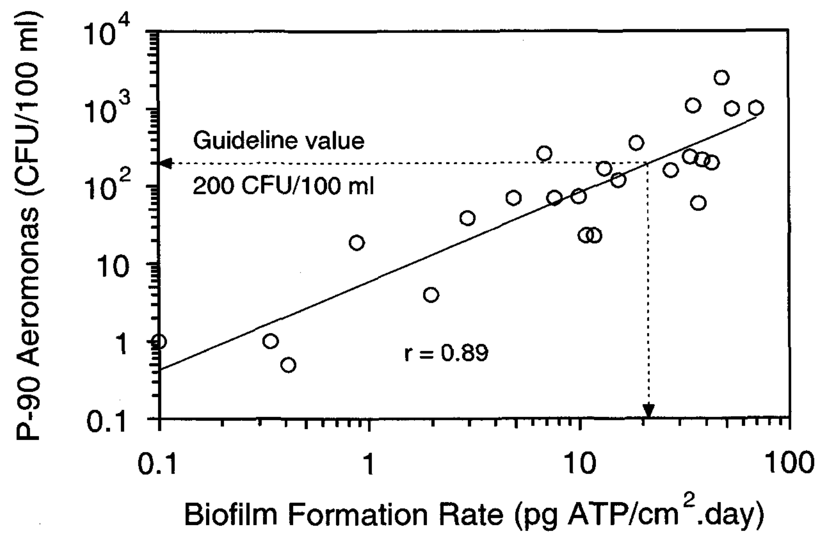


Figure 4.7 *The 90 percentile (P-90) values of Aeromonas in drinking water during distribution as a function of the biofilm formation rate values of water leaving the treatment facility (unchlorinated ground water supplies).*

Biofilm concentrations in distribution system

Measuring the biofilm concentration on the walls of the distribution system pipes also gives information about the biological (in)stability of the water in a distribution system. Such measurements have been conducted on PVC pipe segments mainly collected from a number of unchlorinated ground water supplies. Biofilm concentrations ranged from about 50 pg ATP/cm^2 to 6000 pg ATP/cm^2, with a median value for all observations of 650 pg ATP/cm^2. Also here the lowest concentrations were observed in distribution systems supplied with aerobic ground water, with a very low BFR value. The highest values were found in systems distributing water with a high BFR value, viz. drinking water prepared from anaerobic ground water. BFR values greater than 1000 pg ATP/cm^2 were found in distribution systems with regrowth of aeromonads and invertebrates. The measurements also showed that biofilm concentrations depended on its location on the pipe wall (top, side or bottom), the distance between the pipe segment and the treatment plant, and the nature of the pipe material between treatment plant and pipe segment.

Relationship between AOC concentration and Biofilm Formation Rate

Calibration of the biofilm monitor with acetate dosage experiments had shown that a concentration of 1 µg acetate-C/l corresponds with a BFR value of 35 pg ATP/cm^2.d. (Van der Kooij et al. 1995). Hence, the BFR values observed in treated water correspond with acetate-C concentrations ranging from < 0.01 µg C/l to about 3 µg C/l. These values were all clearly below the AOC concentrations, indicating that a large fraction either did not contribute to the biofilm formation in the monitor or was much more slowly utilised than acetate. Table 4.2 gives a few examples of BFR values and AOC values of drinking water types (without disinfectant residual). These data show that there is no clear relationship between AOC concentrations and BFR values of treated water. Thus, the concentration and nature of compounds contributing to biofilm formation strongly differ between water types even at similar AOC values. The presence of certain compounds, e.g. methane, ammonia, which do not contribute to the AOC concentration, but may enhance biofilm formation further complicates the relationship between AOC and BFR values. For these reasons a clear relationship between AOC concentration and BFR value is not to be expected. Hence, assessment of biological (in)stability of a water type requires determination of both the AOC concentration and the (BFR) value.

Table 4.3. *Biofilm Formation Rate (BFR) values and AOC values of a number of treated water types and untreated river Meuse water*

Water type	DOC (mg/l)	AOC (µg acetate-C/l)	BFR (pg ATP/cm^2.d)
Treated ground water*	7.2	13	29.6
Treated ground water*	4.2	5.1	10.7
Treated ground water*	2.0	4.8	3.5
Treated ground water*	1.6	3.7	49.5
Treated ground water**	0.3	3.4	0.35
Treated ground water**	0.2	2.2	0.4
Slow sand filtrate	1.8	7.1	0.3
Slow sand filtrate	2.6	3.2	0.4
GAC filtrate	2.6	25	8.3
Rapid sand filtrate	4.0	2.8	6.1
River Meuse	3.9	210	2800

*, treated anaerobic ground water: **, treated aerobic ground water

4.3.4 Biofilm Formation Potential of materials in contact with drinking water

Release of biodegradable compounds from materials in contact with treated water can contribute to biofilm formation and regrowth problems. Therefore a method was developed to determine the growth-promoting properties of such materials (Van der Kooij et al. 1994). The test developed in the Netherlands is based on assessing the ATP concentration on samples of the material incubated in slow sand filtrate in a batch ('static') test. The Biofilm Formation Potential (BFP) of a material is defined as the average biofilm concentration on the material observed after incubation (at 25°C) of 56, 84 and 112 days, respectively. A typical example of biofilm development on pieces of material is shown in Figure 4.8. Initially the ATP concentration on the material is relatively high, but this value decreases exponentially reaching a stable residual value after 50 to 100 days. Unplasticized PVC (uPVC) materials typically have low BFR values (< 100 pg ATP/cm^2). Values > 10^4 pg ATP/cm^2 have been observed with natural rubber and plasticized PVC (which are not normally used in contact with drinking water). BFP values of materials such as polyethylene (PE), glass-fiber reinforced polyester are within these extremes. In the Netherlands uPVC is the main pipe material (42%) and the high biostability of this material is a favorable property enabling the distribution of drinking water without disinfectant residual.

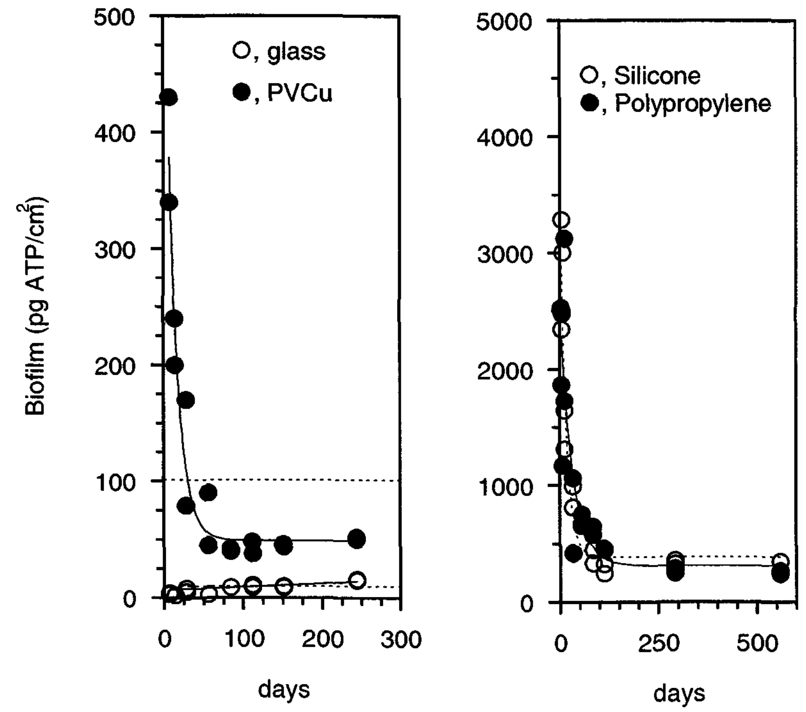


Figure 4.8. *Biofilm formation on materials in contact with drinking water in the BFP test at 25°C.*

4.4 Discussion

The data presented above and in Chapter 3 clearly show that: (i) regrowth of bacteria contributing to HPC values is limited in drinking water distribution systems in the Netherlands; (ii) biological stability can be assessed by measuring the AOC concentration and the BFR value of the water entering the distribution system and (iii) treated water has a high degree of biological stability. Also proper selection of pipe materials based on testing for growth promoting properties is needed to ensure that release of biodegradable compounds from such materials does not enhance biofilm formation. However, defining the biological stability of water is complicated and regrowth processes in drinking water not only depend on the biological (in)stability of the water, but also on many other factors such as (changes in) flow rates, residence time, temperature, nature of materials, disinfectant residual. The effects of the distribution system conditions will not be discussed here. Several groups of researchers have attempted to model regrowth processes in distribution systems. Lu et al. (1995) included the effects of disinfectants in models to predict regrowth. Theoretical considerations concerning mass transport phenomena and growth kinetics play a major role in these models. BDOC is used as the growth substrate in the Sancho model

(Servais et al. 1995), the Piccolo model (Dukan et al. 1996) and in dynamic modeling (Bois et al. 1997), respectively. However, BDOC uptake seems to be rather unpredictable and does not always show a clear relationship with regrowth (Capellier et al. 1992; Mathieu et al. 1995; Kerneïs et al. 1995). Mathieu et al. (1995) observed that the major fraction of the BDOC concentration was present in the water at the tap, even at a relatively long distance from the treatment plant. On the other hand, the study of Prévost et al.(1998) confirmed that at a low BDOC value (0.2 mg/l), less microbial growth occurred than at a relatively high BDOC value (0.8 mg/l).

The complexity of defining biostability is also demonstrated by the lack of correlation between AOC concentrations and BFR values (cf. Table 4.3). The AOC values provide information about the concentration of compounds utilised within about 2 weeks in a batch test at 15°C and the BFR values provide information about the rate of utilisation, respectively. Earlier investigations had shown that calculating the substrate concentration from the observed growth rate of the test strain (P17) gave much lower values than the AOC concentration calculated from the observed maximum colony counts (Van der Kooij, 1984). In various distribution systems the AOC concentration declined exponentially as a function of the concentration of available AOC, which is defined as the concentration in treated water minus the concentration in water leaving the distribution system, but the rate constants were not identical for the systems (Van der Kooij, 1999). Consequently, the rate of utilisation is not a simple function of the AOC concentration, but also depends on the AOC composition and the conditions (flow rate, diameter) in the distribution system.

Fig 4.4 shows that about two thirds of the AOC concentration in treated water is utilised in the distribution systems when AOC concentrations are clearly above 10 μg C/l. Uptake is very limited at AOC concentrations below 10 μg of C/l. At AOC concentrations below 10 μg C/l, the HPC values of the water remain below the guideline value (geometric average over a one year period <100 CFU/ml). For these reasons AOC values below 10 μg C/l are indicative for a high degree of biostability. The low AOC/DOC ratio's (approaching 1 μg AOC/ mg DOC) in these water types are in agreement with this conclusion.

In the USA AOC concentrations in water leaving the treatment facility have been shown to range from about 20 to 200 μg C/l using a modified AOC method (LeChevallier et al. 1996). Free-chlorinated systems with AOC concentrations >100 μg C/l had 19 times higher coliform levels than free-chlorinated systems with AOC values <100 μg /l. Earlier studies had shown that coliform growth is limited at AOC levels < 50 μg C/L (LeChevallier et al. 1991). These observations confirm that a low AOC value is also needed in the presence of a disinfectant residual.

Regrowth of aeromonads was observed in a number of ground water supplies in the Netherlands. Colony counts of aeromonads are assessed in samples with a volume of 100 ml, and values greater that 200/100 ml (2 CFU/ml) are regarded as relatively high. This level of regrowth usually does not lead to increased HPC values. *Aeromonas* counts were highest in peripheral parts of the distribution systems. Furthermore, aeromonads in most cases do not contribute to biofilm formation (Van der Kooij et al. 1995). The highly significant correlation between BFR values of treated ground water and the colony counts of aeromonads in the distribution system may be explained by multiplication of aeromonads on biomass sloughing from biofilms and subsequently accumulating in peripheral parts of the distribution systems. With the biofilm monitor information about the rate of accumulation of iron and manganese, respectively can also be obtained (Van der Kooij et al. 1995). Accumulation of iron and manganese in biofilms may contribute to fouling of the distribution system, including the accumulation of sediments. Sediments play a major role in regrowth phenomena, both by providing food sources for (micro)organisms and by protecting such organisms against disinfectants in systems with a disinfectant residual. Invertebrates, (e.g. Asellus, nematodes), use sediments as food source, and in a number of distribution systems large number of these organisms have been observed in water flushed from the mains (see Chapter 3).

Based on the observations presented in this Chapter it may be concluded that assessment of biostability of treated water should include both AOC and BFR values. Even these two parameters may not give a complete picture of the growth potential of water in the distribution system. Recent findings show that corroding cast iron enhances regrowth, and it appears that organic compounds adsorbing onto this type of pipe material are utilised as growth substrate (Camper et al. 1999; LeChevallier et al. 1993). Also other materials can promote growth and selecting materials with a low degree of reactivity and high degree of biostability, respectively is important for controlling regrowth. Unplasticized PVC, the major pipe material (42%) in the Netherlands, has a very low Biofilm Formation Potential (<100 pg ATP/cm^2).

Multiplication of *Legionella* in institutional and domestic plumbing systems has become an important issue in the Netherlands as a result of a large outbreak of legionellosis following a flower show in 1999 (De Boer et. al. 1999). Legislation has been proposed prescribing risk analysis, followed by control measures when needed to reduce numbers of *Legionella* to values below the detection limit of 50 CFU/l (Vrom, 1999). Increasing the hot water temperature to a level above 60°C is an effective measure, but not applicable in 'cold' water systems. Prevention of an increase of water temperature, prevention of stagnation, but also distribution of biostable water and using biostable materials provide multiple barriers against multiplication of *Legionella* in plumbing systems.

4.4.1 Unified Biofilm Approach

A clear definition of the biostability of drinking water and materials is needed to enable the proper design of water treatment systems and the design and maintenance of distribution systems, especially when disinfectants are not used to control regrowth. Based on the knowledge obtained using the developed tests a framework has been designed to evaluate the role of water and materials on the biostability conditions in distribution systems in the Netherlands. This framework includes three components:

- assessment of the Biofilm Formation Rate of water leaving the treatment facility in addition to determining the AOC concentration;
- assessment of the Biofilm Formation Potential of synthetic materials in contact with drinking water;
- assessment of the biofilm concentration on pipe walls.

All biofilm concentrations are measured by using ATP as the biomass parameter. With this parameter, all observed biomass concentrations can be compared to each other, which gives a framework of data to evaluate biostability of drinking water and materials in contact with drinking water. This framework is designated the Unified Biofilm Approach. Present investigations are directed at providing quantitative data about relationships between regrowth problems in practice and the parameters included in the framework to strengthen the use of the Unified Biofilm Approach for evaluating the biostability of water and materials in contact with drinking water.

4.5 Summary and conclusions

Most water supply companies in the Netherlands are aiming at distributing biostable drinking water without a disinfectant residual. Biodegradable compounds present in treated water and/or originate from materials in contact with drinking water may promote regrowth. For determining the biostability of drinking water the following procedures have been developed:

- the AOC method, which is based on measuring the growth curves of two selected bacterial strains in the water to be tested;
- the biofilm monitor method, which gives the biofilm formation rate (BFR) of the water.

In a series of water types AOC values ranged between 2 and 60 μg C/l. In ground water supplies and in slow sand filtrates AOC concentrations were below 10 μg C/l and uptake was very limited. A significant correlation was found between AOC concentrations and heterotrophic plate counts in drinking water during distribution. HPC values remained below the guideline value (100 CFU/ml) when AOC <10 μg C/l. In a number of ground water supplies regrowth of aeromonads occurred when AOC <10 μg C/l. A significant correlation has been observed between the BFR values and the 90-percentile values of aeromonads in drinking water during distribution. From this relationship it was calculated that the risk of exceeding the 90-percentile value of 200 CFU/100ml remained below 20% at BFR values below 10 pg ATP/cm^2.d. The assessment of the biostability of drinking water is based on determining the AOC concentration and the BFR value in the biofilm monitor.

The evaluation of the biostability of materials in contact with drinking water is based on assessing the biofilm formation potential (BFP, pg ATP/cm^2). The BFP values of materials, the BFP values for water and the Biofilm Concentrations (pg ATP/cm^2) in drinking water distribution systems provides a framework for evaluating the biostability of water and materials: the *Unified Biofilm Approach.*

Acknowledgement

This chapter is based on data collected in studies conducted at Kiwa as part of the Joint Research Programme of the Water Supply Companies in the Netherlands.

5 Microbiological Quality of Drinking Water in the United Kingdom

To provide the data in this chapter WRc, in collaboration with representatives of some of the UK's major water suppliers, selected 12 water treatment plants in the UK. These plants and associated water supply networks were selected on the basis of source water, type of treatment and disinfectant residual used (low 0.2 mg/l and medium 0.5 mg/l).

The information gathered was similar to that collected for chapter 3, although data for some parameters is not routinely collected in the UK (e.g. TOC, Aeromonads).

5.1 The water companies in England and Wales

All of the water companies in England and Wales are private limited companies. There are ten Water Service Companies supplying water to about 80 percent of the population. The remaining 20 percent is supplied by nineteen water supply companies.

The largest Water Service Company supplies about 2900 megalitres per day and the smallest Water Supply Company around 0.6 megalitres per day. In total the water companies supply about 17,000 megalitres of drinking water everyday in England and Wales.

There are over 1500 water treatment plants producing drinking water from a variety of sources. Water resources fall into two basic categories: surface water which is abstracted from rivers and reservoirs, and groundwaters which are derived mainly from aquifers. There are two principal types of raw water reservoir: Direct supply reservoirs and river regulating reservoirs. Direct supply reservoirs are filled by impounding water from rivers and streams, by pumping water from rivers, or by diverting flow from any surface water source. River regulated reservoirs are used to store water when river flows are high.

Groundwaters are abstracted mainly from aquifers. The water is usually of good quality and has traditionally been regarded as requiring little or no treatment other than precautionary disinfection. In some cases other treatments such as aeration and filtration are used depending on the characteristics of the abstracted water.

Surface derived waters generally require much more extensive treatment, with the waters abstracted from lowland rivers requiring the most intensive treatment strategies

The proportions of drinking waters derived from these differing sources is 32% groundwater, 40 percent direct river abstraction and 28% from impounded waters.

5.2 The regulatory control of quality

The water industry in the United Kingdom is highly regulated. Three agencies undertake this regulation.(see Fig 5.1), The Office of Water Services (Ofwat) covers economic regulation, the Drinking Water Inspectorate (DWI) oversees the quality of drinking water and the Environment Agency (EA) regulates water resources and protects the quality of the natural environment. The Secretaries of State for the Environment and for Wales develops policy and the legislative framework which includes that set by the EC Commission.

The basic regulatory instrument in England and Wales is The Water Industry Act 1991 which requires that water companies supply only water which is wholesome at the time of supply (the time when the water passes from the company's' pipe into the consumer's pipe).

Wholesomeness is defined by reference to standards and other requirements set out in the Water Supply (Water Quality) Regulations 1989 which were amended by the Water Supply (Water Quality) (Amendment) Regulations 1989 and 1991. The Regulations impose requirements in respect of 57 prescribed determinands and include all the standards set out in the EEC "Drinking Water Directive" (80/778/EEC) and additionally include some eleven national standards. Microbiological parameters such as total and faecal coliforms are included as are physical, chemical and aesthetic parameters. These include, nitrate, THMs, pesticides, lead, PAH, iron, and taste and odour.

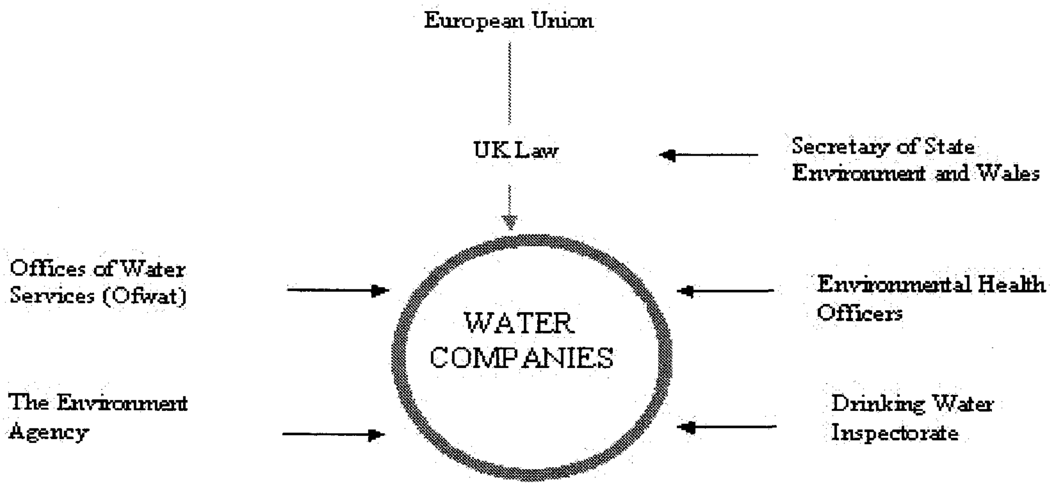


Figure 5.1 *Regulation of Water Companies in England and Wales*

The Water Act puts a duty on the Secretary of State to take enforcement action against any water company which fails to supply wholesome water or water which fails standards and is likely to fail again. However the Secretary of State is not required to take enforcement action if the breach of the regulations is deemed to be trivial or if the water company has given an undertaking to secure or facilitate compliance in an acceptable timescale. If the water company fails to give such an undertaking or does not comply with one which it has given, then an enforcement action would be issued and legal action taken. The Drinking Water Inspectorate is responsible for initiating enforcement action.

The water companies have a statutory responsibility for monitoring the quality of water supplies and this role is subject to checks by the local authorities and the Drinking Water Inspectorate.

5.2.1 The Drinking Water Inspectorate

One of the main tasks of the Drinking Water Inspectorate is to carry out technical audits of water companies. The purpose of these audits is for checking that water companies are complying with their statutory obligations. The audits consist of three main elements:

1. an annual assessment based on information provided by the water companies of the quality of water in each supply zone, compliance with sampling and progress made on improvement programmes;
2. inspection of individual companies covering not only the matters mentioned in 1), but also an assessment of the quality of information collected by the company;
3. interim checks, made on aspects of compliance based on information periodically supplied by companies.

The inspections are carried out by the Inspectorate and are based on the topics shown in Table 5.1.

The Inspectorate also operates a scheme for the statutory approval of chemicals used in water treatment and materials which come into contact with drinking water. Regulation 25 of the Water Supply (Water Quality) Regulations 1989 provides for the approval of new chemicals and materials by the Secretary of State. Regulation 28 allows criminal proceedings to be initiated if Regulation 25 is contravened.

Until 1995 the Inspectorate oversaw the work of the UK Standing Committee of Analysts (SCA) which provides authoritative guidance on methods for the sampling and analysis of drinking water, groundwater, river and seawater, waste waters and effluents, as well as sewage sludges. Since 1995 responsibilities in respect of SCA have been transferred to the UK Environment Agency although the remit of SCA remains unchanged. Reports from SCA form the basis for all recommended procedures for the analysis of water. Of particular note in this respect is The Microbiology of Water 1994 Part-1 Drinking Water (Report 71).

5.3 Monitoring the quality of drinking waters

In England and Wales monitoring the quality of drinking waters is the responsibility of the water companies and the majority have specialist laboratories dedicated to this function. These laboratories are usually supported by teams of fully trained samplers. Statutory sampling frequencies are laid down in the UK Water Supply (Water Quality) Regulations 1989 which reflect fully the requirements of the EEC Drinking Water Directive (80/778/EEC). The mandatory microbiological determinands are shown in Table 5.2 and the requirements for the frequency of sampling in Table 5.3 (consumers' taps) and Table 5.4 (treatment works). The standard parameters for routine monitoring are total and faecal coliforms and colony counts. Other determinands such as faecal streptococci and spores of sulphite-reducing clostridia are carried out in special circumstances when needs dictate.

In table 5.4, the reduced sampling frequency can only be used when sampling at the standard frequency has established, in each of three successive years, an absence of faecal and total coliforms and no significant increase in colony counts. For works supplying >2000 m^3d^{-1} for domestic purposes, the reduced sampling frequency can only be used if the water undertaker is 'of the opinion that there is no foreseeable risk that faecal or total coliforms will be present in the supply or the works are so designed that a failure of the disinfection process will bring about automatically a cessation of the supply'.

Table 5.1 *Topics in Drinking Water Inspectorate Audits*

Topic	Sub-topics
Sampling arrangements	Sampling points, sampling procedure (except where accredited to NAMAS) delineation of water supply zones
Analysis arrangements	Performance and analytical quality control. Detailed audit of selected analyses (except where accredited to NAMAS or DWTS) Sub-contracting of analysis. Competence of laboratory staff
Reporting arrangements	Audit trails. Public record
Compliance programmes	Detailed audit of selected completed and in progress schemes
Water treatment	Inspection of works. Audit of data logging etc.
Water distribution	Service reservoirs. Operation of service reservoirs. Bulk supply, mains rehabilitation
Incident and emergency procedures	Radioactivity monitoring. Review of incidents and lessons learned
Communications with local authorities	
Quality assurance	Progress with implementation of QA procedures. Assessment of internal QA audits

Table 5.2 *Mandatory Microbiological Determinands and Compliance Levels*

Determinand	Units of Measurement	Maximum Concentration
Total coliform organisms	Number per 100 ml	0 (I)
Thermotolerant coliforms	Number per 100ml	0
faecal streptococci	Number per 100ml	0
Sulphite-reducing clostridia	Number per 20ml	< 1 (ii)
Heterotrophic plate count at 37°C and 22°C	Number per ml at 22°C and 37°C	No significant increase over that normally observed

(i) regulation 3 (6) 95% of the results; (ii) Analysis by multiple tube

Table 5.3 *Sampling frequencies at consumers' taps for total coliforms faecal coliforms, residual disinfectant and colony counts*

Water Supply Zone		**Sampling Frequency (number per annum)**
Volume distributed (m3/d)	Population served	
<100	<500	12
101-1000	501-5000	12
1001-2000	5001-10000	24
	10001-20000	49
	20001-50000	Rate of 12/5000 population except for colony counts where standard number is 52

Table 5.4 *Sampling frequency at treatment works*

Parameters	**Volume of water supplied (m3/d)**	**Sampling frequency (number per annum)**	
		Reduced	**Standard**
total and faecal coliforms, residual disinfectant and colony counts	<2000	12	52
	2001-6000	52	104
Total and faecal coliforms and residual disinfectant	6001-12000	104	208
	>12000	104	365
colony counts	>6000	52	104

In addition to the statutory monitoring, water companies carry out a great deal of operational monitoring of treatment works and distribution systems. These monitoring programmes are usually initiated because of specific operational requirement or where priorities for remedial action need to be assessed. Similarly, in the last five years the water companies have responded to the potential threat to the safety of water supplies posed by *Cryptosporidium* by carrying out an increasing amount of monitoring for this specific pathogen. This represents a radical augmentation of previous monitoring which was based solely on indicator organisms. There are currently Government proposals in the UK for regulations requiring Water Companies to monitor specifically for *Cryptosporidium* in treated waters from certain works. The proposed standard is based on an average of less than one oocyst in 10 litres of water over a 1,000 litres collected continuously for 22-24 h.

The detection of coliform bacteria in a sample represents a failure of quality and immediate investigative action is taken. For samples taken from the distribution system this will include the taking of repeat samples from the same sampling points and others in the vicinity. In addition, results obtained at the same time from other locations in the supply zone will be studied as will historic data from that part of the zone.

The main aims of the investigations are to establish if the result is indicative of a real deterioration in quality and if this is due to faecal contamination. If the original result indicates the presence of coliforms but not *E coli*, the repeat samples may be analysed for additional indicators such as faecal streptococci and clostridia. If *E coli* was detected in the original sample then examination for specific pathogens such as viruses and *Cryptosporidium* will be considered and samples collected accordingly. Analysis for these organisms may only occur if the original contamination is confirmed to be of faecal origin.

The detection of coliforms in water from a treatment works also initiates immediate investigation that includes repeat and additional sampling through the treatment train particularly before and after chlorination.

Water Companies are expected and usually do have accreditation under a scheme initiated by the National Measurement Accreditation Service. (NAMAS) which in 1995 became the United Kingdom Accreditation Service (UKAS). In addition the analytical laboratories of water companies may obtain Accreditation to the Drinking Water Testing Specification (DWTS).

The requirements for accreditation under the DWTS are stipulated in a document issued by NAMAS (NIS 70). This document sets out how the requirements for NAMAS accreditation for all types of objective testing and sampling (M10, M10 supplement M11, M17 and M18) shall be interpreted when applied to organisations undertaking sampling and/or testing of drinking water.

The basic requirements are that the procedures used by the laboratory should comply with Regulation 21 of the Water Supply (Water Quality) Regulations (1989) or Regulation 19 of the Private Water Supplies Regulations (1991), the relevant recommendations contained in the document 'Guidance on Safeguarding the Quality of Public Water Supplies (HMSO 1989) and the relevant sections of the Report on Public Health and Medical Subjects No71 The Bacteriological Examination of Drinking water Supplies 1982. In addition reporting procedures shall be sufficiently detailed to permit the water undertaker or local authority to carry out the relevant actions described in 'Guidance on Safeguarding the Quality of Public Water Supplies (HMSO 1989).

Specific requirements for microbiological sampling and testing are that:

1. all laboratories shall comply with the requirements in the NAMAS publication Accreditation for Microbiological Testing, NIS 31;
2. the description of microbiological parameters shall be understood to be as given in paragraph 5,5 of 'Guidance on Safeguarding the Quality of Public Water Supplies (HMSO 1989);
3. the selection of, and performance required of, methods shall be as described in paragraphs 4.5 and 4.7 of the above document;
4. for the purposes of internal analytical quality control all laboratories shall follow the recommendations of paragraph 6.5 of 'Guidance on Safeguarding the Quality of Public Water Supplies (HMSO 1989), the relevant recommendations in Report on Public Health and Medical Subjects No71 "The Bacteriological Examination of Drinking water Supplies 1982", and sub-section 3.2 of the NAMAS publication NIS 31.

By the end of 1997, 20 laboratories had achieved accreditation to DWTS for some or all the parameters in the water regulations.

5.4 Water treatment and distribution

5.4.1 Water treatment

The principle of creating barriers to the transmission of infection has always been recognised for water supply. In water treatment, multiple barriers are used since no single barrier can be relied upon to provide absolute safety from microbiological contamination. Examples of the multiple barriers used in water supply can be illustrated by reference to groundwater and surface waters.

In groundwaters the following barriers are important to the maintenance of good microbiological quality:

- percolation through soil, recharge and infiltration;
- zones of exclusion and protection;
- integrity of the well lining and cap;
- disinfection;
- piped distribution.

In surface water treatment the following barriers are used to achieve good microbiological quality:

- impoundment with restricted access to man and animals;
- pre-chlorination or ozonation;
- coagulation, sedimentation;
- filtration;
- terminal disinfection;
- piped distribution with disinfectant residual.

In the UK groundwater sources account for about 32 percent of the total volume (1.9 x 10^6 m^3 y^{-1}) of water produced for domestic purposes. Surface water is used for the other 68 percent of supplies (4.1 x10^6 m^3 y^{-1}) of which 40 percent is impounded in reservoirs. Groundwaters are generally of excellent microbiological quality although most require disinfection to protect against microbiological contamination at source. Additional treatments may be used for reducing iron, manganese, turbidity and pesticides.

At an increasing number of plants treating surface derived water, more advanced systems are being installed. These are usually aimed at removing specific contaminants such as pesticides, but also provide additional barriers to micro-organisms. The advanced treatment most often employed is ozonation followed by filtration with granular activated carbon. Ozone is a powerful oxidant that can significantly reduce the microbial loading of water. However it may lead to an overall increase in the amount of assimilable organic carbon which can assist the proliferation of micro-organisms. Additionally the filtrate from a GAC filter can contain a significantly higher number of heterotrophic bacteria than rapid sand filters. These organisms are not regarded as being of public health significance.

Disinfection

Disinfection, usually by chlorine, is an important component of the multiple barrier approach in the UK. How important is difficult to quantify, but the literature suggests that, in the UK between 1937 and 1987, the major outbreaks linked to public and private water supplies were associated with failures or deficiencies in chlorination.

More recently, in the UK, outbreaks of waterborne cryptosporidiosis have demonstrated the need for multiple, microbiologically- efficient barriers in addition to chlorination.

Chemical disinfection of drinking water must therefore be considered as only part of the system of multiple barriers providing, in most instances, the final safeguard to public health protection. Oxidants are used to varying degrees in all public water supplies in England and Wales. In the vast majority of cases, the oxidant of choice is chlorine (as hypochlorite), but other oxidants such as ozone and chloramine may be used to help address certain water treatment tasks. Oxidants are used most intensively when the source water is abstracted directly from a river or surface water after impoundment in a reservoir.

5.4.2 Drinking Water Distribution

After treatment the water is distributed under pressure, by pumped or gravity fed mains to the population. There are approximately 316,000 kilometres of mains (>75 mm in diameter) throughout England and Wales.

Distribution systems are divided into supply zones of which there are some 2,419 in England and Wales. A supply zone is an area designated by the water company in which not more than 50,000 people live. Any area regardless of the number of sources of water will be divided into more zones if there could be significant differences in water quality within the area.

According to the population served by the zone the water company is required to take a minimum number of samples for each water quality parameter (see Table 5.4). For the microbiological parameters, at least 50 per cent of these samples must be chosen at random, usually from the dietetic tap of households in the zone. For the remaining 50% percent the water Company may select fixed or random sampling locations.

Structure of the distribution system
Existing mains have been constructed from a variety of materials including cast iron, spun iron, ductile iron, steel, asbestos cement, concrete, PVCu and Medium Density Polyethylene (MDPE). The predominance of a material in a part of the distribution system will reflect when it was built or refurbished and the size. Until the 1930s most mains were cast iron. Subsequently, steel or spun ductile iron with bitumen or concrete lining have been used for larger mains with smaller mains being constructed of spun iron, asbestos cement and ductile iron. More recently the need for greater resilience has led to ductile iron lined with cement mortar being the material of choice. There is also increasing usage (accounting for about 16 per cent of new mains) of uPVC, MDPE and HPPE because they are resistant to corrosion and relatively easy to install.

Figure 5.2 shows the materials in use from 1960 to 1997. The information may not be total accurate but indicates the change in the usage of different materials over these years.

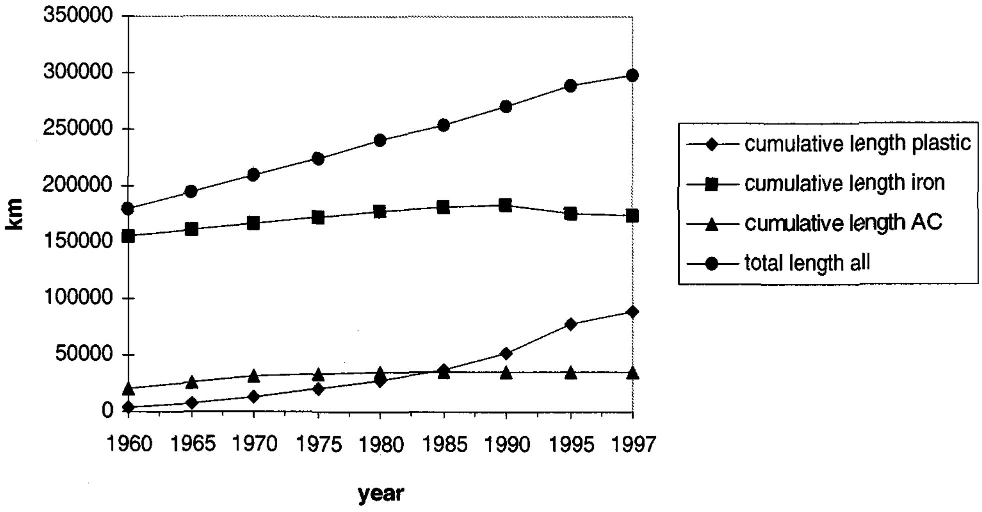


Figure 5.2 *Materials in use in the UK in the period 1960 – 1997*

On behalf of UKWIR, WRc recently gathered data from the UK Water Industry about the percentage use of pipe materials and sizes for service, distribution and trunk mains. The statistics were collected from 8 Water Service Companies, 19 Water Supply Companies, 11 Scottish Regional Councils and 4 divisions of DoE Northern Ireland. The following size ranges applied, Service pipes (<50 mm), Distribution Mains (51-300 mm) and Trunk Mains (>300 mm). The results of the survey are shown in Table 5.5.

Table 5.5 *Pipe materials usage for water supply applications (data for 92/93)*

Material	**Percentage Usage of pipe materials (split by size range)**		
	Service (50 mm)	**Distribution (51-300 mm)**	**Trunk (>300 mm)**
Asbestos	0.3	0.4	7.4
Ductile Iron		15.7	62.6
GRP		0.2	8.8
HPPE		8.9	9.2
MDPE	99.5	51.2	4.7
MOPVC		1.2	<0.1
PSC			<0.1
PVC-u	0.2	21.3	2.2
Steel		0.1	4.3
other		1.0	0.7

Table 5.6 *Change in pipe materials usage for distribution mains (1983/4/5 and 1992)*

Material	**Percentage of total distribution mains(51-300 mm)**			
	1983/4	**1984/5**	**1985/6**	**1992/3**
Asbestos cement	6.7	6.7	4.3	0.4
Ductile iron	34.8	33.7	29.7	15.7
GRRP				0.2
HPPE				8.9
MDPE	2.7	5.2	11.8	51.2
MOPVC				1.2
PVC-u	55.2	53.9	53.7	21.3
Steel				0.1
0ther	0.6	0.5	0.6	1.0

The change in the usage of different pipe materials for four years since 1983 is shown in Table 5.6. In 1983/4 PVC-u and Ductile iron made up 90% by length of the distribution mains laid. However by 1992/3 the use of these materials had been superseded by thermoplastic materials such as MDPE and HPPE. The influence which this change in choice of materials has had on the overall percentage of materials currently in use in the period 1960 to 1995 is shown in Figure 5.3.

Despite the increases in use of plastic pipe materials over 60 per cent of the pipes currently in service are made of iron. It is estimated that the majority are unlined and because of problems with PAH there is a large undertaking to replace these pipe with plastics or to carry-out epoxy re-lining.

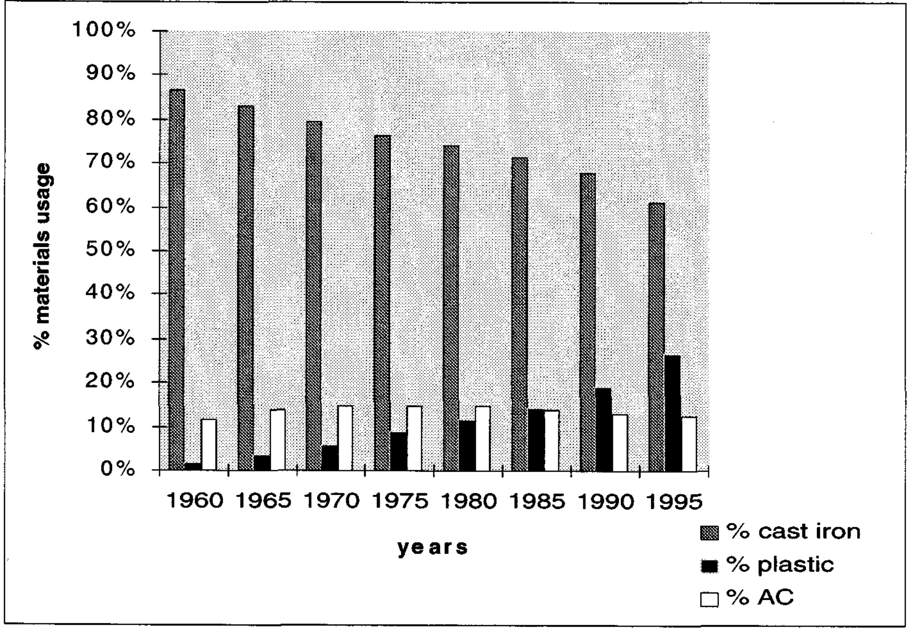


Figure 5.3 *Percentage usage of different pipe materials 1965-1995*

5.4.3 Safeguarding the Quality of Water in Distribution

A well designed and maintained water distribution system is an integral part of the multiple barrier approach to safeguarding public health. As a consequence there is strong motivation to ensure that the materials of construction, mode of operation and general hygienic condition of the system do not compromise the quality of the treated water.

The water companies have a long term programme of investment in the refurbishment of their distribution systems either by relining or replacement or a combination of both. The main purpose is to reduce discoloration events due to corroding pipes. An equally important consideration is to minimise breaks or bursts and leakage each of which can have undesirable effects on the quality of the water in supply.

Precautions during repairs and renovation.
Non intrusive methods of repair are constantly being developed and refined for bursts as are working practices for such situations. The Operational Guidelines for the Protection of Drinking Water Supplies (OGPDWS) provided guidelines and procedures to be used for the disinfection of new, renovated or repaired water mains On the basis of this document each water company developed its own code of practice.

The main points of the guidelines can be summarised as follows:

Procedure	Procedural Guidelines
New Mains	Pre-disinfect with $20mgl^{-1}$ of free chlorine Flush, swab, disinfect with $20mgl^{-1}$ of free chlorine for 24h Sample for bacteriological analysis along length of new section, return to service when samples are acceptable in terms of coliforms, taste and odour and appearance
Repaired without cutting	Disinfect fracture area with $1000mgl^{-1}$ of free chlorine Flush and take samples for bacteriological examination Return to service immediately
Repair with cutting	Disinfection as for new mains, but disinfectant may be $20mgl^{-1}$ for 2 hours or $50mgl^{-1}$ for 30 minutes. If impracticable use $1000mgl^{-1}$ free chlorine on all surfaces which will be in contact with potable water Flush and take samples for bacteriological analysis Return to service immediately
Renovated mains	Flush and disinfect as for new mains Repeated flushing may be required for cement lined mains to reduce pH

These guidelines have now been superseded by the 'Principles of Water Supply and Hygiene (WSA 1996) which provides more generic guidance for water companies to develop their own specific working practices.

Backsiphonage

Backsiphonage can occur when pressure in the mains fails or suddenly reduces due to extraordinary demands for water in other parts of the system (e.g. fire fighting). Customer installations can be a prime source of contamination in these situations. Prevention of backsiphonage is one of the main purposes of the Water Byelaws; they stipulate that devices to prevent backsiphonage should be fitted to all installations that represent a risk. There is a range of devices available that incorporate check valves to prevent the reverse flows of water. Where storage tanks are involved the use of air gaps between the incoming supply and the stored water is a valuable preventive measure.

Materials in contact with water

All construction materials should be evaluated to ensure that they are not likely to impair water quality. The United Kingdom Water Fittings Byelaws Scheme (UKWFBS) run by the Water Byelaws Scheme (WRc) publishes a directory of water fittings and materials that comply with the required standards. As part of the assessment for compliance each material is subjected to a series of tests to determine likely effects on water quality. These tests cover the extraction of metallic substances and the ability of non-metallic materials to impart to water an undesirable taste, odour or to support microbial growth.

Regulation 25 of the Water Supply (Water Quality) Regulations (1989) aims to ensure that the legitimate use of chemicals and materials by companies coming into contact with water during treatment and distribution does not compromise drinking water quality. It also provides, through the Drinking Water Inspectorate, a means of obtaining approval for new chemicals and materials from the Secretary of State. As part of its technical audit of water companies, the Inspectorate assesses water company arrangements for use of substances and products in contact with water supplies. Regulation 28 provides a means by which water companies can be prosecuted for contraventions of Regulation 25.

5.4.4 Biofilms and biostability

In the UK efforts are made to maintain a disinfectant residual to the end of the distribution system. The main function of this chlorine residual is to minimise aftergrowth or regrowth of micro-organisms and therefore preserve the microbiological quality of the drinking water. The residual does not protect the supply from major contamination such as that caused by ingress or backsiphonage, since the chlorine demand introduced by these sources rapidly reduces the residual to ineffective levels.

This philosophy of using chlorine as a preservative has now been extended into considering water as a perishable product that has an inherent shelf life. Means of extending the shelf life whilst minimising the use of chlorine are now been actively pursued by the UK water industry.

Consumer complaints about chlorinous taste in some areas of supply zones are common and are increasing concern to the water companies. In addition, more stringent standards for THMs are making the increases in concentration of these by-products, which can occur in some distribution systems, of significance in terms of achieving compliance with these new standards. The need here is maintain quality with lower and more consistent chlorine residuals across a supply zone.

Work funded by UKWIR at NANCIE (UKWIR 1997a) has shown that the materials of construction of water mains can have a significant effect on the longevity of a chlorine residual and that this can vary according to the condition of the pipe material in terms of biofilm growth and, for unlined cast iron mains, the degree of corrosion. Similarly, work at WRc and elsewhere has shown that scouring and 'Pigging' of pipes to remove corrosion products and biofilm can have a deleterious effect on water quality and the maintenance of a chlorine residual. These cleaning procedures expose a "new" surface that is more reactive than either the formerly corroded layer or one which was "protected" by biofilm.

In studying the stability of a range of waters from differing UK sources WRc, on behalf of UKWIR (UKWIR 1997b), found that waters alone were biostable for periods of up to 14 days. If the residual microbial population that survived treatment was low (22°C plate count <10 cfu/ml), microbiological quality did not deteriorate even when the chorine residual decayed to ineffective levels. Where these waters were inoculated with high numbers of micro-organisms, such as may happen in a water main following disturbance of biofilm or sediment, a deterioration in microbial quality would be initiated when chlorine residual had fallen below about 0.1 mg/l of total available chlorine (UKWIR 1997b).

As in the Netherlands the role of Assimilable Organic Carbon (AOC) on influencing the microbial growth potential of waters has been studied in the UK. The use of this determinand has been able to demonstrate the relative effects of different treatment processes on growth potential. For example it was shown that treatments such as ozone and GAC filtration, introduced to remove pesticides, produced water with an increased AOC content and that failure to remove this AOC can result in a deterioration in water quality in distribution. When used as a biologically active processes, GAC filtration will remove AOC and give a relatively biostable water. However, water filtered by GAC can contain significant numbers of heterotrophic bacteria that have grown within the filter matrix. The potential of a higher AOC content and a high inoculum in terms of heterotrophs means that final disinfection must be optimised and chlorine residuals maintained in distribution if water quality is to be preserved.

The optimisation of AOC generation by oxidants and removal by a biologically active process is essential if benefits in terms of water quality are to be achieved. Studies carried out by Thames Water demonstrated that ozone and biologically active GAC led to a reduction of bacterial counts in waters throughout distribution.

Although the measurement of AOC has been of value in assessing treatment processes it has not proved so rewarding for predicting how it influences the shelf-life of water in distribution. In studies carried out by WRc on behalf of UKWIR (UKWIR 1997b), it was shown that there were substantial differences in the results of AOC analyses carried out by different laboratories even when the same method was used. However, when analysing 'standard samples' WRc and KIWA obtained consistent results using the KIWA method of AOC analysis. These results suggest that the method for AOC determination may still require development before it is robust enough for routine use in the water industry.

The change in AOC content occurring when different types of water were stored under different conditions of temperature and microbial content has recently been studied (UKWIR 1997b). Examples of the results obtained are shown in Table 5.7 which indicates typical AOC concentrations for surface and groundwaters in the UK. In the examples given in table 5.7, the AOC concentration in each of the waters (with the exception of the groundwater) declined during storage. However this was not always associated with large (ten fold) increases in the numbers of heterotrophic bacteria present. Even in waters in which the chlorine residual declined to concentrations below

0.1mg l^{-1}, increases in heterotrophs could only be detected using 7 day incubation of agar plates. In a later part of that study it was demonstrated that the decline in AOC concentration could be demonstrated in the absence of biological activity (presumably due to adsorption to pipe surfaces).

Table 5.7 *Changes in AOC concentration during storage at 15°C*

Water Type	**AOC Concentration $\mu g\ C\ l^{-1}$**	
	0 days	**7 days**
Lowland surface water 1	457	317
Lowland surface water 2	420	319
Lowland surface water 3	470	235
Lowland surface water 4	330	251
Upland water	476	233
Groundwater 2	60	96

As a consequence of the difficulties in understanding the significance of AOC efforts have been extended to try and investigate the role of other factors within the distribution system which could control microbiological quality.

The biostability of a water at any point in a distribution system depends on a combination of factors, including water quality immediately after treatment and the nature of the distribution system through which it is conveyed. These will influence the rate at which chlorine decays and the size of the inoculum from any biofilm or sediment. Studies have therefore been performed in real distribution systems using a small biofilm monitor which can be connected to the water supply at strategic points. In this way the monitor provides a form of in-situ and non-intrusive measure of the rate at which biofilm could be formed at different points in a supply zone. Unlike measurement at the works, use of a biofilm monitor within the distribution system indicates the effect which the water's history, since treatment, is having on biofilm potential.

Used in combination with other measurements and knowledge of the hydraulics and construction of the system it is hoped that these studies will allow a better understanding of shelf-life and the factors which control it.

5.5 The Quality of waters in England and Wales

5.5.1 Summary of compliance monitoring in England and Wales

A summary of the compliance monitoring results for the water companies in England and Wales for the years 91-96 is shown in table 5.8 as the percentage of samples taken at water treatment works, service reservoirs and water supply zones which failed to comply with statutory standards.

Table 5.8 *Percentage of samples for each of the tears 91-96 from treatment works, service reservoirs and supply zones in which coliforms/faecal coliforms were detected*

Parameter		**1991**	**1992**	**1993**	**1994**	**1995**	**1996**
No samples	(000)s	226	219	205	219	205	202
Treatment Works	% coliforms	0.3	0.3	0.2	0.2	0.2	0.2
	% faecal coliforms	0.1	<0.1	<0.1	<0.1	<0.1	<0.1
No samples	(000)s	259	262	261	262	259	259
Service Reservoirs	% coliforms	0.7.	0.6	0.5	0.3	0.4	0.3
	% faecal coliforms	0.2	0.2	<0.1	<0.1	<0.1	<0.1
No samples	(000)s	173	171	164	161	156	157
Supply Zones	% coliforms	1.4	1.2	0.8	0.7	0.7	0.8
	% faecal coliforms	0.2	0.2	0.1	<0.1	<0.1	0.1

Table 5.8 shows the percentage of treatment works, service reservoirs and supply zones in which exceedences of the coliform and faecal coliform standards occurred.

5.5.2 Discussion

The data presented in table 5.8 and table 5.9 shows that there has been a general improvement in microbial quality in each year since 1991. This is shown in table 5.9 by the decline in the percentage of samples taken from treatment works, service reservoirs and supply zones in which total coliforms and faecal coliforms were detected. A similar observation can be made from table 5.9 which shows that the percentage of treatment works and service reservoirs which failed to comply decreased every year in the period 1991-1996. The situation is not so clear for water supply zones, where in 1995 and 96 there were small increases in the percentage of samples and zones in which total coliforms were detected.

A contributing factor to this reported higher incidence of total coliforms may have been changes to the definition of this group of bacteria that were adopted in 1994. Whereas the former definition of the group depended on the demonstration of certain biochemical characteristics, the new definition is genetically based.

Table 5.9 *Percentage of treatment works, service reservoirs and supply zones in which coliforms/faecal coliforms were detected for the years 91-96 in more than 5 % of the samples*

		1991	1992	1993	1994	1995	1996
Treatment	no works	1717	1683	1657	1603	1588	1533
Works	% coliforms	26	23	18	15	15	15
	%faecal coliforms	10	8	7	4	4	3
Service	No reservoirs	4981	4974	5068	5186	5053	4984
Reservoirs	% coliforms	3*	2*	*1	1*	1*	2*
	%faecal coliforms	7	7	4	<1	1	<1
Supply	No of zones	2577	2598	2576	2552	2471	2419
Zones	% coliforms	7*	3.3*	1.1*	0.5*	0.6*	1.2*
	%faecal coliforms	11	10	6.4	4.9	4.2	3.8

In practical terms the old definition required the identity of all organisms provisionally designated as coliforms to be confirmed by the demonstration of acid and gas production in culture media containing lactose. The new definition required that all presumptive coliform organisms were confirmed by demonstrating that they possessed one of the enzymes (B galactosidase) necessary for utilisation of lactose.

One consequence of this change is that certain organisms, which would not formerly have been considered to be coliforms, are confirmed as coliforms under the new definition. The adoption of the new definition therefore represents a tightening of the standard.

In 1994 water companies were invited by the Drinking Water Inspectorate to report the results of coliform analyses in terms of both the old and new definition. The data provided by eight companies showed an average increase of 36 % in the number of coliform detections according to the new definition. The lowest increase was 8% and the highest 129%. The Inspectorate reported that, but for the change in the definition of the coliform parameter there would have been further significant improvements in the microbiological quality of water in supply zones in 1995.

A greater increase in the percentage of supply zones in which coliforms were detected was also reported in 1996. The Inspectorate makes little comment on this fact other than to say that “two companies experienced the majority of this increase”. It is impossible to tell from the data available if this was due to a real deterioration in quality or yet another consequence of the change of definition, either by virtue of the climatic conditions in this year or increased analytical expertise in testing according to the new definition.

5.6 The quality of waters from selected treatment plants and distribution systems

5.6.1 The selected Treatment plants

In total, 12 plants were selected to provide information on the treatment and distribution of drinking water with low or medium chlorine residuals. Of these plants six use surface derived sources and six use ground water sources. The main characteristics of the plants are presented in table 5.10. The data was supplied by four UK water companies designated as A, C, D and M.

Table 5.10 *Main characteristics of the representative treatment plants*

Code	Source	Treatment steps	production volume
A1	River	O_3/RGF/O_3Slow Sand /NH_2Cl	
A2	River	O_3/RGF/O_3Slow Sand /Cl_2	
A3	Ground	Cl_2	
C1	River and ground	pre 1995 clarif/Cl_2/RGF/Cl_2 post 1995 clarif/Cl_2/RGF/SO_2/O_3/GAC/Cl_2	72 MLd^{-1} surface and 8 MLd^{-1} ground
C2	River	pre 1995: clarif(ferric)/Cl_2/RGF/ $S0_2$ post 1995: clarif(ferric)/Cl_2/RGF/ $S0_2$/phos acid	111 MLd^{-1} peak output
C3	Ground	Cl_2	
C4	Ground	Cl_2	
C5	Ground	Cl_2	
D1	Upland	pre1994: coarse filter /storage /RGF /Cl_2 / caustic soda post 1994: coarse filter/ storage/ coag/ floc(ferric)/ DAF/Cl_2/RGF/Cl_2/caustic soda	400 peak 450 peak
D2	Ground	Cl_2	0.75 MLd^{-1}
M1	River	reservoir band screens, clarification (alum and polyelectrolyte) /RGF/Cl_2 (0.40-0.46mgl^{-1})	45.4 MLd^{-1}
M2	Ground	Cl_2	

5.6.2 The selected distribution systems

The best available data on the materials of construction used in the distribution systems associated with the treatment plants detailed in table 5.10 are given in table 5.11. The distribution systems have been given the same codes as the appropriate treatment works. For supplies C2 and M1, data are presented separately for the component water supply zones, labeled C2^a, C2^b, C2^c, M1^a and M1^b.

Table 5.11 *Details of distribution systems associated with the selected treatment works*

Distribution System	Details of materials of construction
A1	mainly cast iron, some spun and ductile iron and plastic (MDPE)
A2	mainly cast iron, some spun and ductile iron and plastic (MDPE)
A3	mainly cast iron, some spun and ductile iron and plastic (MDPE)
C1	25 % plastics, 45 percent spun iron, 26 percent FRC
C2^a	11% plastics remainder mainly cast iron with some ductile iron
C2^b	more than 80% iron (cast and ductile) remainder plastic with some spun iron
C2^c	more than 80% iron (cast and ductile) 11% plastics, 6% steel
C3	28% plastic, 30% of each of cast and spun iron, 5% ductile iron
C4	virtually all iron, 48% cast, 40% spun and 5% ductile
C5	86% iron (70 % cast, 15% ductile) 11% plastic
D1	95 % iron with cement mortar or epoxy lining, remainder constructed of plastics
D2	100 % unlined cast iron , 3-6 inch
M1^a and M1^b	no information
M2	no information

5.6.3 Presentation of data

In the following sections the data from the selected treatment plants and supply zones have been summarised in a graphical form termed ‘box-and-whisker plots’.

Figure 5.4 is an example of a box and whisker plot, so called because it is composed of a box with two lines (whiskers). The parameter is shown on the y-axis, in this case temperature. The box represents the 10 and 90 percentiles with the median (50 percentile) being represented as the line drawn across the box. The tips of the whiskers show the maximum and minimum values. The arithmetic mean is shown as a small dot usually (but not always) within the box

In the following section the data for three years (1992-1994) have been summarised and presented in the box and whisker plots. Where appropriate, data for surface waters is shown in black and data from groundwaters is shown in grey.

5.6.4 Chlorine residuals

Final waters

Water Works A1 uses chloramination as disinfectant. The other 11 works use free chlorine as disinfectant and a free chlorine residual is maintained in supply.

In Figure 5.5, data on the total chlorine concentrations in each of the works final waters are presented as box and whisker plots. There is considerable variation in the total chlorine concentrations in the final waters at each of these works with the maximum and minimum values differing by more than 2.0 mg l^{-1} in some works.

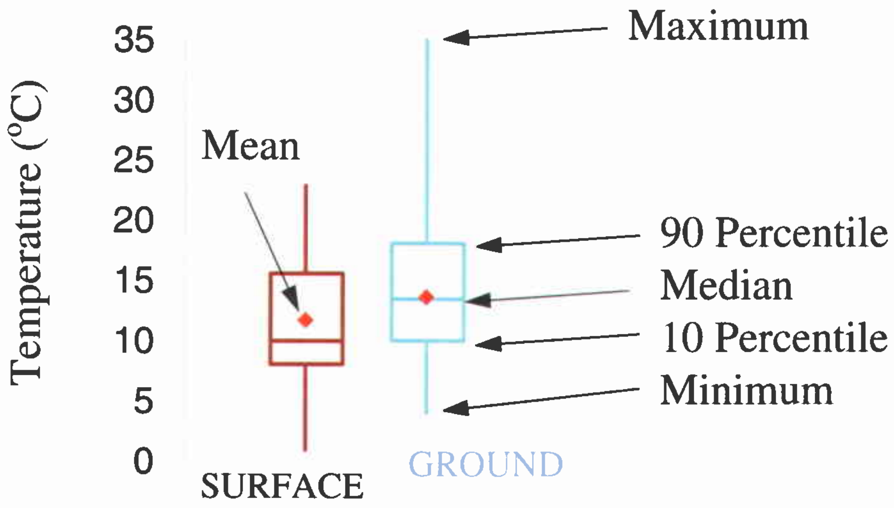


Figure 5.3 *Key to Box and Whisker Plots*

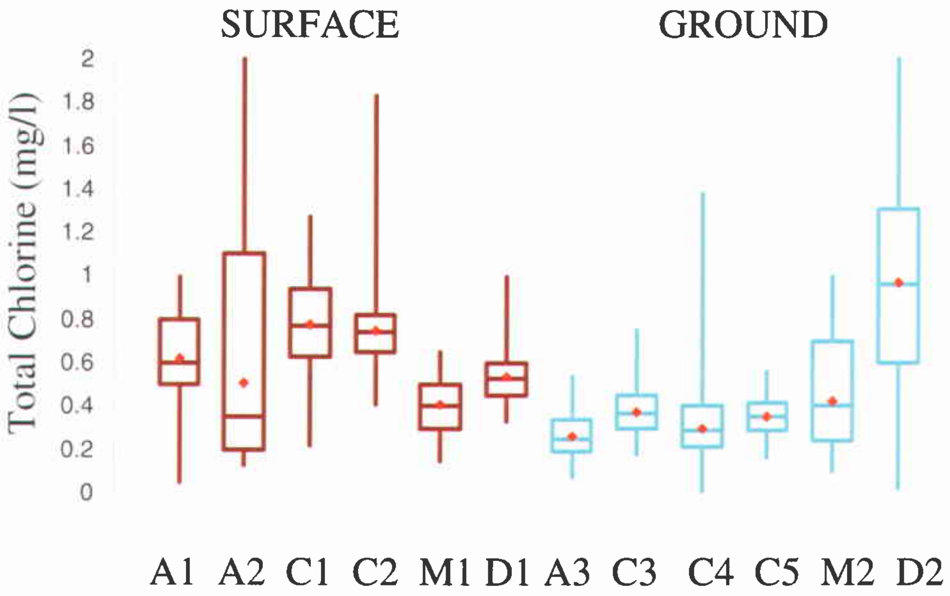


Figure 5.4 *Total Chlorine in works final waters*

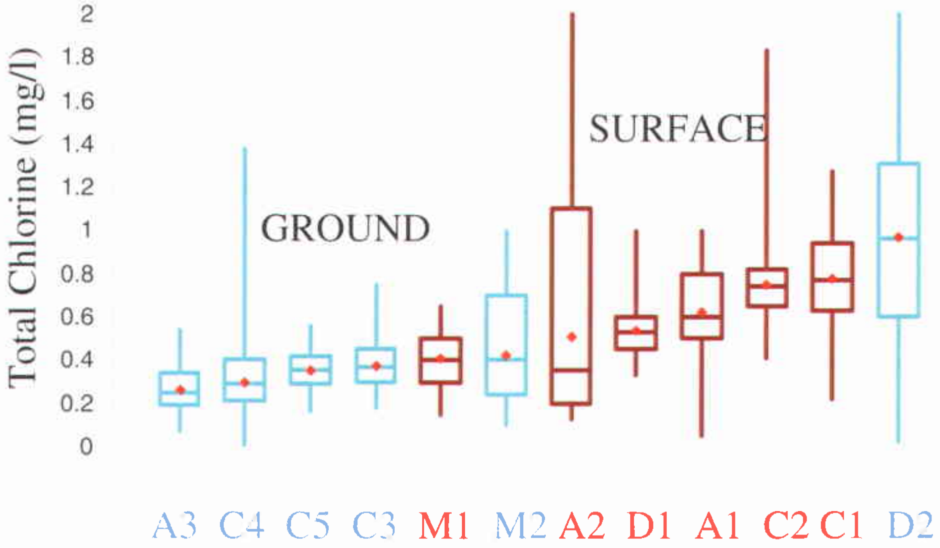


Figure 5.5 *Total chlorine in works final waters sorted by increasing mean*

In all but one case, the works final waters from surface water-supplied works have higher residuals than those derived from groundwater sources. This is shown more clearly in Figure 5.6 in which the box-whisker plots for each supply have been sorted into order of increasing arithmetic mean total chlorine concentration.

A similar situation was found to exist with free chlorine residuals which are presented sorted in order of increasing mean in Figure 5.7.

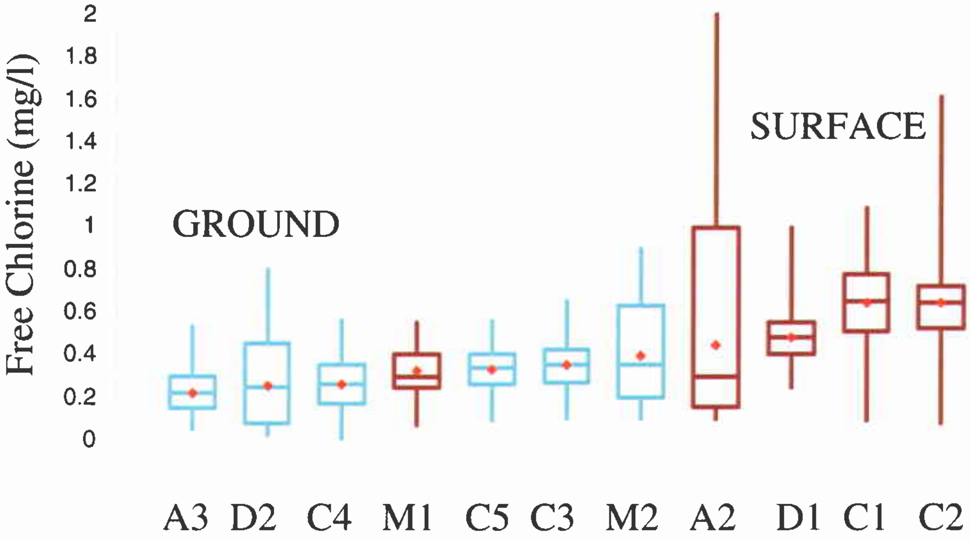


Figure 5.6 *Free chlorine residuals in final waters sorted by increasing mean*

Supply Zones
The supply zones used in the study were supplied exclusively from the treatment works. In the box-and-whisker plots shown in this section they have been given the same code as the appropriate treatment works (figure 5.8).

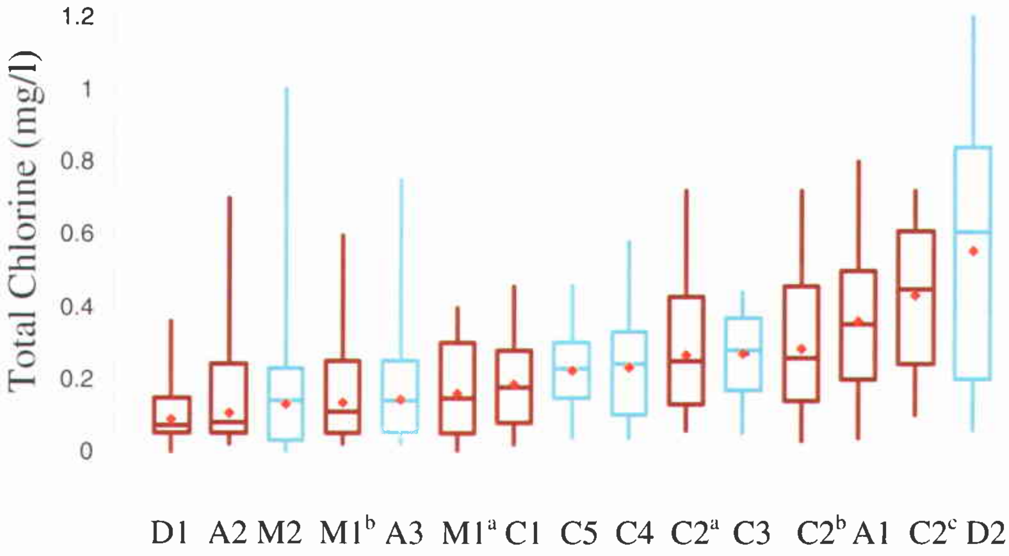


Figure 5.7 *Total chlorine residuals in distribution sorted in order of increasing mean*

In figure 5.8 and figure 5.9 the total chlorine and free chlorine residuals, respectively, for those distributions are plotted in order of increasing mean.

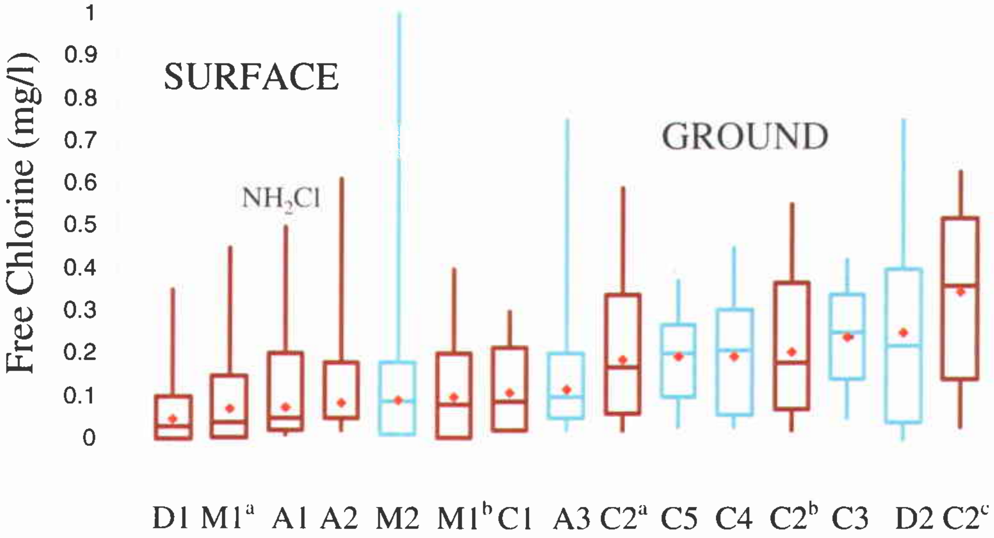


Figure 5.8 *Free-chlorine residuals in supply sorted by increasing mean*

The residuals of total and free chlorine show considerable variation in each of the supply zones. However, unlike the residuals in the final waters the polarisation between ground and surface derived sources appears to have been reversed with surface water exhibiting the lower free chlorine residuals in the supply (figure 5.9). Indeed in some of the surface water supplied zones large areas (up to 75% of samples) contain free chlorine residuals of <0.05 mg/l.

Summary
For the selected works and supply zones the following can be surmised:

- final waters from surface sources have arithmetic mean total chlorine residuals of 0.6 - 0.8 mgl-1. These residuals fall to 0.2 - 0.3 mgl-1 in distribution;
- final waters from ground water sources have significantly lower arithmetic mean total chlorine residuals of about 0.3mgl-1. This residual tends to be reduced in distribution to about 0.2mgl-1;
- large areas of some surface-derived zones contain low free chlorine residuals.

5.6.5 Trihalomethanes

THM data for the distributions were provided by one company (A). Box-whisker plots are presented in figure 5.10. The THM concentrations were highest in the chloraminated surface water zones (A1, mean = 47.0 µg/l) and lowest in the groundwater supplied zones (A3, mean = 2.5 µg/l).

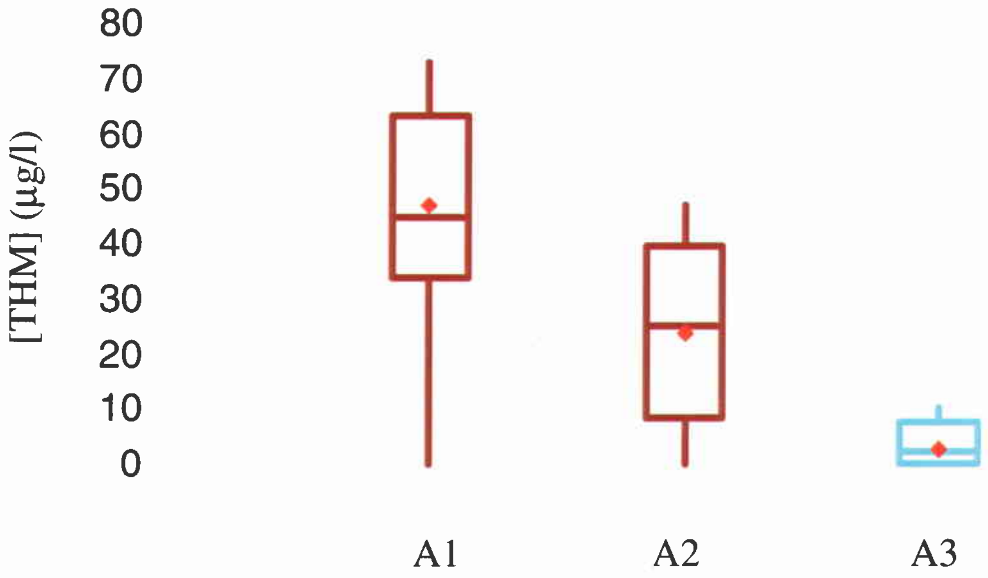


Figure 5.9 *THM data in the distributions for Water Company A*

5.6.6 Total Coliforms

The data for the occurrence of total coliforms in the final waters of each of the selected works is shown in figure 5.11. The vast majority of 100-ml samples do not contain coliform organisms. Indeed the 90%iles all recorded 0/100-ml. However, occasional failures do occur. In these situations the numbers of coliforms can be quite high with 200/100ml being present in one sample from treatment works A1. The box-whisker plots are sorted in order of increasing mean and there is some evidence of segregation into groundwaters and surface waters. Groundwaters can contain coliforms albeit usually at lower concentrations (10/100ml for treatment works A3).

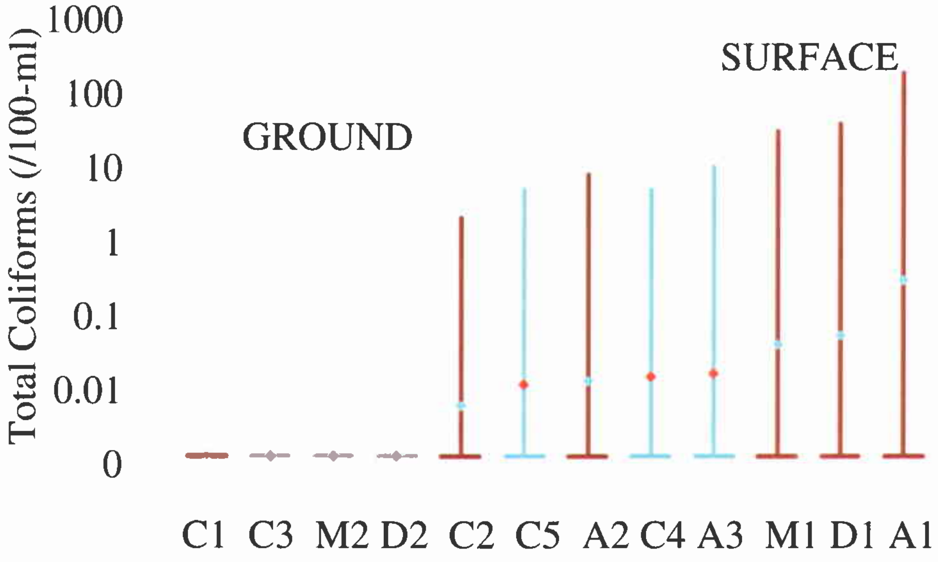


Figure 5.10 *Occurrence of total coliform organisms in final waters*

A similar picture emerges when the data for coliform occurrences in the supply zones are plotted in order of increasing mean (figure 5.11). There is perhaps a less obvious polarisation into ground and surface derived supplies than for the ex-works waters (figure 5.12). The 90%iles were 0/100-ml for all zones. Whilst the vast majority of 100-ml samples do not contain coliforms, the occasional high count was observed. Indeed supply A3 contained one 100-ml sample with 200 coliforms.

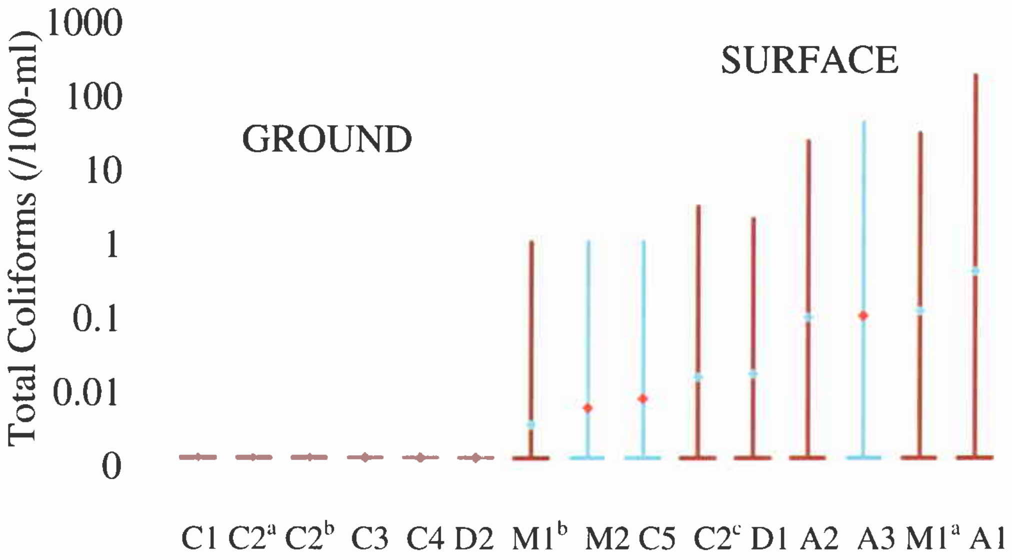


Figure 5.11 *The occurrence of total coliforms in samples from the supply zones. See fig 5.4 for explanation.*

5.6.7 Heterotrophic plate counts (22°C)

In figure 5.13 the 3 day (22°C) plate counts are plotted for each of the final waters of the selected works. In general the surface derived sources have higher counts than those derived from ground waters. This is particularly apparent from the median and 90 percentile values. There is considerable variation in the plate counts from each of the works with some having relatively high counts of 400-500 /ml, and others recording 0/ml. The final waters from ground water sources tend to have lower mean and median plate counts. In the results from monitoring of the supply zones, the same pattern is observed (figure 5.14) with the waters derived from groundwaters in general having lower median counts.

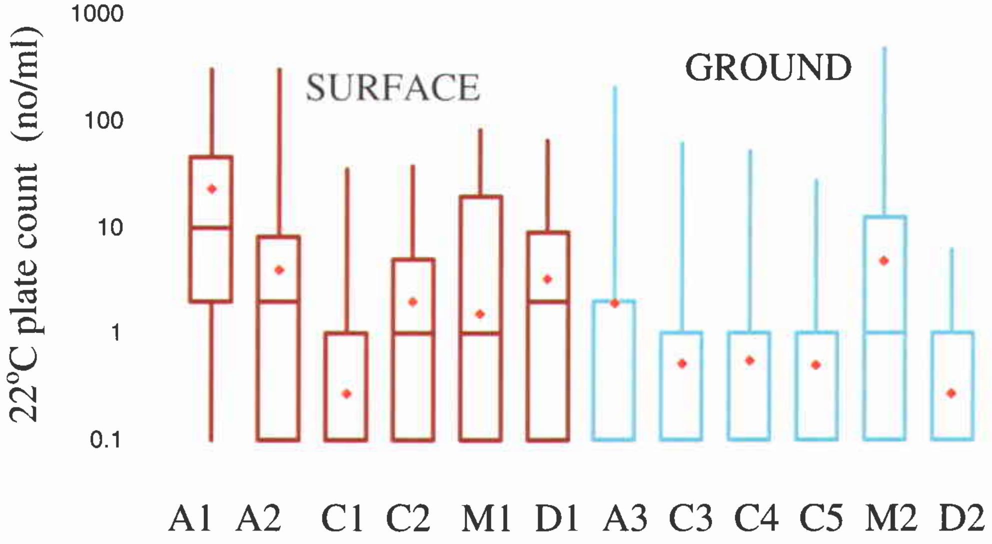


Figure 5.12 *3 day (22°C) plate counts for final waters*

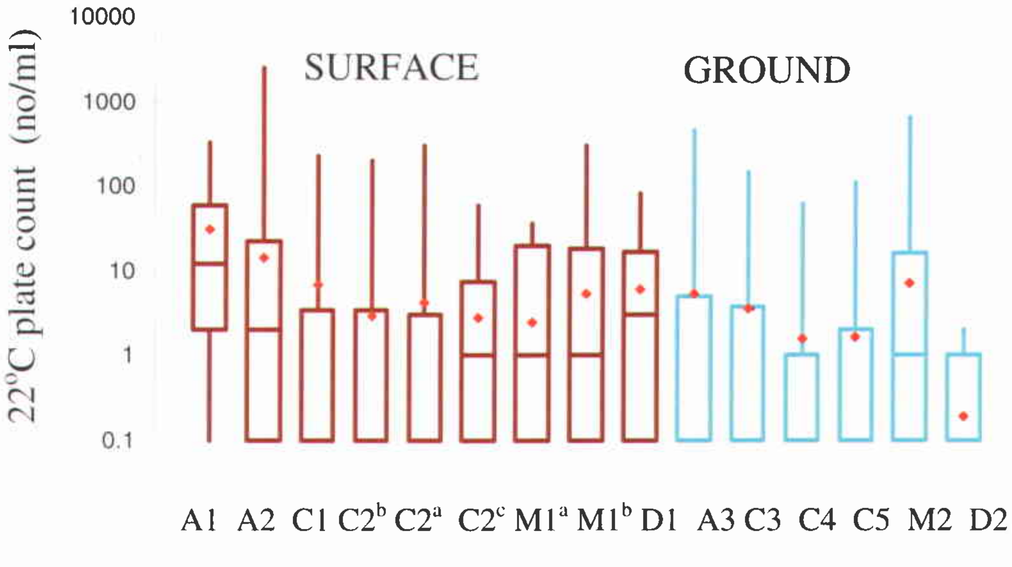


Figure 5.13 *Heterotrophic plate counts (3 day at 22°C) for supply zones*

Comparing the data in figure 5.13 with those in figure 5.14 suggests that plate counts increase in the distribution relative to the ex-works waters. It is not clear whether this increase is due to regrowth or to ingress through cracked pipes and reservoirs. In figure 5.15 the ratios of the mean of the plate counts in distribution to that in the final waters have been plotted.

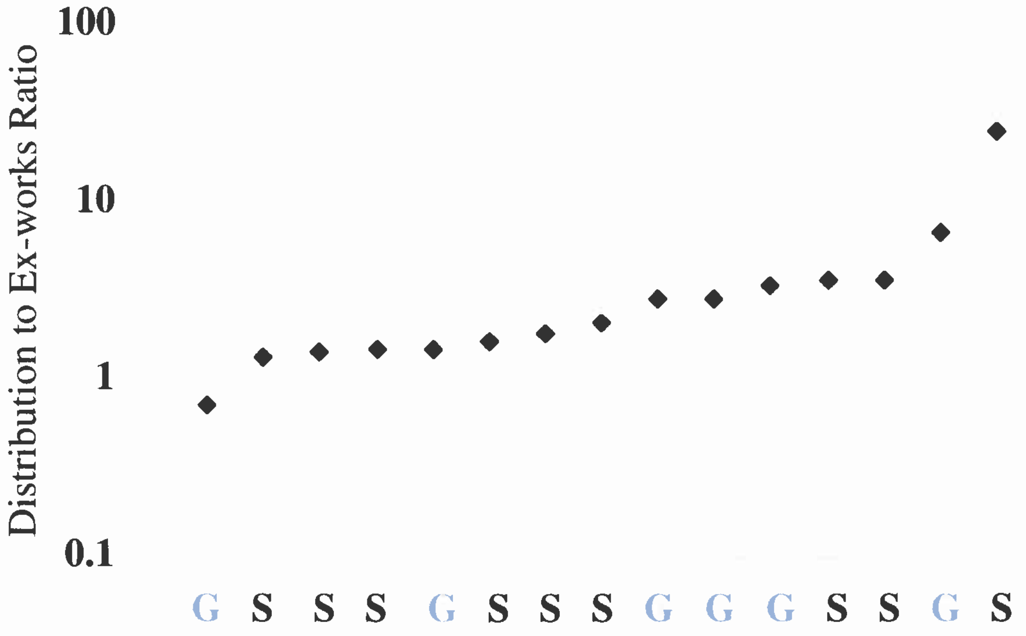


Figure 5.14 *Ratio of means of heterotrophic plate counts (22°C; 3 day) in supply and final waters*

The ratios were greater than one in virtually all cases confirming that the numbers of heterotrophic bacteria increase in supply. If there was a direct association between the type of source water and this increase in heterotrophs, arranging the ratios in ascending order should have given a clear polarisation of the ground and surface waters. However, no polarisation according to source water type is observed in figure 5.15, suggesting that source water is not the only factor controlling the growth of heterotrophs. It is likely that temperature, the way in which chlorine residuals in the selected zones were managed and the age (retention time) of the water in the distribution system would also have an influence on the growth of heterotrophs.

5.6.8 Heterotrophic plate counts (37°C)

In figure 5.16 the data for heterotrophic counts at 37°C in the final waters are shown. The surface derived waters have higher median and 90%ile counts than those from groundwater sources. The maximum counts for two of the plants treating surface water exceed 300/ml. It should be noted that some groundwater final waters do have high counts.

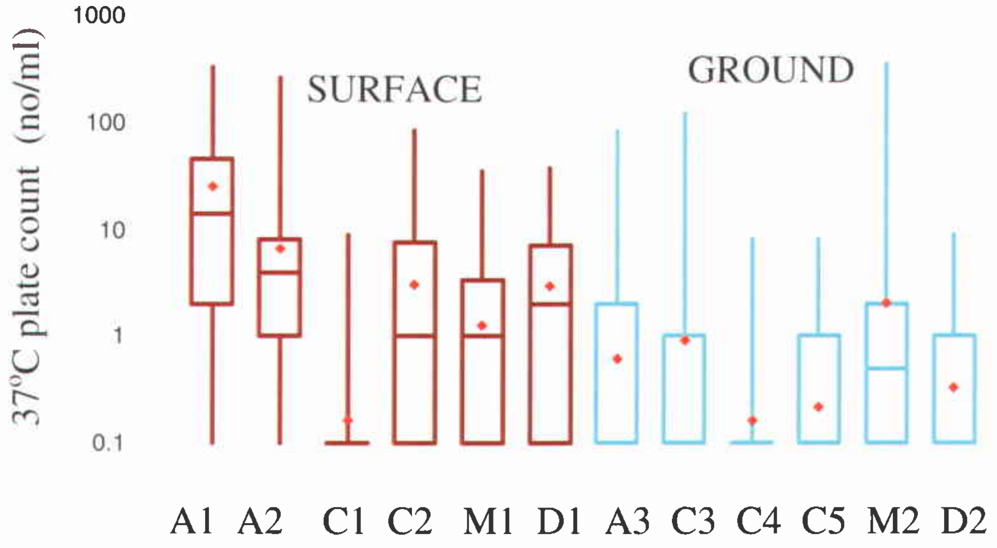


Figure 5.15 *Heterotrophic plate counts (37°C) in final waters*

The data heterotrophic plate counts (37°C) for the supply zones are shown in figure 5.17. Counts are higher in the surface water zones than in the ground water zones.

As should be expected, heterotrophic bacteria which grow at 37°C do not proliferate to the same extent as the 22°C plate counts in the distribution systems even in those supplied by water derived from surface sources. Whilst these heterotrophs do not appear to proliferate they do survive. Again there is some difference between the data for the surface and ground derived waters with the latter generally having lower median counts. However, some distribution samples from groundwater sources do have high counts.

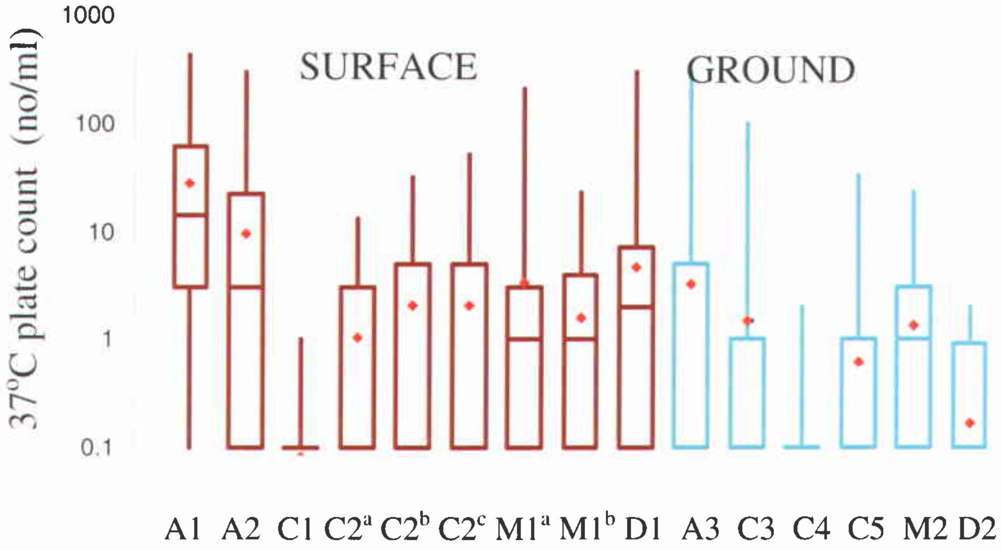


Figure 5.16 *Heterotrophic plate counts (37°C) in the supply zones*

5.6.9 Temperature

Temperature is an important factor in the maintenance of chlorine residuals and in influencing the rate of heterotrophic growth. The temperature data for the final waters is shown in figure 5.18.

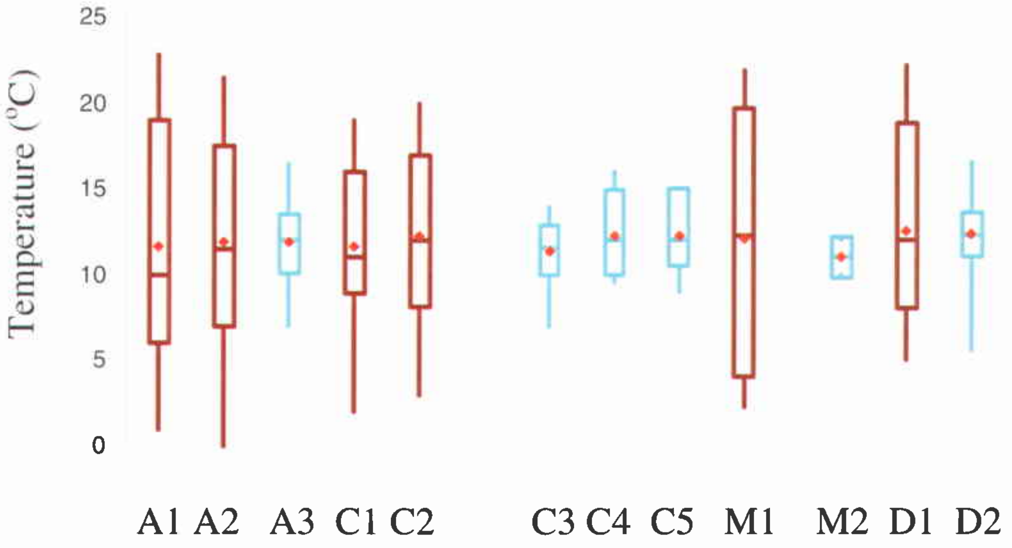


Figure 5.17 *Temperatures of final waters*

In terms of the central tendency there is little difference between ground and surface waters although the latter show much greater variation.

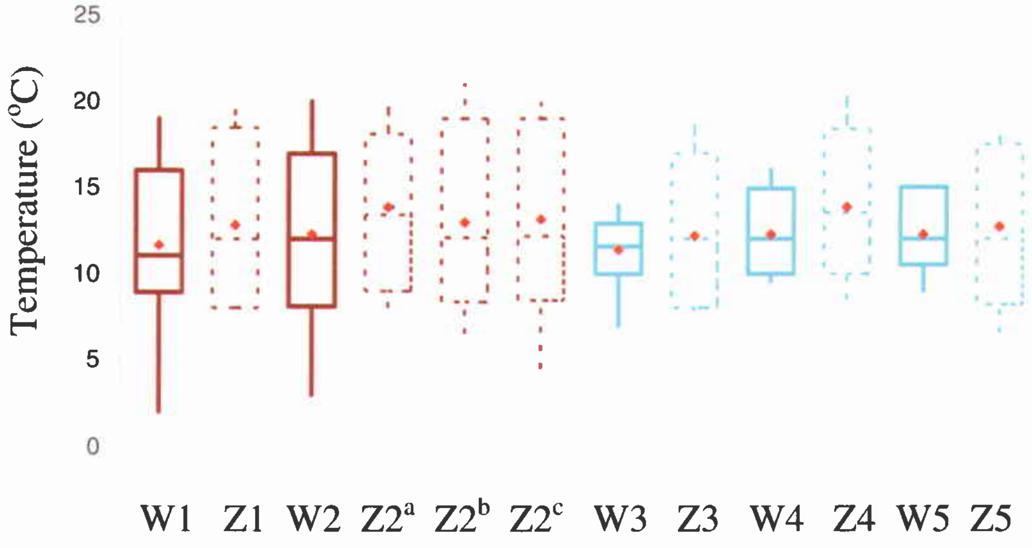


Figure 5.18 *Comparison of water temperatures in final waters (W) and distribution zones (Z) in five supplies (April to October) for Water Company C*

In figure 5.19 the temperature data has been plotted for five systems from Water Company C during the summer months. In general water temperatures are higher in samples from the distribution zones (Z) than from the corresponding the final waters (W). It also shows that surface-derived ex-works' waters are prone to much greater variations in temperature than are groundwaters although in samples from the distribution system this difference is not so pronounced.

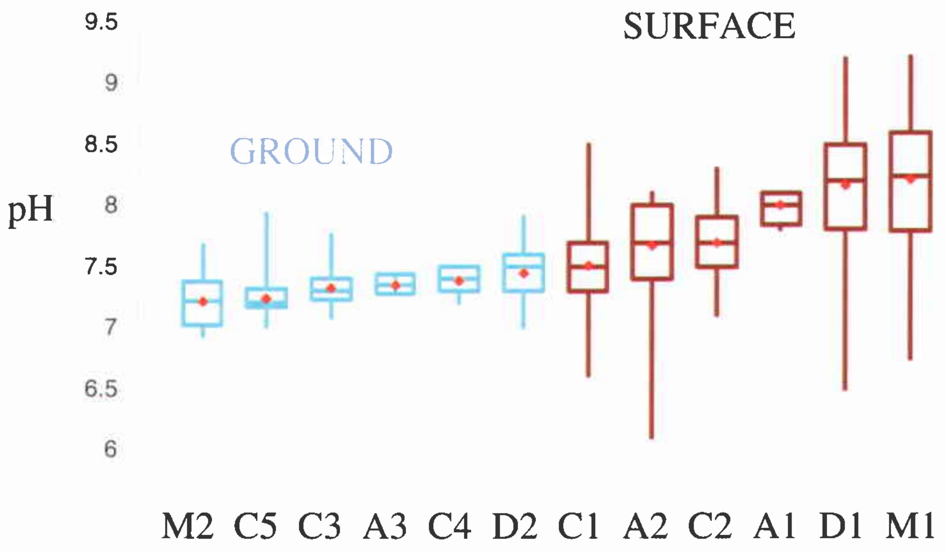


Figure 5.19 *Values of pH of final waters in order of increasing alkalinity*

5.6.10 pH

In figure 5.20 the pH data for the final waters of the selected works is plotted in order of increasing alkalinity. There is a clear polarisation of the groundwaters and the surface waters. The surface waters also show much greater variation in pH with the hydrogen ion concentration varying by more than 100 fold. This variation in pH is likely to influence the efficiency with which these surface derived sources can be disinfected since chlorination is most efficient below pH 7.

5.7 The importance of chlorine in maintaining the microbiological quality of water

In the data collected as part of this study there were insufficient occurrences of coliforms to attempt to study the impact of chlorine. However the data on heterotrophic plate counts (22°C) allow some general conclusions to be reached in assessing the importance of chlorine to UK systems.

In figure 5.21, box-whisker plots for heterotrophic bacteria (22°C; 3 day) in samples from the supply zones have been plotted in order of the increasing mean total chlorine concentration for each supply. It is apparent that there is an association in terms of plate counts decreasing with increasing total chlorine concentration. This effect can be seen more clearly in figure 5.22 in which the mean plate count for each supply has been plotted against the mean total chlorine concentration for that supply. The relationship seen is statistically significant. Indeed a linear regression model can be written as:

$$\log_{10}(\text{Mean plate counts (22°C)}) = 1.12 - 2.6\,[\text{Total Chlorine}]$$

These observations suggest that the UK policy of maintaining chlorine residual throughout distribution has a preservative influence on the microbiological stability of the water.

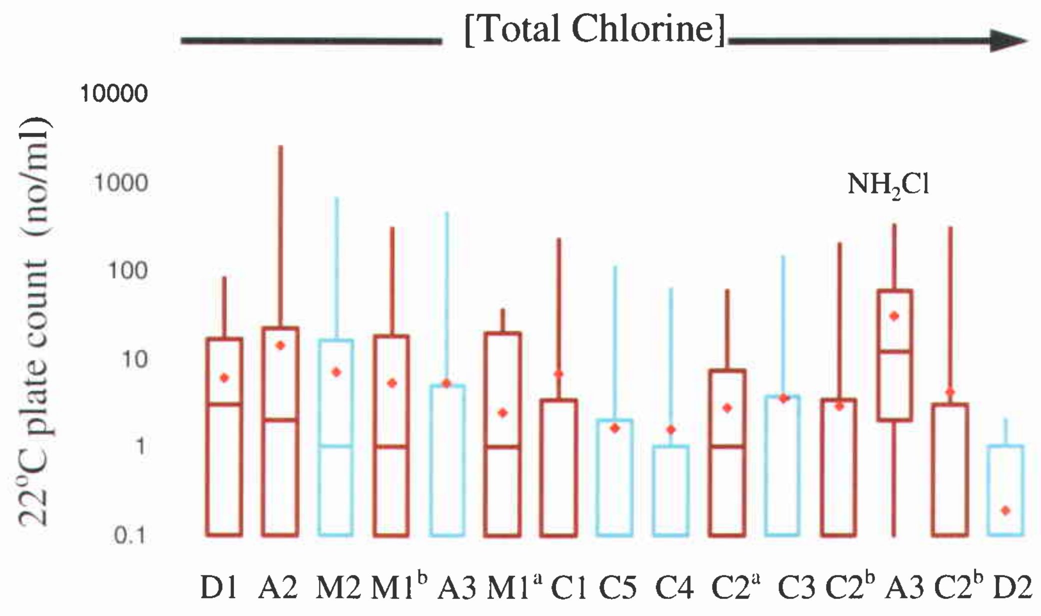


Figure 5.20 Heterotrophic plate counts (3 days at 22°C) for supply zones sorted in order on increasing total chlorine

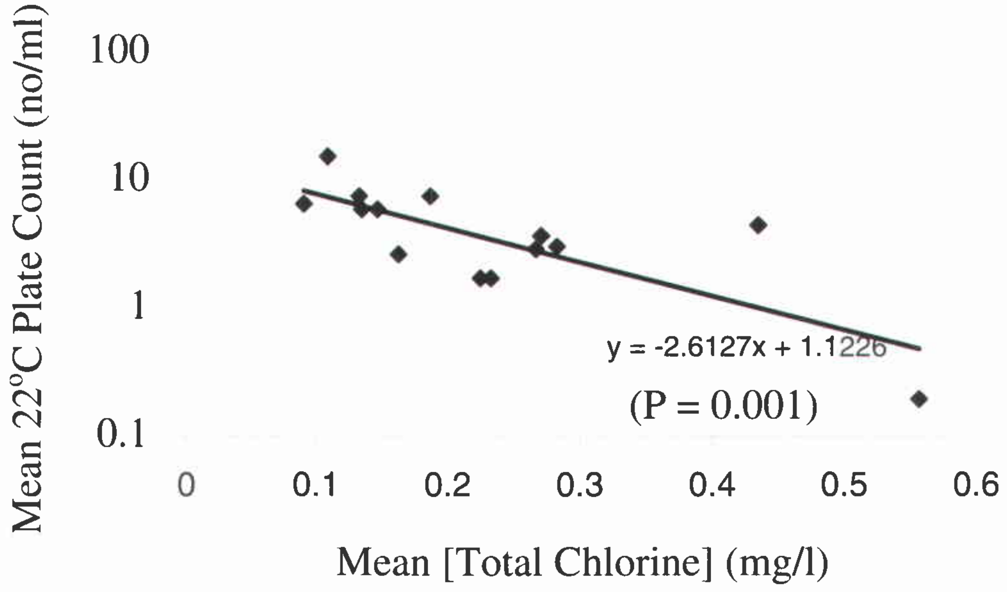


Figure 5.21 *Linear regression analysis for heterotrophic plate count (22°C) and total chlorine concentrations for groups of zones (Chloramine zone A3 omitted)*

Figure 5.23 shows the same box-whisker plots for plate counts (22°C; 3 day) but plotted in order of increasing mean free chlorine concentration for each supply. Again a decrease in plate count numbers with increasing free chlorine is apparent. However, the effect does not appear to be so marked as for total chlorine, although the relationship is statistically significant at 5% (figure 5.24).

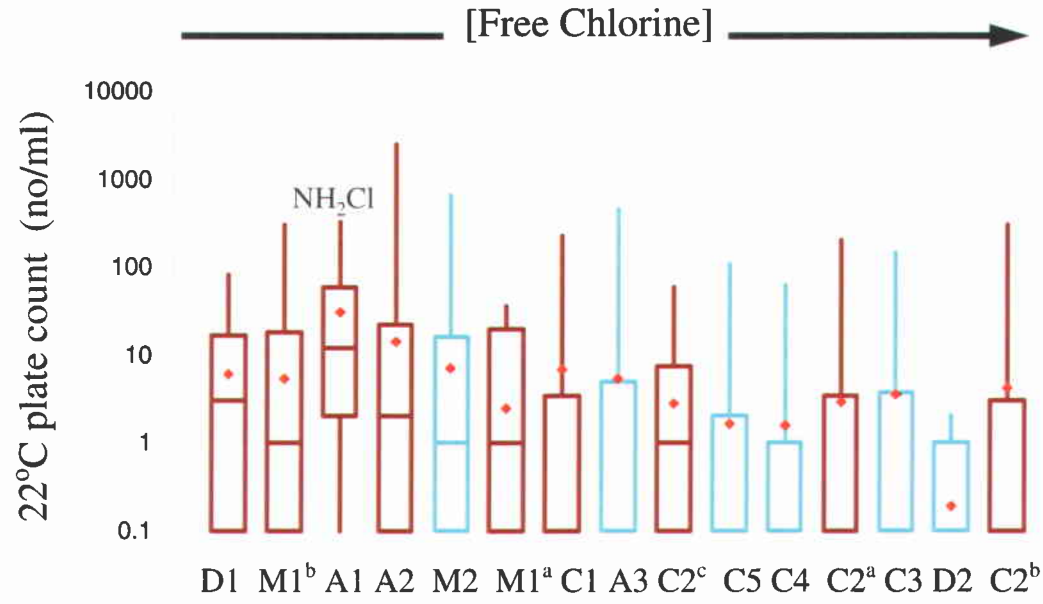


Figure 5.22 *Heterotrophic plate counts (22°C) for supply zones sorted in order of increasing mean free chlorine concentration*

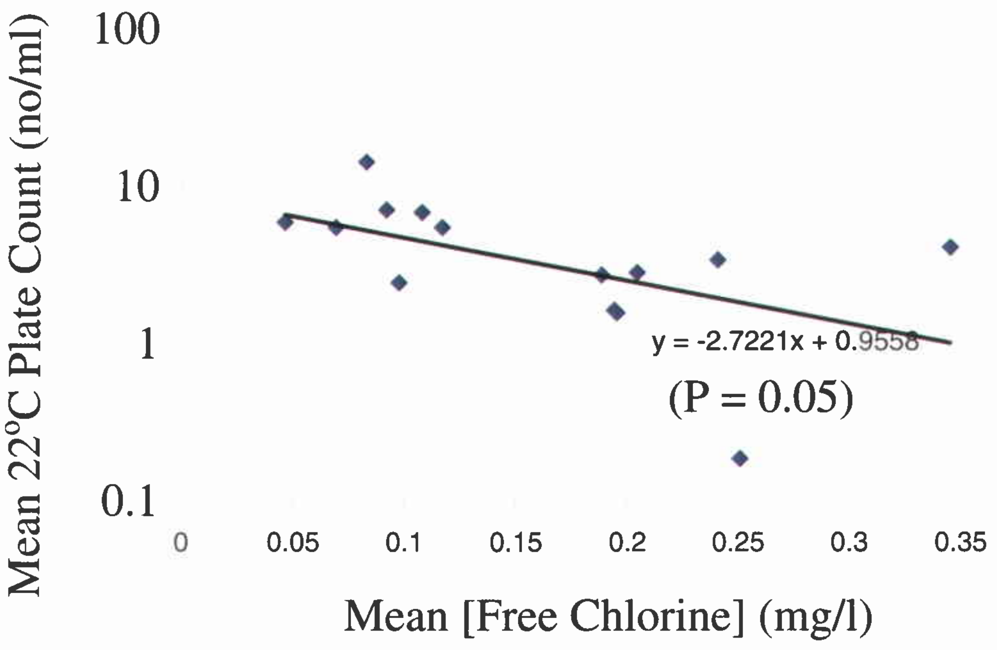


Figure 5.23 *Linear regression analysis of mean heterotrophic counts (22°C) and mean free chlorine residuals for groups of zones (Chloramine zone A3 omitted)*

As part of the work on limiting chlorine residual in distribution other factors such as biostability are being investigated (Section 5.4). Even if levels of biostability similar to those in the Netherlands could be achieved increased levels of heterotrophs in the absence of a chlorine residual may still occur. Figure 5.25 compares the heterotrophic bacteria content of the waters selected for study in the Netherlands and the UK.

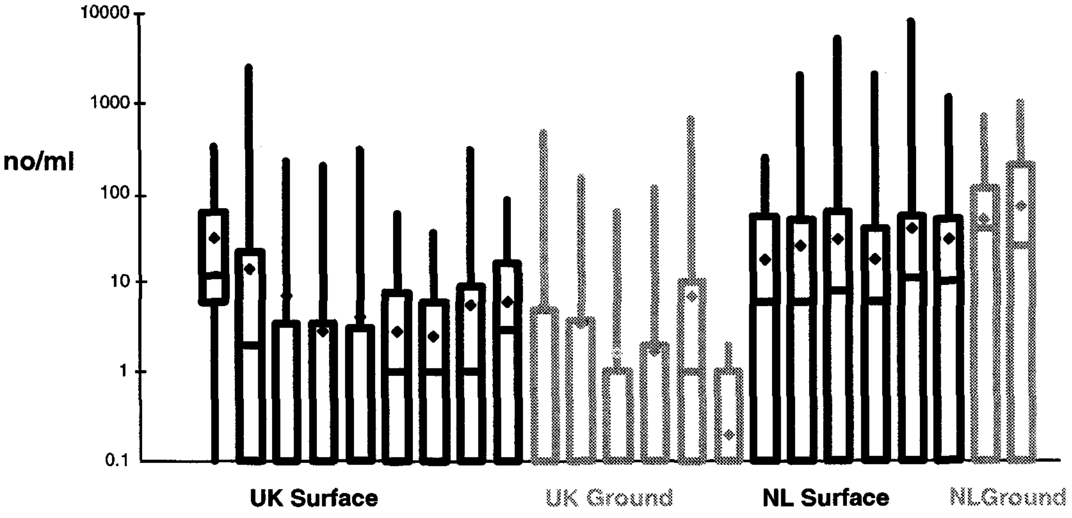


Figure 5.24 *Comparison of 22°C heterotrophs in UK (with chlorine) and NL (without chlorine) systems*

There is an indication that heterotrophic plate counts are higher in the NL where chlorine residuals are not maintained in supply and a policy of treating the water to achieve biostability is preferred. There are however differences in analytical methods in the two countries which could also account for some of the differences.

On the basis of the data for the UK systems an indication may be obtained of the way in which heterotrophic counts could change if chlorine residuals were not maintained and current treatment was not altered.

The effect of reducing chlorine residuals on the incidence of heterotrophic bacteria in the distribution supplied by a surface water source (M1) used in this study has been predicted using a generalised linear model of the type shown in figure 5.25.

Equation 1 $\ln (p / (1 - p)) = \alpha - \beta.[\text{Total Chlorine}]$

Where p is the probability of a 1-ml volume containing more than a certain number of plate count bacteria, α is a constant and β is the coefficient relating p to the total chlorine concentration. This approach has been previously developed by UKWIR for modeling coliform occurrences in drinking water distribution systems (Gale *et al.* 1997).

The results of the GLM analyses are shown in table 5.12. Plate counts were investigated at three levels; >0/ml, >10/ml and >100/ml. Column 4 presents the coefficient (β) for the GLM (table 5.12) relating total chlorine concentration to the probability (p) of the plate count exceeding the chosen count. The coefficients were statistically significant for all three levels. (It should be noted that only three samples contained more than 100 counts/ml and the appropriateness of modeling procedure for plate counts at this level may be limited in this particular example).

Table 5.12 Predicted impact of zero chlorine on heterotrophs in a supply zone

1	2	3	4	5
22°C plate count		**% positive**	**Effect of chlorine (β)**	**Effect of zero chlorine**
>0/ml	Ex-works	59%	nd	
	Distribution	69%	-3.8*	80.0%
>10/ml	Ex-works	1.6%	nd	
	Distribution	7.0%	-13.4*	27.0%
>100ml	Ex-works	0%	nd	
	Distribution	0.4%	-36.3*	7.0%

*statistically significant at 5% level of significance

Column 3 presents the percentage of samples with counts greater than the three chosen levels (i.e. >0, >10, and >100/ml) at the distribution sampling point compared to the works final water. It is apparent that the percentage of counts exceeding each level increases in the distribution compared to ex-works. Column 5 shows the effect on plate counts in each level of removing the chlorine from the distribution as predicted by the GLM. For counts >0/ml the model predicts a change from 70 % to 80%. For samples with counts >10/ml the impact of zero chlorine in distribution is much greater with an increase from 7 to 27%. The model for plate counts exceeding 100/ml, predicted an even greater impact of chlorine with the samples with more than 100 count/ml increasing from 0.5% to 7.0% on removing the chlorine from the distribution. (It should be noted that this model could be improved by recalibrating on a data set with more than just three samples exceeding 100 counts/ml). These latter increases of a factor of 4 and 15 are potentially serious in terms of water quality and suggests that chlorine plays an important role in maintaining the microbiological quality of water in this system.

The modeling suggests that in the UK the maintenance of a chlorine residual in supply provides an effective means of preserving the microbiological quality of drinking water.

Whilst previous work for UKWIR has shown that many of the waters in the UK are reasonably biostable this was dependent on the use of good disinfection at the treatment works to reduce the microbial loading of the water to levels approaching the detection limit of analytical techniques. The period required for the chlorine to decay to ineffective levels preserved microbial quality after which deterioration commenced. However, because of the low initial inoculum, this deterioration required several days before it was detectable using routine plate count techniques. Without chlorine, the presence of a higher initial inoculum and lack of preservation would lead to a more rapid decline in microbiological quality.

It is concluded therefore that before the use of chlorine in distribution can be abandoned or significantly reduced a better understanding needs to be obtained about the relationship between the components of biostability (Assimilable Organic Carbon and Biofilm Formation Potential) and preservation with chlorine.

6 A comparison of the approach used in the United Kingdom and in the Netherlands

In chapters 3 and 5 of this report the approaches taken to the supply of drinking water in the Netherlands and the United Kingdom have been discussed by reference to representative water treatment plants and distribution systems. The major difference identified is that, unlike in the UK, no attempt is made to maintain a chlorine (or other oxidant) residual in the distribution systems in the Netherlands.

To ascertain how important the maintenance of a disinfectant residual is for controlling quality a more detailed comparison of the approaches taken in the two countries is presented in this Chapter.

The approaches used have been compared under the general headings of:

- sources of raw water;
- treatment strategies;
- distribution materials;
- compliance monitoring;
- water quality.

6.1 Sources of water

Groundwaters are usually of excellent microbiological and chemical quality and they require little or no treatment before use as potable supplies. In contrast water derived from surface sources is of poorer quality and as a consequence they require relatively extensive treatment.

The proportion of ground and surface derived sources used in the UK and the Netherlands is shown in Table 6.1.

Table 6.1 *Proportion of water sources by type and volume in the NL and the UK*

SOURCE	**NL** **Population 15.6 m**		**UK** **Population 57.6 m**	
	10^6 $m^3.y^{-1}$	percent	10^6 $m^3.y^{-1}$	percent
Groundwater	803	62	1956	32
Direct surface	0	0	2493	40
Reservoir and dune filtration	416	38	1688	28
Total	1219	100	6137	100

The volume of water produced in the UK is about 5 times greater than that in the Netherlands. About 60 percent (by volume) of the drinking water produced in the Netherlands is derived from groundwaters compared to 30 percent in the UK. Accordingly surface water sources are used more extensively in the UK. Of the 60 percent derived from these sources only 28 percent is impounded whereas in the Netherlands all surface water sources are treated by storage in reservoirs or dune infiltration.

Table 6.2 *Proportion (%) of ground and surface waters used in he UK, NL, France and Germany*

Country	Groundwater(%)	Surface water (%)
UK	30	70
NL	66	34
France	61	39
Germany	64	36

It can be seen from Table 6.2 that in the context of our European neighbours the UK relies to a much greater degree on surface derived sources. The proportion of groundwaters used in the Netherlands being very similar to that used in France and Germany.

6.2 Treatment strategies

As might be expected the strategies used in the UK and the Netherlands for the treatment of surface derived sources are basically similar with a multiple barrier approach being used in both countries. Although combinations of physico-chemical treatments and disinfection are used in both countries, differences exist and these are illustrated and discussed in the following sections

6.2.1 Treatment in the UK

Surface Waters Sources

A typical treatment strategy in use for surface water sources in the UK is shown in Figure 6.1.

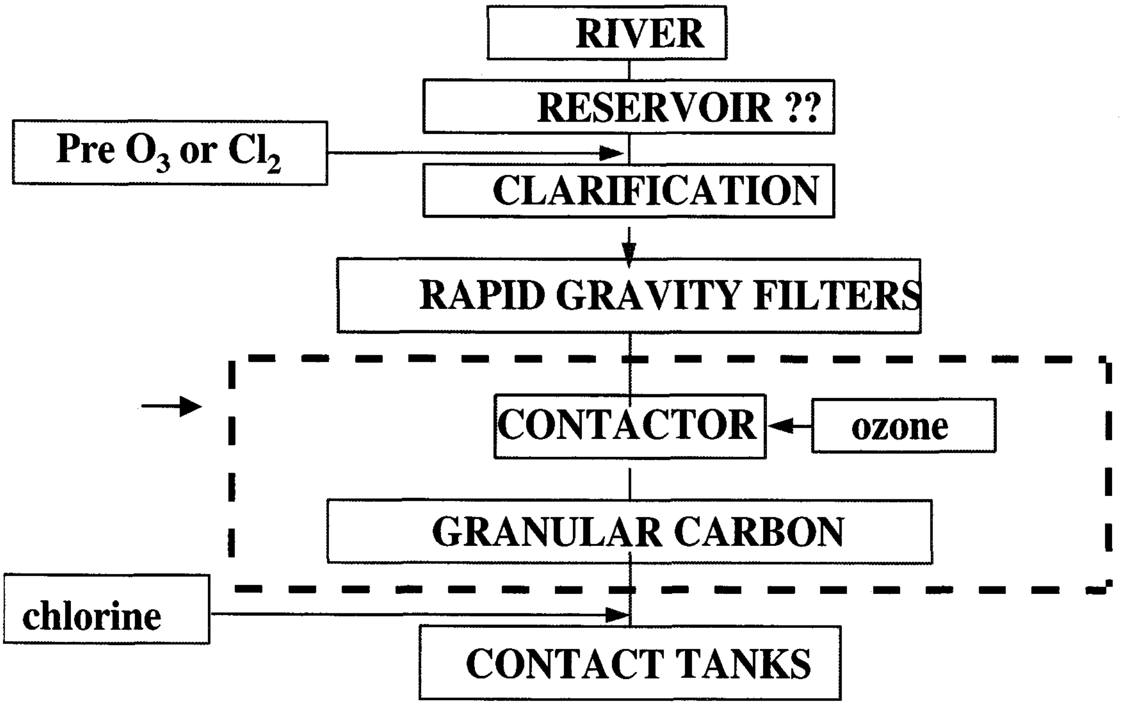


Figure 6.1 *Typical UK treatment strategy for surface derived sources. In box: additional treatments used in Advanced Water Treatment.*

Impoundment in reservoirs is only used in 40 percent of surface derived sources and the use of pre-chlorination or ozonation is decreasing because of problems with the formation of disinfection by-products. The physical process of coagulation and sedimentation are in widespread use with ferric and alum coagulants being the most popular. Rapid Gravity Filtration using sand as the filter medium is most commonly used although at some works Granular Activated Carbon is replacing sand. The processes enclosed within the dashed box in figure 6.1 are being added to up rate treatment works to what is termed Advanced Water Treatment. These processes are being added to bring improvements in the removal of specific contaminants such as pesticides. The most common treatments in the UK are therefore: coagulation and sedimentation followed by rapid sand filtration and final disinfection (chlorination).

Groundwater Sources

The majority of groundwater abstractions from aquifers in the UK receive little treatment other than chlorination. The major aquifers in terms of extent and potable water abstraction are the chalk; covering much of south east England and; the Permo-Triassic sandstones, extending from the north east, through the midlands down into Southwest England. Several minor aquifers are also used, including the Lower Greensand, Jurassic Limestone, Magnesian Limestone and the Carboniferous Limestone, as well as drift deposits such as the Thames Gravels.

The factors affecting the quality of groundwaters are complex and include:

- the ability of overlying strata and soils to retain contaminants from infiltrating waters;
- the extent of these deposits;
- the residence times of water within the unsaturated zones;
- the chemical matrix of the aquifer deposit;
- the degree and importance of matrix versus fissure flow;
- physico-chemical properties such as cation exchange capacity or organic matter content.

The Soil Survey and Land Research Centre have developed a three-fold classification of soil types based on the physical properties of the soil , with soils classified as having high, intermediate or low leaching potential. Like the unsaturated zone of an aquifer, the soil can be important in attenuating micro-organisms through physical, chemical and biochemical process.

6.2.2 Treatment in the Netherlands

An example of the treatment strategy used in the Netherlands to treat water abstracted from a river water is shown in Figure 6.2.

In the Netherlands most surface waters are impounded or dune filtered either before or after further treatments are applied. The subsequent treatment strategy may be similar to that used in the UK as part of Advanced Water Treatment. Where a disinfectant is used the residual produced is allowed to decay and there is no policy of trying to maintain a low residual throughout the distribution system. Final chemical disinfection is used in only 22 per cent of the distributed volume derived from surface water sources. In areas where the natural geology allows the use of dune infiltration the strategies shown in Figure 6.3 are used. Even after dune infiltration a number of treatment processes are used such as biologically active carbon and slow sand filtration. Being biological as well as physical these treatment processes reduce the assimilable organic carbon (AOC) content of the water increasing its biostability and reducing its biofilm formation potential.

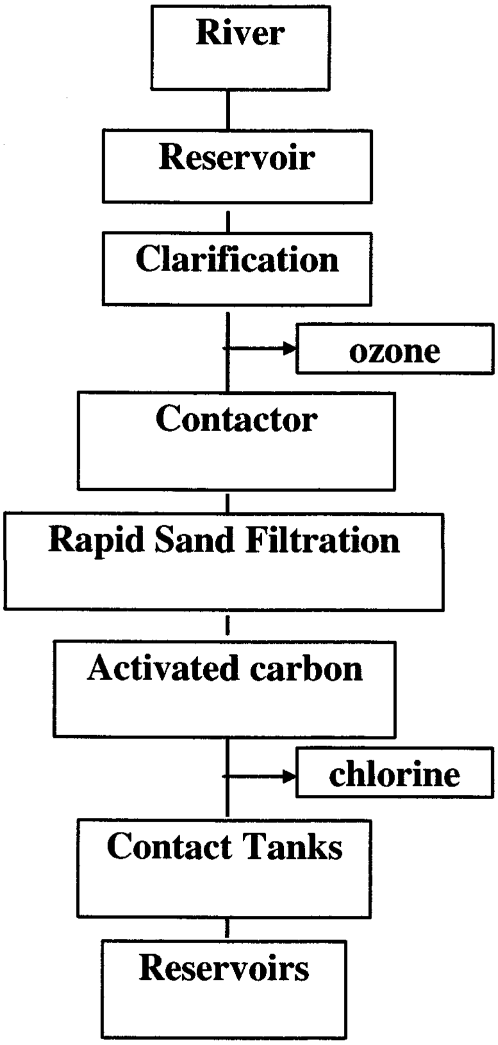


Figure 6.2 *Strategy for treating river water sources in the Netherlands.*

6.2.3 Comparison of UK and NL treatment strategies

In the Netherlands there is greater use of biological treatments such as storage in impoundment reservoirs, soil (dune/bank) passage, biological activated carbon filtration and slow sand filtration. Chemical disinfection (chlorine and ozone) are used within the treatment train in both countries, but there is much less emphasis on final disinfection in the Netherlands. The number of barriers (treatment processes) used at any one plant tends to be greater in the Netherlands. The main differences in treatment used in both countries are given in Table 6.3.

In the Netherlands the use of oxidants is in most cases combined with impoundment, and also with dune infiltration. Rapid sand filtration is common for the treatment of ground waters. Dual media filters are used as part of the treatment of surface waters.

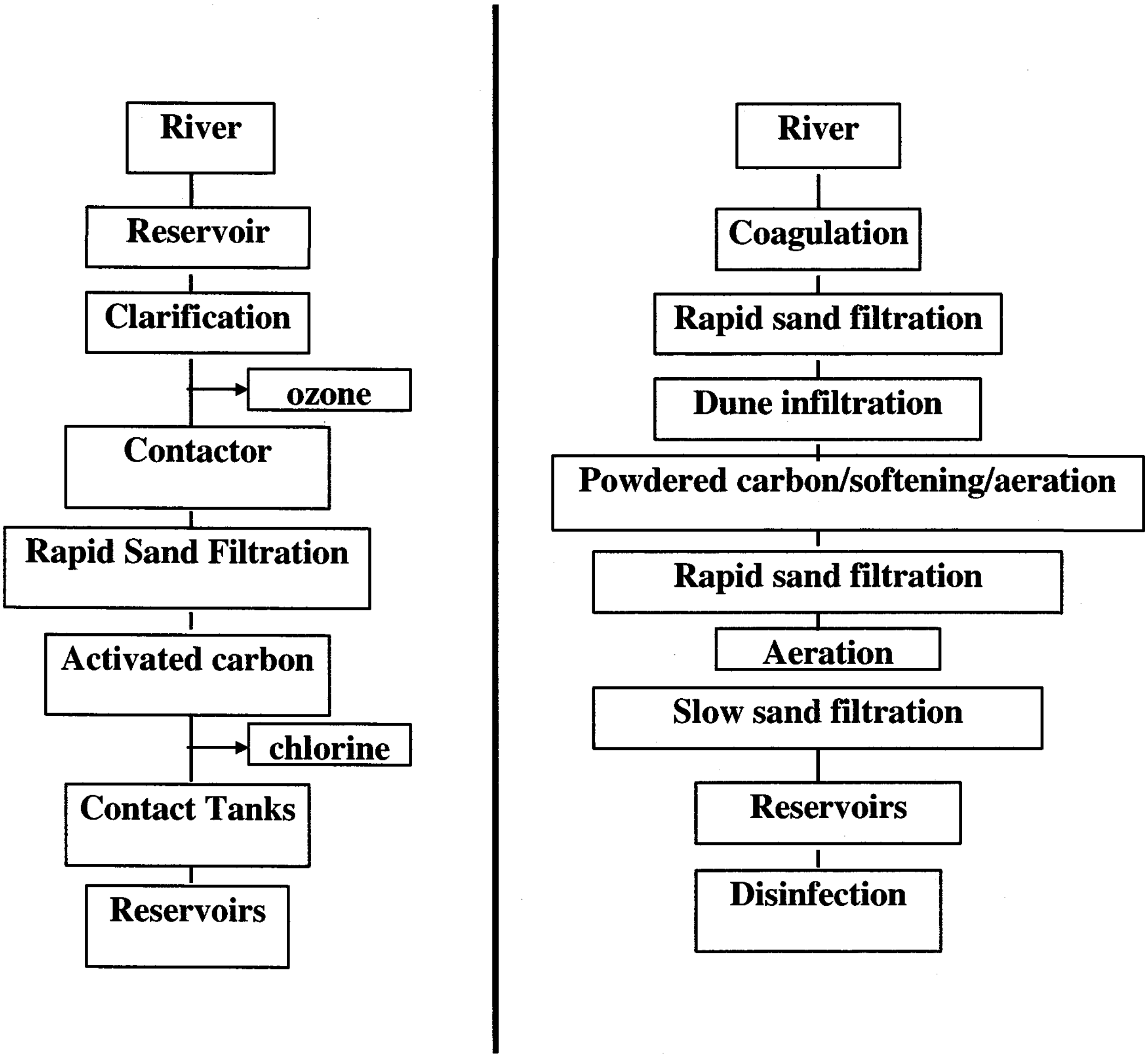


Figure 6.3 *Treatment strategies with dune infiltration in the Netherlands*

Table 6.3 *Comparison of UK and NL surface water treatment strategies*

Treatment	NL	UK
Impoundment	Most works	40%
Dune passage	4 of 10	not
Pre chlorination/ozonation	Most	Some but decreasing
Biological filtration	Common	rare
Final disinfection	22% of surface sources	vast majority of supplies
Main disinfectant	Chlorine dioxide	Chlorine
Maintain residual in supply	No	Yes

6.3 Materials in distribution

The distribution system of the Netherlands consists of approximately 100,000 kilometres of pipe with a diameter of more the 63 mm (see Chapter 5). The UK distribution network is three times larger consisting of more than 316, 000 kilometres of pipe with a diameter greater than 50 mm.

Over the last sixty or more years there have been differences in the materials used to construct and refurbish the distribution systems in both countries. In the early part of this century cast iron mains were almost exclusively used, but materials such as asbestos cement gained in popularity until disadvantages were found with the use of this material.

In more recent years unplasticised PVC (uPVC) has become the main material of choice in the Netherlands. PE has been a main material since the 1980s, but has been used to a much lesser degree (< about 2%) than PVCu. It is used in the majority of service lines. In the UK ductile iron with a cement mortar lining has been increasingly used but plastics such as uPVC and MDPE now make up about 16 percent of all new mains.

Based on the best available information the current position with respect to the amount of different materials now in use is given in Table 6.4. This shows that in the UK iron still predominates although PE is now used for 99% of service pipes and 60% of mains (50-300 mm in diameter). In the NL uPVC and Asbestos Cement are the most common materials in use.

Table 6.4 *Different materials currently in use in the UK and NL distribution systems*

Material	NL (km)	UK (km)
Iron	15.000	173.500
AC	35.000	35.000
uPVC	39.000	49.000
PE	2.500	25.000

The differences between the Netherlands and the UK in the change of use of materials over the years 1960-1995 can be seen in Figs 6.4 and 6.5, respectively. These figures show the percentage of different materials which were in use for each of these years.

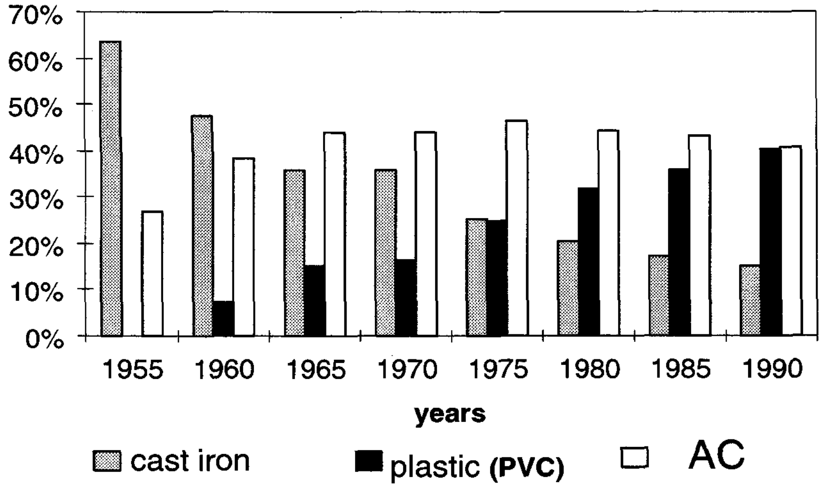


Figure 6.4 *Percentage of different materials in use in distribution systems (NL)*

Figure 6.4 and figure 6.5 show that there has been a different approach in the two countries with regard to the refurbishment of existing and construction of new distribution systems. In the UK relining of cast iron has been the predominant method whereas in the NL replacement with uPVC and PE pipes has occurred. As a consequence, in the UK more than 60% of the pipework is still made of cast iron and just under 30% is constructed of plastic materials. In the Netherlands less than 15 % is constructed from cast iron and plastic materials account for more than 40 per cent. Cast iron still predominates in old town centres and villages.

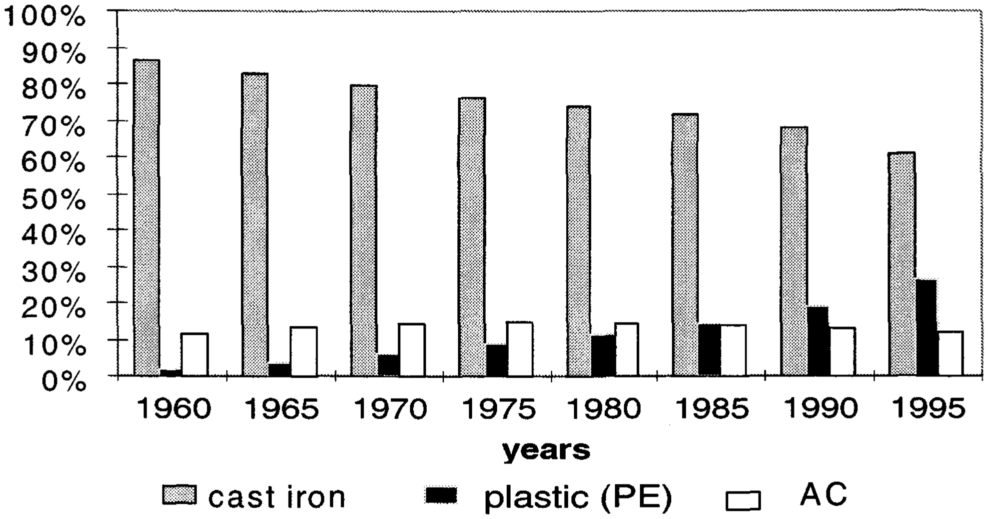


Figure 6.5 *Percentage of different materials in use in distribution systems (UK)*

6.4 Statutory monitoring

Monitoring is carried out by water company laboratories in both the NL and the UK and results are reported to similar Government Departments.

The same microbiological parameters are used in both NL and UK. These are:

- Total coliforms 37°C.
- Thermotolerant coliforms (faecal coliforms) 44 °C (*E. coli*).
- Faecal streptococci.
- Clostridia spores.
- Heterotrophic Plate Count 22 °C.
- Heterotrophic Plate Count 37 °C.

In the Netherlands standards for indicator bacteria are all <1/100 ml except at treatment works where the standard for coliforms is more stringent being <1/300 ml. Standards in the UK are all 1/100 ml except for clostridia which is <1/20 ml. Only repeat samples are analysed for faecal streptococci and clostridia.

In the UK all occurrences of coliforms are considered failures of microbiological quality and must be reported as such. In the NL the detection of coliforms in a sample does not constitute a failure unless indicator organisms are also detected in repeat samples taken at the same location.

Since disinfection residuals are not used to maintain microbiological quality in distribution in the NL there is a greater emphasis on monitoring that regrowth does occur. As a consequence, in the NL there are standards for heterotrophic bacteria in samples taken from the distribution system. These standards (only for distribution systems) are yearly geometric means of <100 cfu/ml (22°C) and <10/ml (37°C), respectively. In addition there is guidance, but no standards, on the numbers of aeromonads in samples from the distribution system since these organisms are considered a more sensitive indicator of potential regrowth than heterotrophic bacteria. Present guidance values are: a 50 percentile of 20 cfu/100 ml and a 90 percentile of 200/100 ml. In revised legislation, expected to become effective at the end of 2000, a maximum value of 1000 cfu/100 ml for aeromonads will be included.

In the UK there are no quantitative standards for heterotrophic bacteria except that there should be no significant increase over that normally observed. This 'standard' applies to works final waters and samples taken within the supply zones.

6.5 Water quality

6.5.1 National Data

To gain an insight into the relative values of the approaches being taken in the UK and NL the statutory monitoring data for the years 93-95 has been compared, in Table 6.5, in terms of the occurrences of coliforms.

Table 6.5 *Summary of national monitoring data from the UK and NL*

	Works final water		**Distribution**	
	% positive	no samples	% positive	no of samples
NL				
Coliforms	0.10	15 000	0.03	30 500
Thermo coliforms	0.18	2 200	0.006	16 000
UK				
Total coliforms	0.2	209 000	0.73	160 000
Thermo coliforms	<0.1	209 000	<0.1	160 000

The results for the works final waters from both countries seem reasonably comparable and both countries comply with high standards. However, the occurrence of total coliforms in supply samples for the UK is higher than for the NL although it is impossible to judge how the different definitions of a 'failure' have affected the data.

6.5.2 Representative plants

Coliforms

The occurrence of coliform organisms in the final waters from the selected UK and NL water treatment works are shown in figures 6.6 and 6.7. The failure rates in terms of coliform bacteria are fairly similar in that, in both countries, coliforms were not detected in the final waters produced by several of the plants selected used in the study. However, at plants where coliforms were detected, the failure rate tended to be slightly higher at the UK compared to the NL treatment plants even though in the UK all waters had been disinfected. However differences between the two countries in the definition of a failure will exaggerate this difference.

The results indicate that the approach used in the NL of using more physical and biological treatment barriers and no final disinfection produces water of quality at least as good as that in the UK where final disinfection is an integral part of the treatment strategy.

Figure 6.7 presents the results of monitoring for coliform bacteria in the selected UK and NL distribution systems. Coliform bacteria were not detected in six of the chosen UK distribution systems. Coliform bacteria were detected in all chosen NL systems at rates similar to those of the UK systems in which coliforms did occur. These results indicate that maintenance of a chlorine residual in distribution, as used in the UK, may be at least as good as the NL approach of relying on producing biostable water.

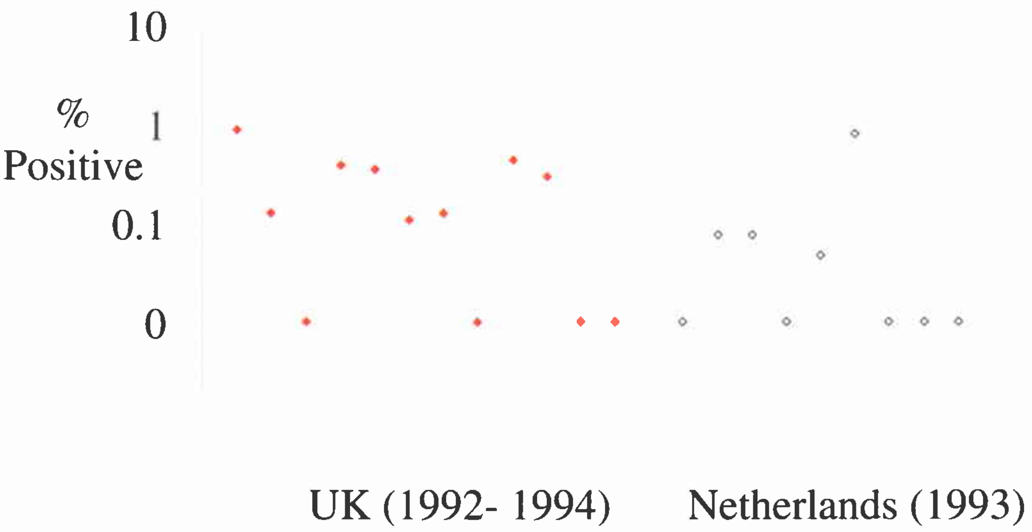


Figure 6.6 *Comparison of the occurrences of coliforms (37°C) in the final waters of the UK and NL selected treatment works*

Heterotrophs
Figure 6.8 and figure 6.9 show the concentrations of heterotrophs (22°C) in works' final waters and distribution samples, respectively, for UK and NL ground and surface waters. It should be noted that 10% and 90%ile plate counts are represented by the boxes for both UK and NL data. The numbers of heterotrophs are similar in the works' final waters in both NL and the UK systems, particularly for those using surface water sources, although final waters from groundwater-supplied works appeared to have higher counts (figure 6.8) in the NL than in the UK. More importantly, the plate counts measured in distribution samples show a more marked increase (relative to the works' final waters) in the NL systems compared to the UK systems (figure 6.9).

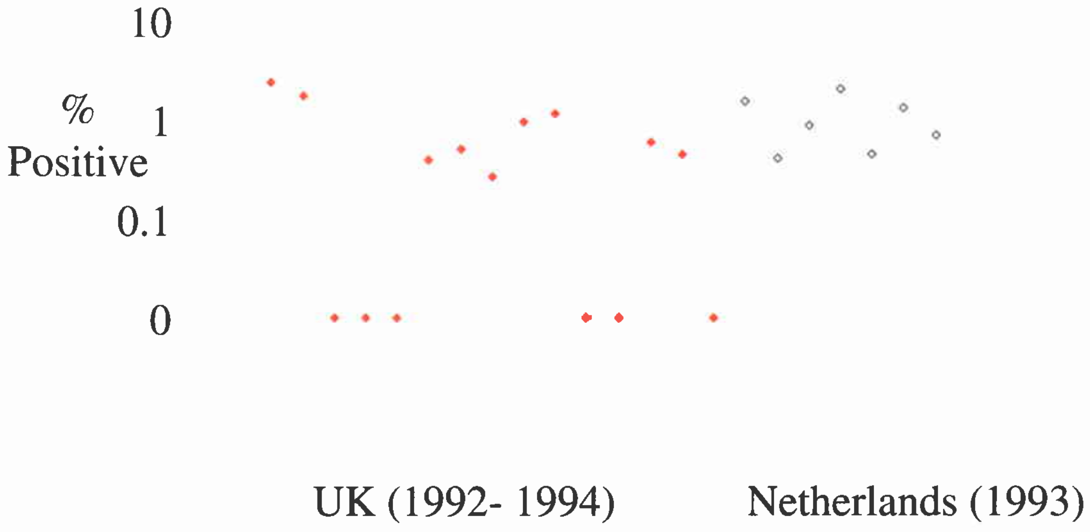


Figure 6.7 *Comparison of the occurrences of total coliforms (37°C) in the UK and NL selected distribution system*

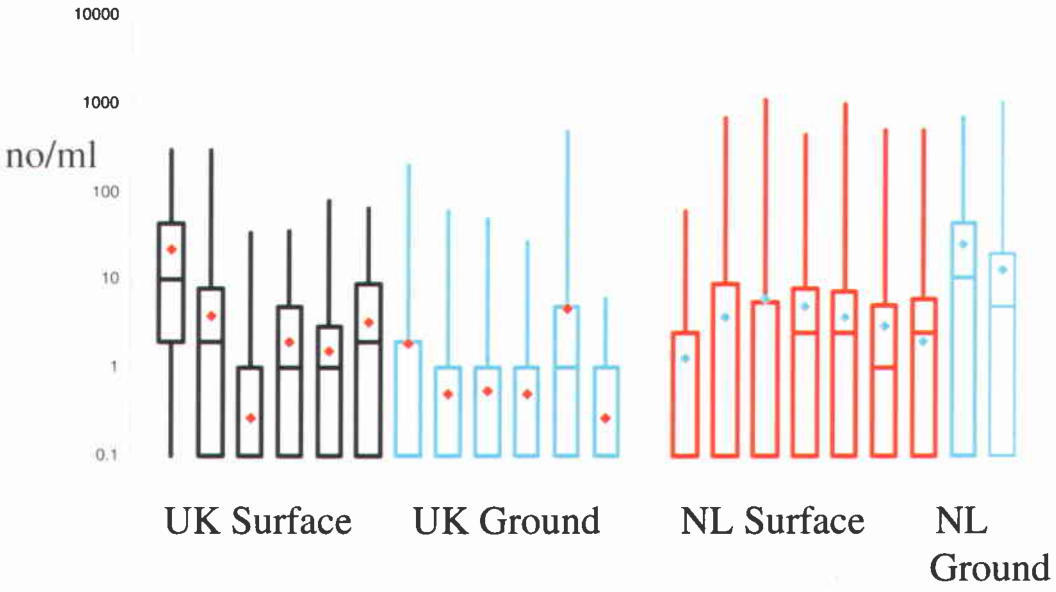


Figure 6.8 *Comparison of 22°C heterotrophs in UK and NL final waters (10 and 90 % iles)*

The data suggest that even in relatively biostable ground waters the maintenance of a chlorine residual minimises regrowth of heterotrophic bacteria and that if the use of chlorine in distribution was stopped in the UK increases in heterotrophs would occur.

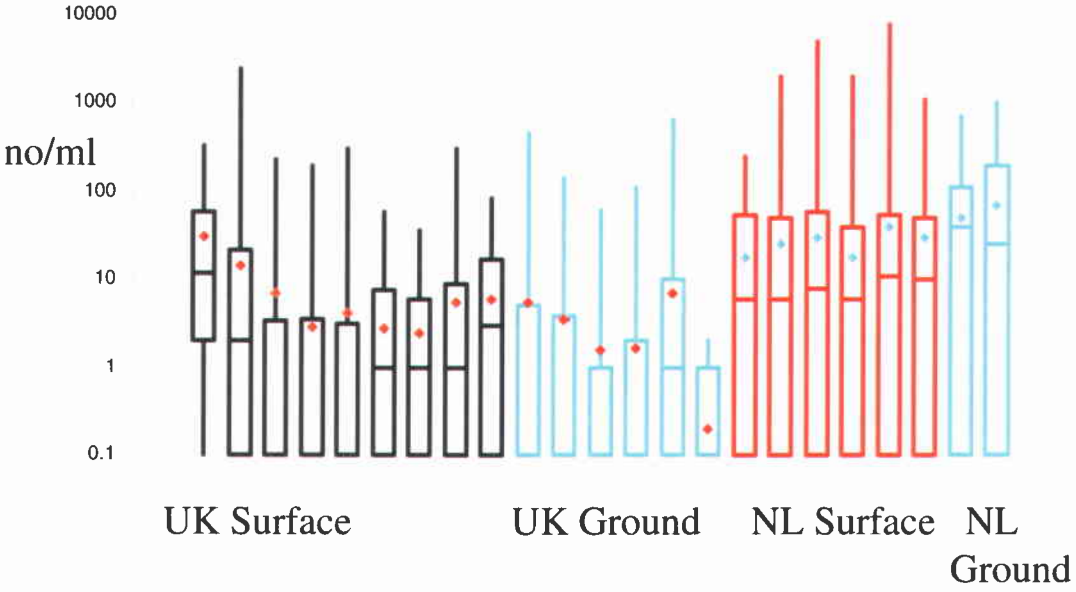


Figure 6.9 *Comparison of 22°C heterotrophs in UK (with chlorine) and NL (without chlorine) distribution samples (10% and 90%iles)*

6.6 Summary of differences in approach

This study has highlighted the following differences in approach to water supply in the UK and the NL:

- Resources are different;
  - all surface waters in the NL are impounded and/or dune filtered,
  - 30% of sources in the UK and 65 % in the NL are from groundwater,
- Treatment strategies differ in NL;
  - <22% of supplies in NL have final disinfection,
  - more biological treatment in NL,
- Pipe materials;
  - iron predominates in UK, plastics (uPVC) in NL,
- Regulatory monitoring similar;
  - difference in designation of coliform failure,
- Differing approaches give ;
  - waters of overall similar microbial quality,
  - heterotrophic growth is higher in NL systems.

The approach used in the NL is based on reducing microbial load and producing biostable waters by the use of more physical chemical and biological water treatment processes. The UK approach users fewer treatment processes and preserves microbiological quality by the maintenance of a chlorine residual.

6.7 Conclusions

The previous sections of this chapter have indicated that whilst the Dutch and UK approaches to water supply are basically similar there are some differences particularly with respect to maintaining microbiological quality in distribution. Both countries undoubtedly treat water to a high standard using a multiple barrier approach.

Whilst chemical disinfectants, such as chlorine and ozone, play important roles in the treatment strategies of both countries, in the NL ozone is becoming increasingly important as an oxidiser and/or disinfectant. However the main emphasis is being placed on the use of more treatment barriers both to remove micro-organisms and produce water which is biostable. Although in the UK the use of chemical disinfectants is being managed more closely than was previously the case, chlorine residuals are still used to preserve the microbiological quality of waters in supply.

The greater use of groundwaters has undoubtedly allowed the NL to adopt their current approach as has the availability of the geological features which makes dune filtration a cost effective treatment option. In the UK greater reliance has had to be placed on the use of surface water sources which require more treatment and it seems unlikely that the production of inherently biostable water from many of these sources would be cost effective in comparison to the use of chlorine to preserve microbiological quality.

The data from the representative plants suggest that microbiological water quality in the NL and the UK is comparable. This suggest that the NL approach of using extra treatment barriers to reduce microbial load and induce biostability is at least as effective as the UK approach of using chlorine residual as a preservative to maintain quality.

These results suggest that in the UK the use of chlorine in distribution could be reduced or abandoned only where waters are known to be relatively biostable. However, even in these situations an increase in heterotrophic bacteria is likely to occur.

7 UKWIR/KIWA Workshop

7.1 Objectives of Workshop

The workshop was held to disseminate the output of the joint project to members of the Client organisations in the UK and the Netherlands. The programme consisted of a series of presentations on the project work and country experiences of operating with or without disinfectant residuals (Day 1). This was followed by more detailed discussions and in-depth debate on why and how the two countries used such different operating regimes in terms of disinfectant residuals to achieve high quality drinking water (Day 2).

The aims of the workshop were:-

- to disseminate the research findings
- to present operational experiences in the UK and the Netherlands
- to compare the different practices in the UK and the Netherlands
- to discuss whether low or zero chlorine disinfection is an option for the UK
- to discuss future research needs

The Workshop took place in London on the 9th and 10th February 1998. This appendix describes the output from the Task Groups, and identifies topic areas where research should be directed.

7.2 Proceedings

The London Workshop took place over two days with about 50 delegates attending. The majority were representatives of Water Utilities in England, Wales, Scotland and the Netherlands. The UK Drinking Water Inspectorate also attended the meeting.

7.2.1 Presentations

On Day 1 of the Workshop the main contractors for the project WRc and Kiwa and invited participants gave presentations of their own experiences. The presentations covered the following areas:

Introduction and UK Approach: David Holt (UKWIR)

Introduction and Netherlands Approach: Dick van der Kooij (Kiwa)

Drinking Water in UK - Surface Water supply: David Holt (Thames Water)

Drinking Water in Amsterdam - Surface Water Supply: R.A.G te Welscher (GWA)

Drinking Water in UK - Ground Water supply: Gary O'Neill (UK Water)

Drinking Water in Overijssel - Ground water supply: Geo L. Bakker (WMO)

Disinfectant Residuals and Drinking Water Quality in the UK: Paul Gale (WRc)

Disinfectant Residuals and Drinking Water Quality in the Netherlands: J.Hein M. van Lieverloo (Kiwa)

Comparison of the UK and the Netherlands Approach: Geoff Stanfield (WRc)

Biological Stability in Distribution Systems: Dick van der Kooij (Kiwa)

The presentations provided background and raised key issues for discussion during Day 2

7.3 Discussion Groups

7.3.1 Definition of Issues

The start of Day 2 was devoted to considering the key issues arising from operating distribution systems under the different regimes in the UK and the Netherlands. The UK delegates considered that chlorine was necessary but wanted to reduce the residuals in distribution. The work by WRc with Box and Whisker plots had demonstrated that chlorine residual control was difficult at some works and this may lead to complaints due to variations in the concentrations of chlorine in the water over short periods. Chlorine disinfection was considered as a safety barrier and there were perceived risks of deterioration in quality to reducing residuals in distribution. The main driver for lower disinfectant residuals was to reduce customer complaints. In many of the distribution systems in the Netherlands there was no residual chlorine and the number of customer complaints is low. There was interest in how customer complaints were reported and coded. However much of the interest was in understanding and improving management and operations on distribution networks.

The following issues were identified for more in-depth consideration and assigned into one of three categories for evaluation by the subsequent Task Groups:

1. Distribution systems - management and operation
2. Treatment and operations

3. Drivers for low/non chlorine - Pros and cons + risks

7.3.2 Task Groups 1-3: Discussions and Research needs

The following findings arose from the Task Group sessions:

Task Group 1 - Distribution systems - management and operation

The discussions in Task Group 1 focused on identifying how distribution systems were operated and maintained in the different countries. The bullet points below mainly show how systems are operated in the Netherlands.

General operations

- Operating pressure is normally 3-5 bar with a lowest minimum of 2 in the main (legal requirement). Have pressure loggers to control and manage distribution network.
- Netherlands is flat and pressure control is more manageable. UK mains in high ground can be put under vacuum when pressure drops
- pressure does not appear to drop with increased demand due to high storage capacity. There are many reservoirs and most supplies are pumped
- Air is vented manually
- Hydrants are generally buried but in Amsterdam are on surface (450,000 connections, 33,000 hydrants);
- There is a trend to reduce hydrants available for domestic premises. Fire engines hold enough water for domestic premises but not industrial estates. Some companies are also reducing pressures - which fire brigade is not happy about.
- Discussions on downsizing of main for water only (mains mainly designed for fire control);
- Have inspectors to look at by-laws in Netherlands 7-8 people - more than UK.

Bursts

- Netherlands 3400 bursts from 10,000 km over 3 years; UK 3500-5000/year;
- Leakage is much lower (1-5%) than in UK;
- In Amsterdam the average consumption is 160l/day which may be higher than other parts of the Netherlands?
- Replacement strategies are 0.5% /annum
- High % of non iron pipe in distribution systems
- Replace all iron in the next 10-15 years

Flushing

- Aerobic ground waters do not require flushing very often, other water types dependent on water quality
- Flush dead-ends every 3 months
- Some companies do all mains every two years
- Water from flushing goes to surface water drains
- Flushing 1.5 meters per sec or 3x volume of the main
- Some companies do not flush unless there are problems
- One company flushes 15 dead-ends every week and in summer twice per week to remove aeromonads. Supply water is anaerobic groundwater with methane

Air Scouring

- Air scouring - has been stopped on iron
- Other companies also air scour on iron mains
- Air scouring for animals - could remove them from mains but rapid re-colonisation from other mains

Distribution sampling

- Often at dead-ends (one company 80%)
- Repairs in Netherlands always take two samples (not after repair with clamps). Sample the day after repair and then the following day (i.e. not immediately after repair).
- In UK take more samples for customer complaints

Task Group 2 - Treatment and operation

The discussions in Task Group 2 focused on treatment of water in terms of whether the water was biologically stable (biostability) in the Netherlands and UK. In the Netherlands there are well defined methods to measure biostability and many water types have been assessed. In the UK a number of techniques for biostability had been used (Assimilable Organic Carbon (AOC), Biodegradable Organic Carbon (BDOC), however there are no standard methods as in the Netherlands and a number of questions were raised on the quality of data available on biostability of UK waters.

Problems

- UK needs a good method to measure and identify which waters are biostable
- What are biostable waters (does this include those that have a chlorine residual or only those that that have limited nutrients for biological growth)
- Where are biostable waters in the UK?
- How do biostabilities compare in the UK with the NL
- What is the biostability value for waters if low Cl_2 residuals are allowed in UK waters

Statements

- Need standard method for biostability measurements in the UK that can be linked to the Netherlands database
- Apply testing across the UK to different treatment works. This can be linked to the Netherlands database on biostability and the UK shelf life database
- Define biofilm formation rate as a tool. At treatment works the ATP test can be used to define the total amount of active biomass that can be generated in a distribution system

Research needs

- Develop common method in UK for assessing biostability
- Obtain biostability database for UK works using Kiwa method to enable comparison of UK and NL biostabilities
- How particles affect biostability
- Explore the option of chloramination versus chlorination for improved biostability

Task Group 3 - Drivers for low/non chlorine - Pros and cons + risks

Task Group 3 discussed the drivers for operating distribution systems with a low or zero disinfectant residual. The benefits and disadvantages and risks for both countries were identified. These are summarised below

Negative aspects

- Decreased sensitivity of monitoring (coliforms)
- Taste
- DBP's (UK less concerned than Netherlands due to different risk calculations)
- AOC enhancement
- Addition of chemicals (Perception of customers)

Positive aspects

- Compliance
- Microbial security (as a disinfectant)
- Preservative
- Invertebrate control
- Aeromonad control (could be an issue)
- Disinfectant as a sensor

Research

- On invertebrates and aeromonads in low/zero disinfectant residual distribution systems
- Cost benefits of reducing chlorine - cost of flushing etc.,
- Others - What to do with cast iron, - life time expectancy of new materials

7.4 Conclusions

1 The source of raw surface waters in both countries are very similar, however, their treatment prior to distribution are more extensive in the Netherlands than in the UK.

- Surface source waters, in particular, undergo extensive process treatment in the Netherlands which has the benefits of reducing the nutrients available for microbiological growth producing biostable waters. This allows distribution with low or zero disinfectant residuals. Even in systems with a low residual this rapidly dissipates in the distribution network.

- In the UK many of the ground waters probably have similar nutrient content to those of the Netherlands. However unlike the Netherlands there is no extensive database due to insufficient testing using standard techniques such as assimilable organic carbon (AOC) measurement.

2 There are many similarities in the way that the UK and Netherlands water companies manage, operate and maintain their distribution systems. However there are some distinct differences.

- In the Netherlands the water is distributed by pumped supplies which provide more stable and higher pressures (3 bar) than gravity fed systems. Whilst the pressures may be higher the reported frequencies of bursts are lower than in the UK (only 0.33-0.55 of the UK average) and leakage is also reported as lower (1-5%)

3. Flushing appears to be more proactive in the Netherlands than in the UK; where it is more reactive. However in both countries flushing programmes are ill-defined in terms of frequencies and are based more on practical experiences of problems encountered.

4. The UK and Netherlands have similar asset replacement programmes 0.5%/annum. In the Netherlands most of the pipes are asbestos cement or PVC and many of the iron pipes have been replaced. In the UK iron pipes are the vast majority of the asset stock.

5. Areas of research that are common to both countries are
   - Determining the optimum and minimum operational maintenance programme
   - Determining which parameters should be established for biostability
   - Characterisation and uniform registration of customer complaints

8 General conclusions

8.1 General comment

This study, aiming at comparing operational practices in drinking water distribution in the UK and in the Netherlands, shows that approach and practice in both countries have many similarities. However, a main difference is that in the Netherlands drinking water in the great majority of supplies is distributed without a disinfectant residual, whereas in the UK a disinfectant residual is maintained in the distribution system.

1. Ensuring the hygienic safety of drinking water, including compliance with national water quality standards, is top priority for the water supply companies in the UK and in NL. This objective is achieved by:
   - adequate removal of pathogens in water treatment;
   - prevention of contamination of drinking water during distribution.

2. Customer satisfaction, including appreciation of drinking water quality, is becoming increasingly important for the water supply companies in a market-orientated society. Drinking water should be attractive from an aesthetic point of view, meeting high standards for taste and odour, colour and turbidity.

3. Drinking water quality may change during distribution. Distributing drinking water with a disinfectant residual has both positive and negative effects on water quality. The positive effects are:
   - limiting regrowth of coliforms (indicator bacteria) and heterotrophic bacteria at low costs;
   - some reduction of bacterial pathogens entering the distribution system in low numbers.

   The negative effects are:
   - taste and odour complaints;
   - formation of undesirable by-products;
   - inactivation of indicator bacteria without sufficient inactivation of pathogens drinking water.

4. A disinfectant residual reduces the concentrations of micro-organisms in drinking water, i.e. bacteria contributing to HPC values and coliforms. This effect is limited by:
   - protection of micro-organisms in sediments and biofilms. These micro-organisms are much less inactivated than freely suspended microorganisms.
   - the decay of the residual in the distribution system;

- the increase of the concentration of biodegradable compounds as the result of the effect of the disinfectant on organic compounds present in the water.

5. A disinfectant residual is not an adequate barrier against contamination of the distribution system with pathogens:
    - typical residual concentrations of either chlorine or monochloramine are not effective against protozoa;
    - monochloramine has a very limited affect on viruses;
    - in case of a contamination with polluted water or soil the disinfectant is inactivated in contact with organic and inorganic contaminants, shielding the pathogens;
    - pipe materials, biofilms and water components cause a decay of the disinfectant concentration rendering it ineffective in parts of the system;
    - a disinfectant residual may inactivate the indicator bacteria (coliforms) without sufficient inactivation of the pathogens, thus making the indicator bacteria an unreliable measure for the safety of the distribution system.

8.2 Distributing drinking water with no or a low disinfectant residual in the Netherlands

1. Practical experience in the Netherlands shows that compliance with stringent criteria for microbiological quality, public health and aesthetic standards is achieved when distributing biologically stable drinking water without a disinfectant residual in a system with a high level of integrity, using materials with a high level of biostability.

2. Good engineering practices are of major importance to effectively protect drinking water in the distribution system. Quantitative data about contamination risks, including the frequency, detection and importance of small contaminations, are needed to improve the protecting measures.

3. In the absence of a disinfectant residual, testing for faecal coliforms is a sensitive method for detecting contamination. Total coliforms are not appropriate for detecting faecal contamination because these organisms can multiply in the environment.

4. The biological stability of drinking water can be assessed by a combination of techniques, viz. the AOC determination and the biofilm formation characteristics. The increase of HPC values is prevented at AOC values below 10 μg C/l. Regrowth of aeromonads is prevented at Biofilm Formation Rate values below 10 pg ATP/cm^2.day as assessed with the biofilm monitor.

5. In a few systems, which mainly consist of cast iron pipes, the percentage of coliform positive samples may reach a value of 1 to 2% on an annual basis. In such systems aeromonads can multiply. Drinking water in these systems is highly stable (slow sand filtrates). Most likely, interactions between pipe surface and water are responsible for the presence of coliforms and/or aeromonads.

6. The biological stability of drinking water can be assessed with a combination of techniques, viz. the AOC determination and the biofilm formation characteristics. The increase of HPC values is prevented at AOC values below 10 μg C/l. Regrowth of aeromonads is limited at Biofilm Formation Rate values below 10 pg ATP/cm^2.day as assessed with the biofilm monitor.

7. A database is available about numbers and types of invertebrates in distribution systems of groundwater supplies. Asselids form the major part of the collected biomass.

8. Procedures for collecting and processing data about the microbial quality of drinking water in the distribution system should be improved to enable their use as a tool for managing water quality in distribution system on a day to day basis and on the longer term.

9. Effective cleaning procedures are an essential part of managing the biological quality of drinking water in distribution systems.

8.3 Distributing drinking water in the United Kingdom

1. In the UK, distributing drinking water with a controlled disinfectant residual has proved to be the most practical and cost effective means of maintaining good microbiological quality.

2. Combined with good engineering practices, which are tailored to suit particular water types and distribution system characteristics, the maintenance of a chlorine residual has allowed compliance to be achieved with increasingly stringent national and European standards.

3. Over recent years, figures released by the UK Drinking Water Inspectorate have shown a trend of increasing water quality at consumers taps. Nationally the standard for coliform compliance has been made more stringent by the adoption of a different definition of coliform organisms. This change caused water quality to apparently decline in the year it was adopted, but changes introduced since this time have lead to further improvements in microbiological quality.

4. In the UK, microbiological quality is seen as the most important measure of wholesomeness. Any sample collected from the treatment works or the distribution system is judged to have failed if coliform bacteria are detected. Remedial measures are taken immediately whilst re-sampling is carried out.

5. Maintenance of a chlorine residual has not been viewed as a universal solution for problems that can occur. The water companies in the UK have an ongoing programme of investment aimed at improving distribution systems both with regard to management of hydraulic characteristics and refurbishment of pipelines.

6. This refurbishment has allowed better control of the concentration of chlorine residuals to be achieved as well as ensuring systems have a greater integrity.

7. Better working practices have been introduced by all water companies to ensure that contamination does not prejudice water quality during refurbishment or after mains repairs.

8. Modelling flow characteristics within a distribution system have allowed better control of residuals to be achieved by, amongst other factors, reducing transit times. In this context it has been possible to remove many service reservoirs installed previously to guarantee continuity of supply.

9. Two thirds of the water supplies in the UK are derived from surface water sources and so, even after treatment, contain relatively high concentrations of organic carbon. As a consequence the alternative strategy, as used the Netherlands, of distributing biostable water without a disinfectant residual is in the majority of cases not a cost-effective or feasible as an engineering option.

10. Groundwaters in the UK are usually of very good quality requiring little if any treatment before distribution. However, disinfection has invariably been employed as a safety precaution against contamination at the wellhead or during distribution.

11. Increasing management of groundwater catchments and refurbishment of associated distribution networks is now indicating that the use of disinfection may not always be required particularly since these waters contain little organic carbon and can be regarded as being biostable.

12. However the cost of using chlorine is relatively low and the sense of security it brings supports its continued use.

8.4 Comparison between operational practices in the Netherlands and in the UK

1. Water sources, water treatment and water distribution in the two countries show a number of significant differences:

   - in the Netherlands, two thirds of drinking water is derived from ground water. In the UK two thirds is derived from surface water. Ground water sources in the Netherlands are free from pathogens and ground water treatment does not include a chemical disinfection. In the UK ground water quality is less reliable as a result of a different geological situation and chemical disinfection is applied in treatment;
   - surface water treatment in the Netherlands includes soil passage in 50% of the supplies. In all cases multiple barriers including biological filtration is used. Surface water treatment in the UK does not include soil passage and biological filtration is less commonly applied.
   - in the Netherlands drinking water is distributed without a disinfectant residual in all ground water supplies and in most surface water supplies. The main pipe material is PVC and cast iron is used in 15% of the mains.
   - in the UK drinking water is distributed with a disinfectant residual. Cast iron is the most common pipe material and PE is the most common plastic used in contact with drinking water.

2. Water quality standards in the Netherlands are slightly more stringent for indicator bacteria and disinfection by-products than in the UK.

   - in the Netherlands surface water supplies are sampled daily (300 ml samples) for the presence of coliforms. Samples of 100 ml are collected weekly for determining the presence of faecal streptococci and spores of sulphite-reducing clostridia. In the UK samples of 100 ml are tested for the presence of coliforms.
   - in the Netherlands standard for DBP's are based on a negligible cancer risk (10^{-6} of additional risk on a life time basis). A total THM concentration of 21 μg is proposed for inclusion in national legislation. In the UK a maximum THM concentration of 100 μg/ l is used.

3. Water quality in the UK and in the Netherlands complies with the national water quality standards and with European legislation. Percentages of coliforms are very low in both countries.

   - the low HPC values and the low percentages of coliforms positive samples in the UK are due to the presence of a chlorine residual in a number of cases.
   - in the Netherlands biological stability is the reason for low HPC values and the low percentage of coliform positive samples.

4. In both countries good engineering practice are the critical factor to protect drinking water against contamination during distribution.

5. The frequency of consumer complaints about taste and odour in the UK is higher than in the Netherlands.

   - chlorine is the most common cause for taste complaints.

6. The rate for drinking water in the UK is similar to the Netherlands.

   - in the UK the rate ranges from £0.5 to £0.8/m3;
   - in the Netherlands the rate ranges from fl 1.5 to fl 3.00 /m3.

7. Methods for assessing the biostability of drinking water and materials in the Netherlands differ from those used in the UK:

   - in the Netherlands the AOC method and assessment of the biofilm formation characteristics are used. Relationships between these parameters and regrowth have been established resulting in reference values for biological stability.

8.5 Areas for further study

1. Good engineering practices are indispensable for the protection of drinking water quality in the distribution system. Analysis and assessment of the risk of microbial contamination of drinking water in the distribution system is needed to further improve these measures.

2. Assessment of faecal contamination of drinking water in the distribution system is based on using *E. coli* as an indicator, but this organism is more susceptible to chemical disinfectants than viruses and protozoa. This aspect needs further study to evaluate the efficiency of different disinfectants (chlorine, monochloramine, chlorine dioxide) to protect against contamination.

3. Distributing drinking water with a high degree of biostability is needed both in the absence and in the presence of a disinfectant residual. Standardisation of methods for testing biostability of water and materials will enable a more efficient use of available databases.

4. Registration of customer complaints about water quality differs between water supply companies and between countries. Uniform registration procedures will provide more reliable information about operation practices and customer satisfaction.

5. *Legionella* may multiply in institutional and domestic tap water systems. The effect of water quality, including the presence of a disinfectant residual, on such multiplication is not clear.

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ANNEX 1 - Properties of disinfectants

The disinfectants based on chlorine give, in liquid solutions, the hypochlorite ion in equilibrium with hypochlorous acid:

$$Cl_2 + H_2O \Leftrightarrow HOCl + Cl^-$$

and also:

$$HOCl \Leftrightarrow H^+ + OCl^-$$

The 2nd reaction depends on the pH. Hypochlorous acid is the active compound and this can be attributed to the neutral charge of the molecule at lower pH. Consequently, the rate of inactivation of micro-organisms under the influence of chlorine decreases with increasing pH.

The chlorine reactions are mainly based on oxidation-reduction but also addition and substitution reactions can occur with the formation of halogenated hydrocarbons. The oxidation reaction is given by:

$$HOCl + H^+ + Cl^- + 2e^- \rightarrow H_2O + 2\ Cl^-$$

Detailed information on the various reactions and equilibrium constants are presented elsewhere (White, 1972).

Chloramines are formed by the reaction of chlorine with ammonia. Depending on the ratio between chlorine and ammonia, mono- di-, or trichloramine are formed:

$$HOCl + NH_3 \rightarrow NH_2Cl \text{ (monochloramine)} + H_2O$$

$$NH_2Cl + HOCl \rightarrow NHCl_2 \text{ (dichloramine)} + H_2O$$

$$NHCl_2 + HOCl \rightarrow NCl_3 \text{ (trichloramine)} + H_2O$$

The formation of the different forms of chloramine also depends on the pH (Daniel and Price, 1993; Wolfe and Olson, 1984), so that the formation of the mono, di or trichloramine can be influenced. In the UK ammonia is normally added only after a long residence and reaction time of the chlorine. In this way the greater inactivation of chlorine in the treatment process can be combined with a higher stability of chloramine in distribution. A disadvantage of this method is the formation of disinfection byproducts by chlorine. This is described in more detail in section 2.

Chlorine dioxide is prepared in situ, generally with the use of sodium chlorite and the addition of chlorine or hydrochloric acid:

$$2\ NaClO_2 + Cl_2 \rightarrow 2\ ClO_2 + 2\ NaCl$$

$$5\ NaClO_2 + 4\ HCl \rightarrow 4\ ClO_2 + 5\ NaCl + 2\ H_2O$$

Chlorine dioxide can decompose into chlorite and chlorate, depending on the pH. Chlorine dioxide is reduced to chlorite and depending on the presence of further reducing substances, can be converted to chloride.

2. Formation of disinfection byproducts (DBP)

Assessment of the toxicological aspects of chemical disinfection requires information about the toxicity of the disinfectant itself, its degradation products and the byproducts that can be formed after addition of the disinfectant. These byproducts are the most difficult part to evaluate because (i), formation of such products depends on the composition of the drinking water and (ii) not all the substances that are formed can be identified. In 1974 the first investigations on the formation of byproducts (Rook, 1974; Bellar and Lichtenberg, 1974) were based on the analytical methods available at that time. Initially most of the attention was directed at the formation of chloroform and haloforms. Later it appeared that other halogenated organic compounds were being formed such as trichloroacetic acid, dichloroacetic acid, trichloroacetone, dichloroacetonitrile and a group of substances which are characterised by the parameter AOX (absorbable organic halogen). Most of these compounds are formed as the result of a reaction with the disinfectant and the humic acids that are naturally present in water sources (Rook, 1974, De Leer, 1987; Peters, 1991). An indication of the extent of the organohalogens can be obtained by the parameter TOX (total organic bound halogen). Less then 20-50% of the total fraction of organohalogens are currently identifiable (Singer and Chang, 1989). The formation of TOX mostly parallels the formation of trihalomethanes, so that if a limit has been set for the trihalomethanes, similarly the formation of the other organohalogens will be limited. A linear relation exists between TTHM (total trihalomethanes) and the total amount of DBP's. If bromide is present in significant quantities a shift occurs from chlorinated to brominated compounds. A total of 25% of the TOX could be ascribed to known and identified compounds. The THM's and HAA's (haloacetic acids) are the most frequently occurring groups of DBP's (Nieminsky et al. 1993).

In the Netherlands about 15% of the total organohalogen concentration can be attributed to the haloacetic acids (Peters, 1991). These compounds have only been detected in drinking water that was subjected to chlorine treatment. The concentrations of individual haloacetic acids is between 0-6.5 μg/l and the total concentration of the group is between 3.8 and 14.7 μg/l. The brominated compounds comprised 65% of the total HAA concentration.

A different approach to characterise the formation of DBP's is based on using biological methods to express a certain characteristic property such as mutagenic activity for bacterial strains (Ames tests). It is estimated that a great part of the mutagenic activity is present in the non-volatile, not yet identified fraction of the DBP's. In some situations very strong mutagens can be detected i.e. the group of furanones, containing MX (3-chloro-4-(dichloromethyl)-5-hydroxy-2(5H)-furanone.

The formation of DBP's can be reduced by removing the precursors, mostly the humic acid compounds. The capacity of formation of THM is expressed as THMFP (trihalomethane formation potential). Lowering the level of precursors however, does not always decrease the THM formation. This is because the ratio between the precursor and the chlorine concentration plays a role: a higher reactivity remains at a lower precursor content in the same chlorine concentration. Moreover a shift can be seen from chlorinated to brominated compounds after lowering the carbon content (Kruithof, 1986). These generally have a higher toxicological significance. The formation of the various kinds of DBP's depends highly on the pH. The formation of THM's is favoured by a high pH and TCA by a low pH. The level of THM formed at pH 9.4 can be a factor 3 higher than at pH 5 (Stevens et al. 1989).

In the distribution system the production of DBP's can continue by more than a factor 2 compared to the values at the treatment plant (Clark et al. 1994; Nieminsky et al. 1993). The decrease of chlorine parallels the increase of THM (Casey and Chua, 1997). The presence of a biofilm can also influence chlorine consumption and the formation of DBP's (Meyer et al. 1993).

Generally chloramines and chlorine dioxide do not give rise to THM formation under similar conditions. An example of trials in the Netherlands is presented in table 2.4 (Hrubec et al. 1984). The application of chlorine dioxide is however, limited by the formation of chlorite and the taste and odour of chlorine dioxide. Chloramine has a low potency for formation of THM's but low levels of trichloroacetic acid and cyanogen chloride have been reported (Trussell, 1993).

Table 2 *Formation of halogenated hydrocarbons in water after the addition of either 1 mg/l* Cl_2 *and 1 mg/l* ClO_2*, respectively (Hrubec et al. 1984).*

Compound	**Before treatment (µg/l)**	**Treated water supplemented with 1 mg/l of:**	
		Cl_2	ClO_2
EOCl	0.3	1.4	0.3
AOCl	25	95	21
VOCl	0.01	16.8	0.01
$CHCl_3$	<0.1	5.3	<0.1
$CHCl_2Br$	<0.1	8.6	0.1
$CHClBr_2$	<0.1	10	0.1
$CHBr_3$	<0.1	5.4	<0.1

In the USA median values for cyanogenchloride of 1.6 µg/l have been reported (Krassner et al. 1989). The formation of DBP's by chloramine depends markedly on the manner of preparation. Sometimes ammonia is added after a longer residence time of chlorine, so that chlorine is able to react freely for a certain time before its reaction to ammonia. In addition, the method of mixing the chlorine and ammonia can have an effect (Daniel and Price, 1993). At higher ratios of chlorine : ammonia the formation of haloforms can increase as does the formation of dichloramine and trichloramine. A higher risk then exists for the production of substances with a low taste and odour value. The formation of dichloramine will be less at higher pH (White, 1972).

Application of chloramine can, in warm periods (above 15°C), lead to formation of nitrite due to nitrification processes (Wolfe et. al. 1990; Odell et al. 1996; Wilzcak et al. 1997). Nitrification starts most easily with low concentrations of chloramine, but if the process has been initiated it can continue at higher concentrations. Higher concentrations of chloramine do not always completely kill the nitrifying bacteria (Lieu et al. 1993).

The phenomena described above are important when considering the addition of chlorine at other points in the distribution system to boost chlorine residual. In this case, the concentration of DBP's will also increase. If a low level of byproducts has to be achieved, the choice of disinfectants should be considered together with the treatment process. When chemical disinfection is used in water treatment the highest production of DBP's usually occurs in the treatment process. The application of other disinfectants such as ozone, peroxone and UV can lower the production of DBP's at the treatment plant. Using a disinfectant during distribution with a low production potency of DBP's or distribution of drinking water without (addition of) a disinfectant results in a lower level of DBP's (Jacangelo et al. 1989).

ANNEX 2 - Characteristics of selected treatment plants and their distribution systems in the Netherlands

This annex contains detailed information on the selected treatment plants (see paragraph 3.4.2) of the 5 water supply companies that participated in this study.

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Data on water supply company 1

(treatment plant D1)

This water supply company has 7 treatment plants available, 3 of which use surface water after dune passage and 3 of which use ground water. The 7th treatment plants, which is described in detail below, uses surface water after impoundment in a reservoir.

Treatment plant D1

Resource: Lake (70% water from river Rijn, 30% runoff from polders).

Treatment:
- Impoundment reservoir (residence time approx. 40 days);
- Electrical fish-repellant fence, debris screens and surface skimmer;
- Daily disinfection to prevent growth of zebra mussels (*Dreissena polymorpha*);
- Micro-strainers 35 :m;
- 'Breaking point' chlorination in closed reservoirs (free chlorine 1 mg/l, contact time 0.5 hr);
- Dechlorination;
- Flocculation and sedimentation;
- Rapid sand filtration to remove remaining flocs;
- Primary GAC filtration to remove odour and organic pollutants (contact time 15 min.);
- Secondary GAC filtration (identical to primary);
- Microstrainers 30 :m;
- Post-disinfection (ClO_2, 0.05-0.1 mg/l);
- pH adjustment;
- Finished water reservoir;
- Main part is transported (ι 1000 mm) to booster with reservoir before distribution, a small part is distributed directly.

Production: 20,000 megalitres per annum (maximum 4,0 megalitre per hour, 24,000 megalitres per annum).

Distribution system of treatment plant D1

Area type: Rural area with small towns and villages (approx. 1400 km^2), interconnected with the distribution systems of 4 other treatment plants.
max. transport and distribution distance: 70 km.

Water price: / 2,69/m^3 (yearly rate / 81,00)[1].

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[1] All water prices in the report were valid in 1997, unless stated otherwise.

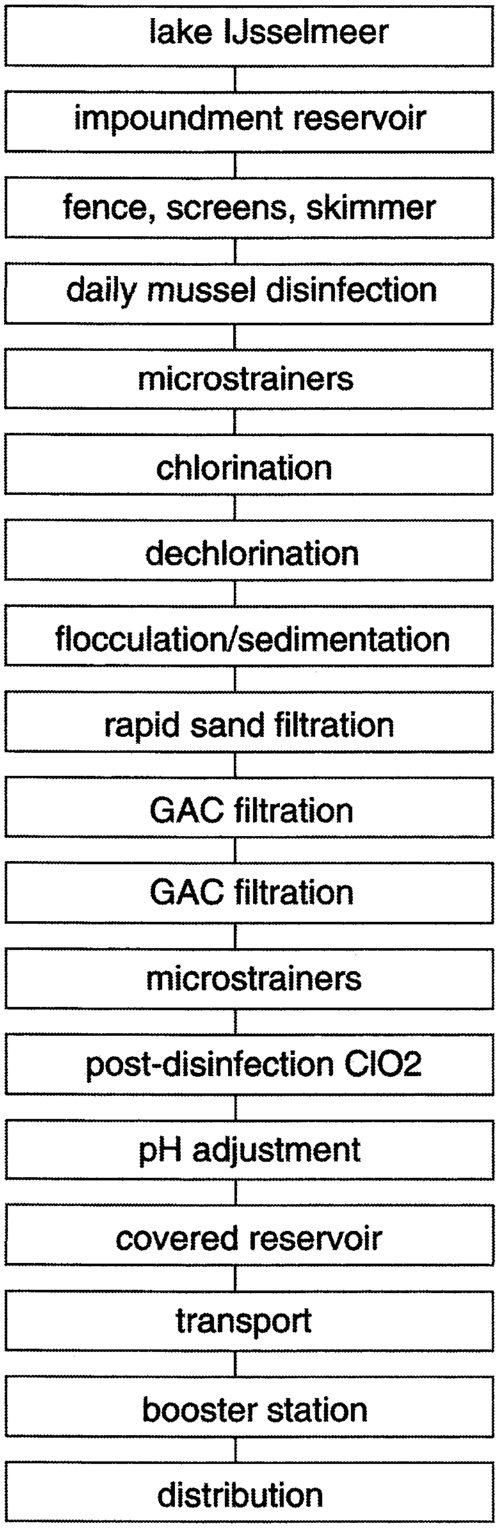

Figure 1 *Schematic overview of treatment plant D1*

Data on water supply company 2

(treatment plant D2 and D3)

There are 4 treatment plants available to the water supply company, 3 of which are permanently operational, the other one is available on stand-by.

Treatment plant D2

Resource: River Maas.

Treatment:
- 3 serial reservoirs (residence time approx. 150 days).
- Milk of lime dosage in the last reservoir to reduce hardness from 2,1 mmol/l to 1,6 mmol/l.
- Transport (main: ι 1400 mm, 34 km) with 1 mg/l Cl_2 to prevent growth of mussels;
- Open buffer reservoir;
- Flocculation;
- Floc-removal with lamella-separators;
- Ozonation (1.2 - 2.0 mg ozone/l, 8-10 minutes);
- Double layer rapid filtration;
- GAC filtration (7,5 minutes);
- Post-disinfection with chlorine (Cl_2-gas), 0,3 mg Cl_2/l. The finished water has been chlorinated since the treatment plant was established in 1982.
- Finished water reservoirs. All vents are equipped with filters retaining all (micro-)organisms and particles.

Production: 41.10^6 m^3/yr (1996).

Biological objectives: Ozonation followed by two filtration steps produces a drinking water with low concentrations of easily assimilated organic substances, measured as AOC. These substances, partly produced from complex organic substances during ozonation, are removed by bacteria in the filters. Reproduction of micro-organisms in the distribution system is therefore limited. Post-disinfection with chlorine is necessary to meet targets for aeromonad plate counts in the produced water and heterotrophic plate counts in the distribution system. Disinfectant residuals in the distribution system usually are too low (< 0.03 mg/l) to expect any disinfecting activity. Because the lack of a disinfectant residual leaves the distribution system unprotected against recontamination, hygiene precautions during the laying and repair of mains have special attention within the water supply company.

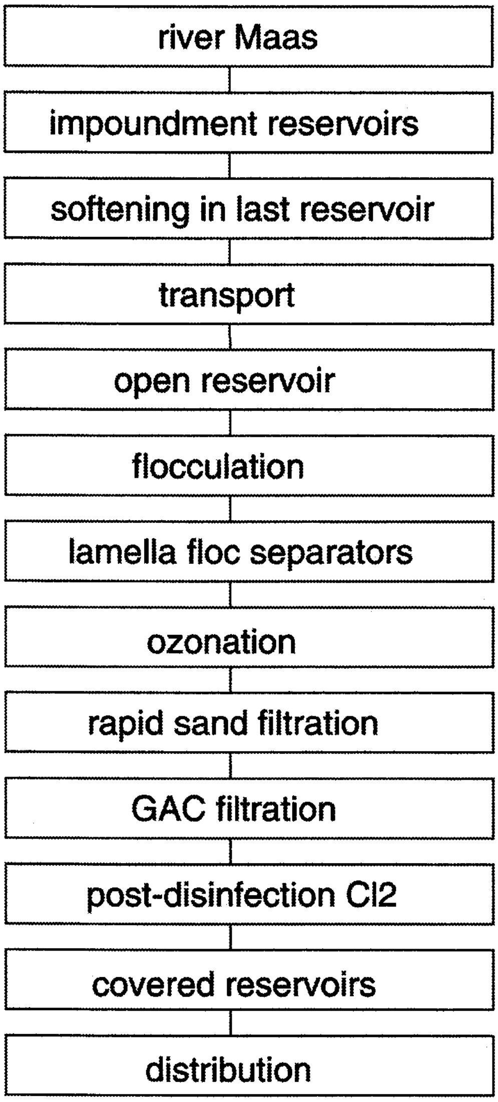

Figure 2 *Schematic overview of treatment plant D2*

Treatment plant D3

Resource: River Maas.

Treatment:

- Reservoirs (residence time approx. 150 days).
- Milk of lime dosage in the last reservoir to reduce hardness from 2,1 mmol/l to 1,6 mmol/l;
- Transport (main: ι 1800 mm, 30 km) with 1 mg/l Cl^2 to prevent growth of mussels;
- Open buffer canal/reservoir;
- Micro-strainers (35 :m);
- Dosage of hypochlorite (NAClO), 1 mg/l, 30 minutes;
- Flocculation;
- Sedimentation by sludge blanket filtration;
- Rapid GAC-filtration;
- Aeration with cascades;
- Post-disinfection with hypochlorite (NAClO) ∀ 0,5 mg Cl_2/l. The treatment plant was established in 1966 to replace the only treatment plant of the city (est. 1874). The finished water from this former treatment plant was also chlorinated;
- Finished water reservoirs. All vents are equipped with filters retaining all (micro-)organisms and particles.

Production: 102.10^6 m^3/yr (1996)

Biological
objectives: Almost identical to the objectives for treatment plant D2.

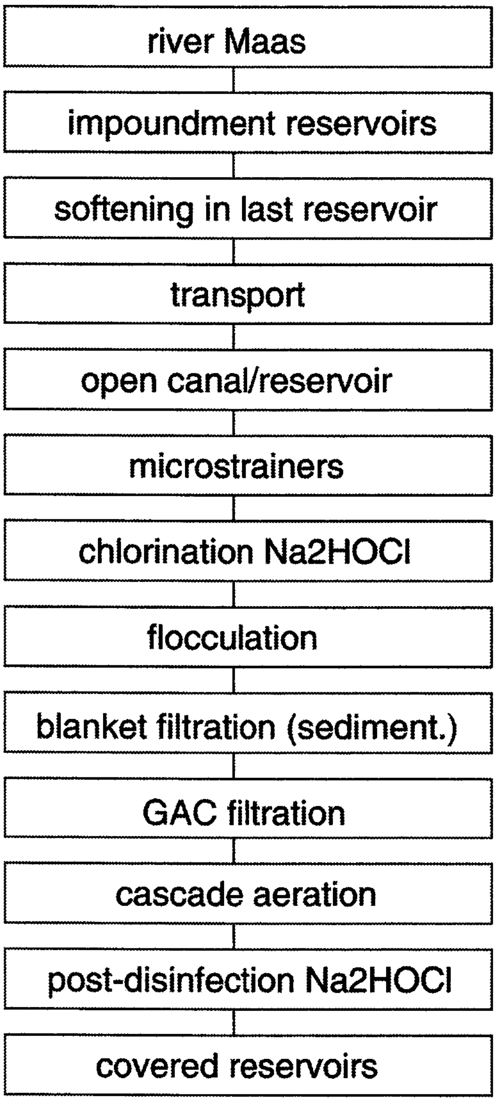

Figure 3 *Schematic overview of treatment plant D3*

Distribution system of company 2

Area type: Treatment plant D2: Part of a large city and a town in a rural area (approx. 150 km^2), partly interconnected with the distribution system of treatment plant D3. However, large parts of the distribution system are supplied by one treatment plant only. Max. transport and distribution distance is 15 km.

Treatment plant D3: Part of a large city and a large industrial area in a rural area (approx. 950 km^2), partly interconnected with the distribution system of treatment plant D2 or the third treatment plant of the company (10.10^6 m^3/yr). However, large parts of the distribution system are supplied by one treatment plant only. Max. transport and distribution distance is 35 km.

Mains length: 5,800 km (3,000 km in urbanised area).
Connections: 706,863 (December 31, 1996)
Water price: / 2.44 - / 2.89/m^3 (yearly rate / 53,00 - / 97,00).
Inhabitants: 1,439,366 (December 31, 1996)
Hydrants: 79,000 (24,000 in urbanised area).
Distribution: - 153.10^6 m^3/yr (1996)

- Transport (concrete or cement-lined steel, ι approx. 1600 mm);
- Boosters, some with finished water reservoirs, under normal operating conditions chlorination is not applied in boosters;
- Distribution mostly via ι 100 mm and ι 150 mm mains;
- PVC is the most abundantly used distribution mains material, followed by asbestos-cement mains. Older parts of the system contain cast-iron mains, partly cement-lined. Some steel mains (partly cement-lined) and HDPE mains have also been applied.
- In some areas ι 100 mm and ι 150 mm mains diameters are chosen solely for fire fighting purposes, not for water supply.
- There is no long term mains replacement plan.
- Mobile devices for local chlorination are available;
- Part of the connections are not yet supplied with water meters, therefore leakage rates cannot be determined accurately, but is estimated to be less than 10%.
- There are no air-valves in the distribution system.

Water quality:

- All sample locations are fixed locations. Fortnightly at least 1 sample per area is collected on alternating locations.
- Taste/odour complaints (1993: 96; 1994: 85; 1995: 806) usually constitute approx. 50% of all complaints. Numbers were high in 1995 because part of the distribution system was temporarily supplied by treatment plant D3 (before by D2).
- Chlorine decay: in the distribution system of treatment plant D2 the level of total Cl_2 drops from 0.12-0.15 mg/l (ex-works) to <0.05-0.07 mg/l (5 km from treatment plant). Concentrations remain around detection limits (0.05 mg/l) in most parts of the distribution system.
- Invertebrates: in most parts of the distribution systems asellids are not found. Complaints about invertebrates (usually oligochaete worms) are very rare (once every few years).
- Parts of the distribution system are flushed after coloured water complaints or when high sediment concentrations are found during routinely collected samples of flushing water.

Data on water supply company 3

(treatment plant D4 and I1)

This company has two treatment plants available and both are described below.

Treatment plant D4

Resource: Seepage water from a polder area, in dry periods suppleted with canal water from river Lek (origin: river Rijn)

Treatment:
- Coagulation/sedimentation to remove particulate (in)organic matter as well as phosphates;
- Open reservoir (residence time approx. 100 days) to level out changes in water quality;
- Rapid sand filtration to prevent the necessity of transport-chlorination;
- Transport;
- Ozonation (i) to disinfect, (ii) to decolorise and (iii) to form AOC;
- Hardness correction from 13 ED to 8.4 ED;
- GAC-filtration since 1992 to remove DOC, colour and odours, biologically as well as by adsorption (contact time 40 minutes);
- Slow sand filtration to remove bacteria and particulate (in)organic matter;
- Finished water reservoirs. All vents are equipped with filters retaining all (micro-)organisms and particles (changed every 4 years).

Production: 24.10^6 m^3/year (max. capacity: 30.10^6 m^3/year).

Objectives: Continuous post-disinfection with chlorine has been stopped in 1983. The presence of coliforms in the finished water in short periods during the winter, due to the abundant presence of birds in the open dune collection canals, was responded to by temporary post-disinfection. Since ozonation and GAC-filtration were introduced temporary post-disinfection has not been necessary. Because the lack of a disinfectant residual leaves the distribution system unprotected against recontamination, hygiene precautions during the laying and repair of mains have special attention within the water supply company.

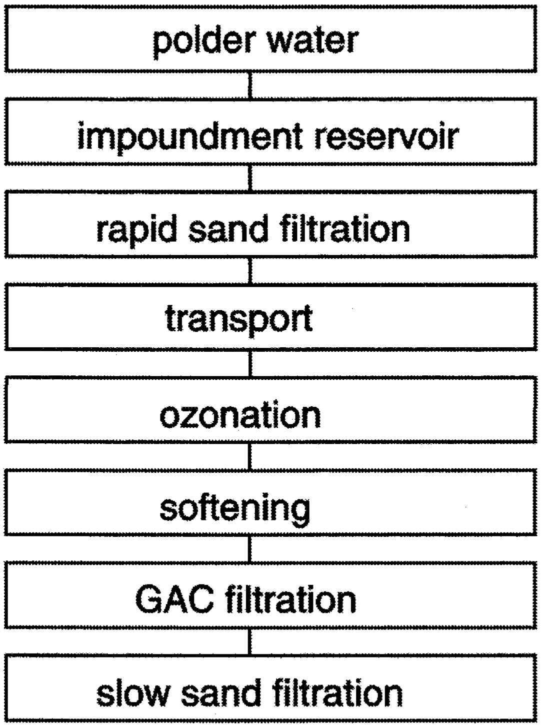

Figure 4 *Schematic overview of treatment plant D4*

Treatment plant I1

Resource: Canal with water from river Lek (origin: river Rijn).

Treatment:
- Selective intake, based upon resource water quality and dune stock quantity;
- Coagulation/sedimentation to remove particulate (in) organic matter, flocs binding phosphate, heavy metals and silt;
- Rapid sand filtration to remove remaining flocs making transport chlorination superfluous since 1985.
- Dune infiltration to remove bacteria and viruses from the source water and level water quality fluctuations (open infiltration canals; open collection canals; residence time 2 months, mixing with local water). Open collection canals however allow recontamination with bacteria, protozoans and non-human viruses from birds and fish.
- Aeration and rapid sand filtration to remove natural (in)organic matter;
- Ozonisation (since June, 1995) to disinfect and to form AOC, fuelling biological processes in GAC filtration (ozone produced from liquid oxygen; dosage based upon bacteria presence and removal; summer 0.75 mg/l (Ct < 1.5 mg x min/l); winter 0.9 mg/l (Ct = 1.5 - 2.0 mg x min/l);
- Softening from 15 ED to 8.4 ED;
- Primary GAC-filtration (since March 1995) to remove pesticides, colour and odours, biologically as well as by adsorption (contact-time 20 minutes);
- Secondary GAC-filtration (since March 1995) identical to primary GAC-filtration;
- Slow sand filtration to remove bacteria and particulate (in)organic matter;
- Finished water reservoirs. All vents are equipped with filters retaining all (micro-)organisms and particles (changed every 4 years).

Production: 60.10^6 m^3/year (max. capacity: 83.10^6 m^3/year).

Biological objectives: Post-disinfection in winter with chlorine was stopped in 1995 when ozonation and GAC-filtration was started. Because the lack of a disinfectant residual leaves the distribution system unprotected against recontamination, hygiene precautions during the laying and repair of mains have special attention within the water supply company.

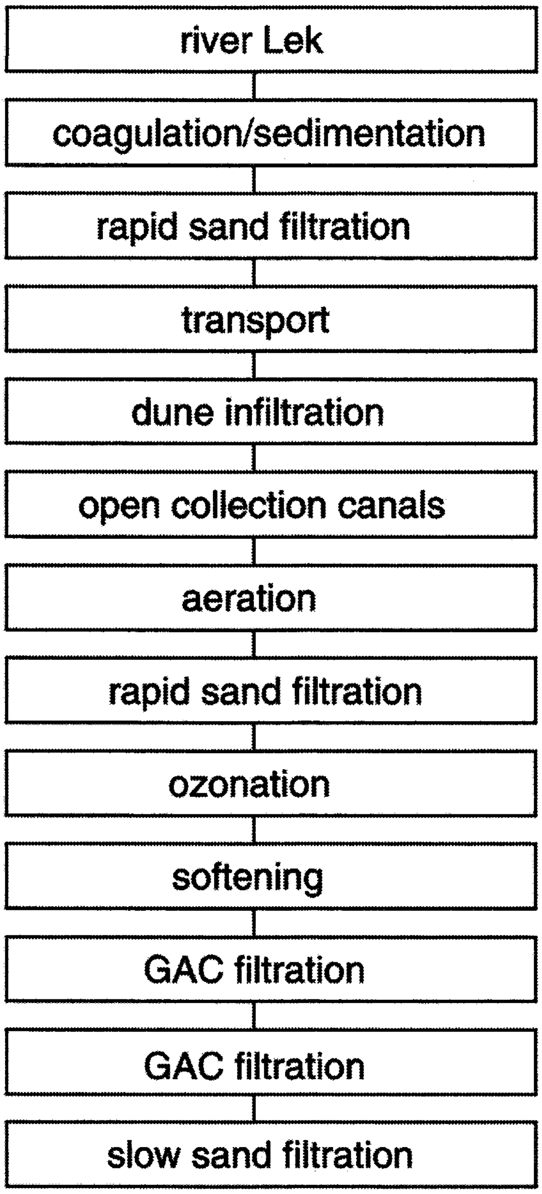

Figure 5 Schematic overview of treatment plant I1

Distribution system of company 3

Area type: Treatment plant D4: The eastern part of a large city and a nearby village (approx. 30 km^2), fully interconnected with the distribution system of treatment plant I1. Max. transport and distribution distance is 10 km.

Treatment plant I1: The western part of a large city and an industrial area (approx. 80 km^2), fully interconnected with the distribution system of treatment plant D4. However, large parts of the distribution system are supplied by one treatment plant only. Max. transport and distribution distance is 25 km (the treatment plant is located 15 km outside the city borders, the water is distributed via 2 large boosters with covered reservoirs and 2 smaller boosters without reservoirs).

Mains length: 370 km transport (∃ 300 mm); 1525 km distribution.
Connections: 150,000
Water price: / 2,94/m^3 (no yearly rate)
Inhabitants: 718,000 (December 31, 1996).

Distribution:
- 84.10^6 m^3/yr (1996)
- Cast-iron is the most abundantly used distribution mains material (cement-lined 18%, unlined 49%), followed by PVC mains (27%). Transport mains are mainly made of cast-iron (cement-lined 4%, unlined 38%), PVC (28%), concrete (31%) and steel (cement-lined 5%). Asbestos-cement (∀ 0,5%), HDPE (∀ 2%) and glass fibre reinforced plastics (∀ 0,3%) are no longer used.
- Transport mains are too large, resulting in high residence times.
- There is no long term mains replacement plan. 90% of all replacements are initiated by mains failure. Mains laid before 1945 are replaced during city renovation projects.
- The connections are not equipped with water meters. Statistically estimated the leakage rate is 3%.
- There are only manually operated air-valves in the distribution system, with automatic drains to prevent freezing.

Water quality:
- All sample locations are fixed locations, grouped into area's. Fortnightly a minimum of 1 sample per area is collected on alternating locations.
- Taste/odour: number of complaints (1993: 73; 1994: 88; 1995: 14) dropped dramatically since treatment plant I1 was changed in 1995, because temporary chlorination during winter was stopped.
- Chlorine decay: before 1995, chlorine was added in short periods in winter: 0,2 mg Cl$_2$/l after 20 min. contact time. Ex-works the concentrations were barely detectable (0.02-0.05 mg/l), but in the distribution system chlorine never was detectable.
- Water quality problems are mainly caused by the abundance of unlined cast-iron mains. Main problems are iron rust release, forming deposits that may lead to coloured water, and increased biofilm formation, leading to regrowth of (micro-) organisms.
- In 1991 a 6-year periodic cleaning program for air-scouring of the entire distribution system was introduced. Since then, coloured water complaints have been reduced with 65% (488 > 172/yr) and other complaints were halved (60 > 28/yr).

Data from water supply company 4

(treatment plant I2)

The company has 3 treatment plants available since the merger with another company in 1995. All use the same pretreated surface water that is further treated separately after dune infiltration at 3 locations.

Treatment plant I2

Resource: Dead arm of river Maas since 1976, (1955 - 1976: river Lek; 1874 - 1955: no dune infiltration, only natural dune water was used).

Treatment:
- Dead river arm (natural reservoir, residence time approx. 60 days);
- Coagulation in river arm to remove particles and phosphate;
- Transport (35 km; when water temperature is over 12 EC, transport chlorination is used to prevent increase of main resistance);
- Possibility to use water from river Lek (origin: river Rijn) in case ofpollution in river Maas;
- Rapid sand filtration to remove particles, also acting to remove Fe, Mn and NO_3;
- Transport to dunes (50 km, chlorination infrequently);
- Dune infiltration (since 1955, open infiltration canals, also deep subterranean infiltration after coagulation/flotation and rapid sand filtration; residence time in dunes approx. 60 days);
- Collection in open reservoir from drains, shallow wells and deep wells (5900 m^3/hr on average);
- Powderised carbon dosage in reservoir to remove pesticides and odours;
- Softening from 13 ED to 8.5 ED since January 1994;
- Aeration with cascades;
- Inundated rapid sand filtration;
- Slow sand filtration to improve microbiological water quality;
- Finished water reservoirs, including water tower (total 14,000 m^3).
  No roof vents, all reservoirs supplied with absolute-filters.
- Disinfection (since January 1995; NaClO; 15 min. contact time; dosage to keep residual after contact tank on 0.04 mg Cl/l.

Production: 51.10^6 m^3/yr (on average 5900 m^3/hr).

Biological objectives: Since dune infiltration was started in 1955, finished water has been chlorinated only when this was necessary to obtain good microbiological water quality. Periods of chlorination have differed from one week to recently more than 2 years. In January 1994 softening reactors were activated. One year later the company decided to start chlorination of finished water to improve bacteriological water quality, especially to reduce numbers of coliforms and *Campylobacter* bacteria, introduced by birds in the open dune water collection reservoir, cascades and rapid sand filters. Slow sand filtration logarithmic removal is approx. 3.5 units, 15 minutes of chlorination to a tank effluent residual of 0.04 mg Cl/l provides another 2 log units of removal.

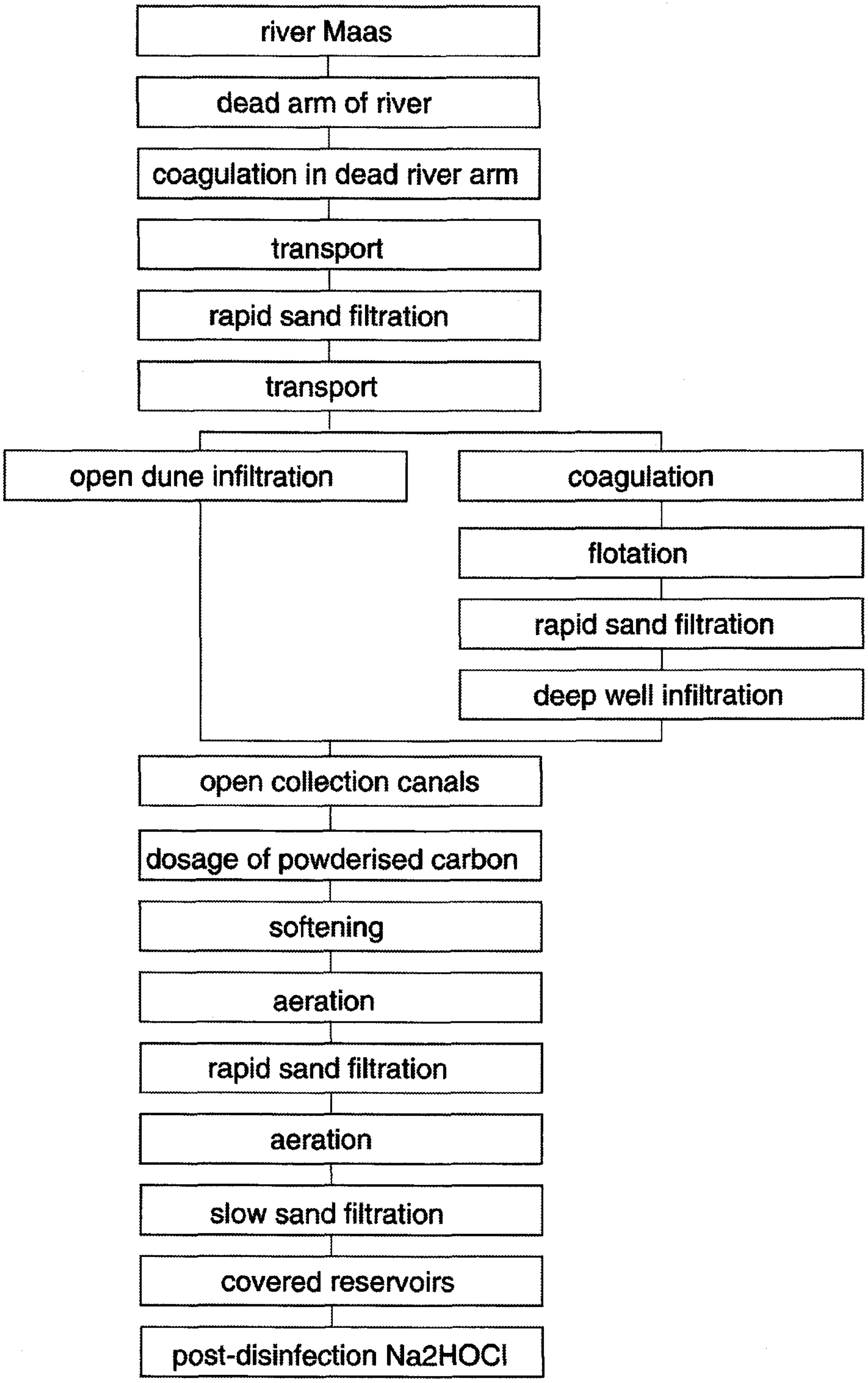

Figure 6 *Schematic overview of treatment plant I1*

Distribution system of company 4

Area type: Treatment plant I2: The western part of a conglomerate of a large city and a number of smaller cities and villages with little rural areas (approx. 500 km^2), fully interconnected with the distribution systems of the other treatment plants (and part of the water is supplied by other companies). However, large parts of the distribution system are supplied by one treatment plant only. Max. transport/distribution distance is 25 km.

Mains length: 100 km transport (∃ 400 mm); 950 km distribution (63 - 400 mm).
Connections: 501,000
Water price: f 3.43/m^3 (yearly rate / 105,00 - / 127,00)
Inhabitants: 1,200,000
hydrants: 7,081
Distribution: - 74.10^6 m^3/yr (1996)

- Cast-iron is the most abundantly used distribution mains material (73%), followed by asbestos-cement (20%), PVC (8%) and concrete (5%).
- There is no long term mains replacement plan.
- Water loss due to mains leakage and mains flushing totals 3%.
- There are no air-valves in the distribution system.

Water quality: - All sample locations are randomly chosen, but in a way that it fortnightly provides a complete overview of the supply area.

- Taste/odour: 29 in 1995, in most cases related to mixing zones.
- Chlorine decay: Finished water < 0.03 mg/l free chlorine.
- The entire distribution system is flushed every 4 years (1/4 per year).

Data on water supply company 5

(treatment plants A1, A2 and O1)

There are 28 treatment plants available to the water supply company, including treatment plants A1, A2 and O1 of which information is presented in this report. One of the 28 treatment plants uses surface water via deep infiltration, another one (A1) indirectly uses river water by bank filtration (= ground water). At none of the treatment plants has a disinfectant has ever been routinely added to the finished water.

Treatment plant A1

Treatment plant A1 is divided into two parts (L1 and L2), that join at the secondary effluent reservoir of L2. From this point on the water is treated equally. The treatment plant has been built in 1952 and has been completely renovated in 1987.

Resources: Bank filtrated ground water,
L1: 5 deep wells;
L2: 27 shallow wells;

Treatment:

L1:

- Aeration to remove CH_4 and H_2S and to add O_2;
- Sprinklers to spread and further aerate the water;
- Inundated rapid sand filtration to:
  - chemically oxidise S^{2-} to SO_4^{2+}
  - chemically oxidise Mn^{2+} to Mn^{4+}
  - chemically oxidise Fe^{2+} to Fe^{3+}
  - biologically oxidise NH_4^+ to NO_3^- (nitrification)
  - biologically oxidise CH_4 to CO_2 (methane-oxidation)
- Secondary effluent reservoir of L2.

L2:

- Sprinklers to spread and aerate the water;
- Inundated rapid sand filtration (objective: see L1)
- Aeration;
- Primary effluent reservoir;
- Inundated rapid sand filtration to further remove Fe and Mn and to remove bacteria and organic matter produced in primary filters
- Secondary effluent reservoir (also receives water from L1);
- GAC filtration to remove odours, bromacil and bentazon (;
- Aeration;
- 2 finished water reservoirs (total capacity 5800 m^3). No roof vents. Other vents are never placed over filters, always over wastes;
- Hardness (2,4 mmol/l) and Cl^--concentration (110 mg/l) are high.

Production: 12.10^6 m^3/yr.

Biological objectives: Bacterial biomass and AOC is mainly formed in the first rapid sand filters. The second rapid sand filters and GAC filters remove these for a large part, limiting regrowth in the distribution system.

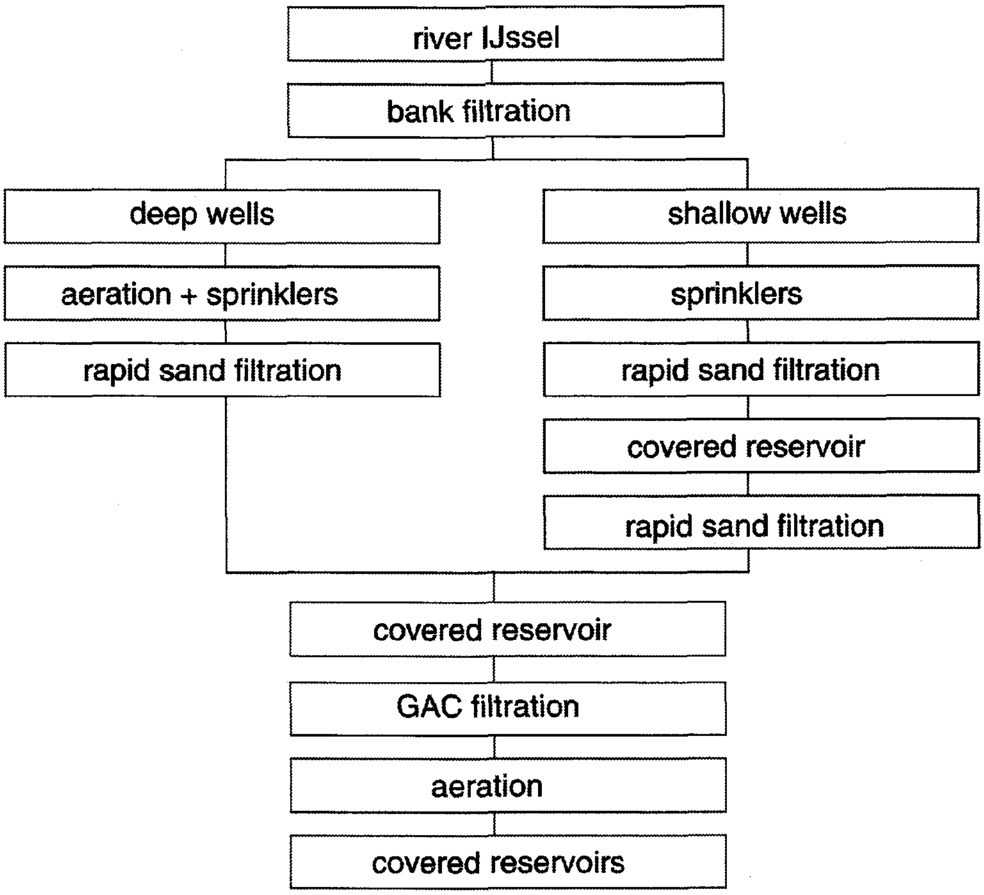

Figure 7 *Schematic overview of treatment plant A1*

Treatment plant A2

The treatment plant was built in 1936 and was completely renovated in the period of 1994 to 1996. The new primary filters were put to use in the period of November 1994 to May 1995. Information about primary filtration is divided in old (PO) and new (PN).

Resources: Anoxygenous ground water, 19 wells (55 - 80 m below ground level).
Deep wells are protected by a layer of loam, providing a better water quality. Shallow wells are located in swamps. All well-filters are embedded in sand-pockets. NH_4^+ and CH_4 levels of a number of wells are very high.

Treatment: PO: Inundated rapid sand filtration (19 steel tanks).
PN:
  - Aeration and degassing to remove CH_4 and H_2S and to add O_2 (2 perforated plate aerators);
  - Inundated rapid sand filtration (objectives: see plant A1);
- Primary effluent reservoirs (2 x 330 m^3);
- 2 aeration columns to add O_2;
- Inundated rapid sand filtration to further remove Fe and Mn and to remove bacteria and organic matter produced in primary filters;
- Tertiary filtration: identical to secondary filtration;
- Finished water reservoirs (2 x 825 m^3). No roof vents. Other vents are never placed over filters, always over run over wastes;
- Hardness (2,30 mmol/l), colour (24 mg/l Pt/Co) and DOC (6,7 mg/l) are high.

Production: 5.10^6 m^3/yr

Objectives: Because the raw water contains high level of CH_4, large quantities of biomass were formed in the filters by methane-oxidising bacteria.
Perforated plate aerators are installed to remove a large part of CH_4 from the water before rapid sand filtration, thus:
(i) limiting growth of methane-oxidising bacteria in the filters;
(ii) limiting CH_4 levels in the finished water and therefore limiting growth of methane-oxidising bacteria in the distribution system;
(iii) limiting oxygen-demand in the filters, thus improving nitrification and chemical oxidation processes in the filters.
These improvements have led to an improvement of the biological stability of the finished water.

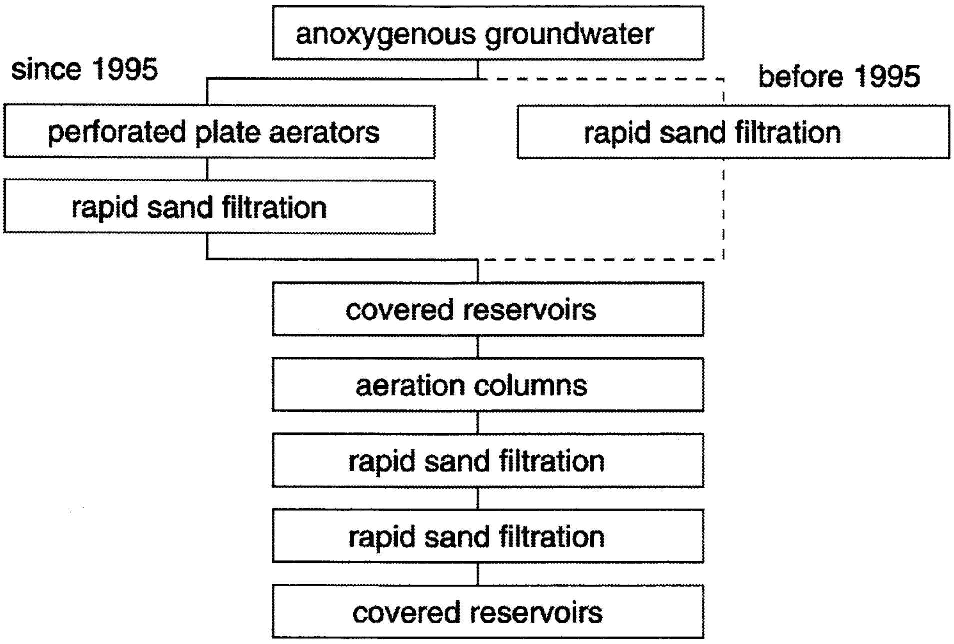

Figure 8 *Schematic overview of treatment plant A2*

Treatment plant O1

There are 28 treatment plants available to the water supply company, including treatment plants A1, A2 and O1 of which information is presented in this report.

Resources: Oxygenous ground water, 21 wells in heterogenous sand layers, not protected by layers of clay of loam (total capacity 70 m^3, 60 - 80 m below ground level). The treatment plant is built in 1954.

Treatment:
- Lime stone filtration for pH adjustment;
- Finished water reservoirs (2 x 480 m^3 + 2 x 1510 m^3). No roof vents, other vents are never placed over filters, always over run over wastes;
- Hardness (0,80 mmol/l) is low, the water is aggressive (SI = -0,5).

Production: $5.2.10^6$ m^3/yr

Objectives: Because the raw water is oxygenous and collected from relatively deep wells the water contains low levels of organic substances and no dissolved Fe and Mn or NH_4^+, CH_4 and H_2S. The water is biologically stable, but is aggressive. Lime stone filtration reduces the aggressiveness of the water.

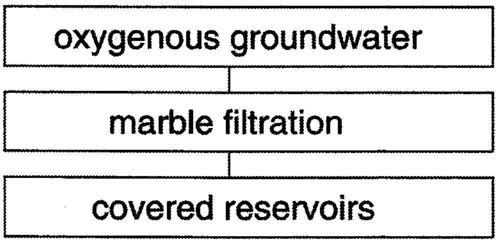

Figure 9 *Schematic overview of treatment plant O1*

Distribution system of company 5

Using 28 treatment plants, the water supply company supplies a large province via relatively small mains (ι 50 - 600 mm, mostly ι 100 mm). To be able to sufficiently supply at daily peaks, the company has 72 reservoirs, 24 of these are water towers or located on high ground levels, and 6 boosters. Supply however is not sufficient. The entire system is interconnected, although on some locations valves are closed to split pressure zones or to prevent water quality changes noticeable to consumers (colour, hardness).

Area type: <u>Treatment plant A1:</u> A rural area with a medium-sized city (450 km^2), maximum transport/distribution distance: 25 km;
<u>Treatment plant A2:</u> A rural area with a small city (450 km^2), maximum transport/distribution distance: 25 km;
<u>Treatment plant O1:</u> A rural area with villages (150 km^2; including mixed water zones: approx. 500 km^2); maximum transport/distribution distance: 40 km;

Mains length: 11,000 km
Connections: 450,000
Water price: / 2.41/m^3 (yearly rate / 32,00)
Hydrants: 35,000

Distribution:
- 86.10^6 m^3/yr (1996)
- PVC is the most abundantly used distribution mains material (73%), followed by asbestos-cement (17%) and cast-iron (10%).
- Long term mains replacement plan: starting 1998 0.5% of all mains will yearly be replaced. Priority: cast-iron, asbestos-cement.
- Total water loss at distribution is 4.6%. Statistically estimated the leakage rate is 1% (meter errors: 3%, flushing 0,5%).
- There are no air-valves in the distribution system.

Water quality:
- Sample locations are fixed streets, but not fixed houses. Sample locations are usually selected at dead ends of mains, except in cities. The locations are grouped into area's and fortnightly a minimum of 1 sample per area is collected on alternating locations.
- Taste/odour: there are no complaints in area's supplied with drinking water produced from oxygenous ground water. In other area's the number of complaints is very limited. The major part of the complaints originate from the mixing zones of the distribution system of treatment plant A1 and other treatment plants. Although the cause of the complaints is not clear yet, they probably are due to the origin of the ground water (bank filtrated river water), although GAC-filtration theoretically would counter this problem.
- Invertebrates: consumer complaints are very rare.
- Dead ends are flushed every 3 to 6 months. Transport mains are flushed every 5 years. Some area's are entirely air-scoured every 2-3 years. Pigging is also used. Cleaning methods and strategies are currently under review.

ANNEX 3 - Characteristics of selected water supply systems in the Netherlands

Table 3.1 Characteristics of the selected water supply systems

ID	**Source**	**Treatment**[*]		**System**	**Annual production**
code	type	type	train	type	(x 1000 megalitres)
D1	lake	direct[**]	res/Cl_2/coag/RSF/GAC/GAC/ClO_2	rural	20
D2	river	direct	res/floc/O_3/RSF/GAC/Cl_2	urban/rural	41
D3	river	direct	res/floc/GAC/NaClO	urban/rural	102
D4	lake	direct	coag/res/RSF/O_3/GAC/SSF	urban	24
I1	river	dune	coag/RSF/dune/open/RSF/O_3/ GAC/GAC/SSF	urban	60
I2	river	dune	res/RSF/dune/open/PAC/RSF/SSF[##]	urban/rural	51
A1	river	anoxyg[#].	RSF/RSF/GAC	rural/urban	12
A2	ground	anoxyg.	degas/RSF/RSF/RSF	rural	5
O1	ground	oxyg[#].	aeration and pH-adjustment	rural	5

[*] main characteristics and treatment steps are mentioned; for details see annex 1.
res = impoundment reservoir; coag = coagulation/sedimentation;
RSF = rapid sand filtration; floc = flocculation and floc-removal;
SSF = slow sand filtration; dune = dune infiltration and passage;
open = open collection; PAC = powdered activated carbon dosage;
GAC = granular activated carbon filtration; degas = degassing.

[**] surface water treatment without infiltration always includes impoundment reservoirs.

[#] oxyg. = oxygenous; anoxyg. = anoxygenous.

[##] temporary chlorination with NaClO since 1995 until dune water collection is covered.

Water quality monitoring and maximum allowable levels in the Netherlands

Table 3.2 Monitoring of drinking water and maximum allowable levels

Variable*	**Monitoring frequency** (samples per period)			**Maximum allowable levels** (per sample except HCC's)	
	TSW**	TGW**	DS**	TP*	DS*
coli36	day	week	2 weeks	$< 1/300$ ml	$< 1/100$ ml
coli44	day	week	2 weeks	$< 1/300$ ml	$< 1/100$ ml
FS**	week	-	-	$< 1/100$ ml	$< 1/100$ ml
SSRC**	week	-	-	$< 1/100$ ml	$< 1/100$ ml
HCC22***	12/yr$^{\&}$	12/yr$^{\&}$	6 months	-	GM < 100/ml$^{\#}$
HCC37***	12/yr$^{\&}$	12/yr$^{\&}$	6 months	-	GM < 10/ml$^{\#}$

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* Abbreviations of variables are explained in paragraph 3.3.1.

** TSW = treatment plants (also) using surface water.
TGW = treatment plants using ground water exclusively.
DS = distribution systems: 1 sample per 10,000 inhabitants (minimum = 2).
TP = treatment plants.

*** When coliforms or thermotolerant coliforms are found in a sample, another sample has to be collected and the number of faecal streptococci and spores of sulphite-reducing clostrida in this sample have to be assessed as well.

& When disinfected: 1 sample per 10,000 m^3 daily produced or distributed drinking water or 1 sample per 50,000 inhabitants.

GM = annual geometric mean.

\- No directive.

ANNEX 4 - Heterotrophic plate counts and *Aeromonas* colony counts in water supplies in the Netherlands

In this annex cumulative frequency distributions are presented of the national data on the numbers of heterotrophic colony counts 22 EC (HCC22), heterotrophic colony counts 37 EC (HCC37) and *Aeromonas* bacteria (30 EC). In each graph the annual minima, geometric means and maxima of 3 years (1993-1995) of the treatment plants and distribution area's are presented. Because there are no maximum allowable levels for HCC values in the finished water, HCC values are not always determied in finished water. In Figures 10 and 12 data are presented of approx. 182 and 198 treatment plants respectively. For the other determinands, data of most of the 249 treatment plants and their distribution area's are presented.

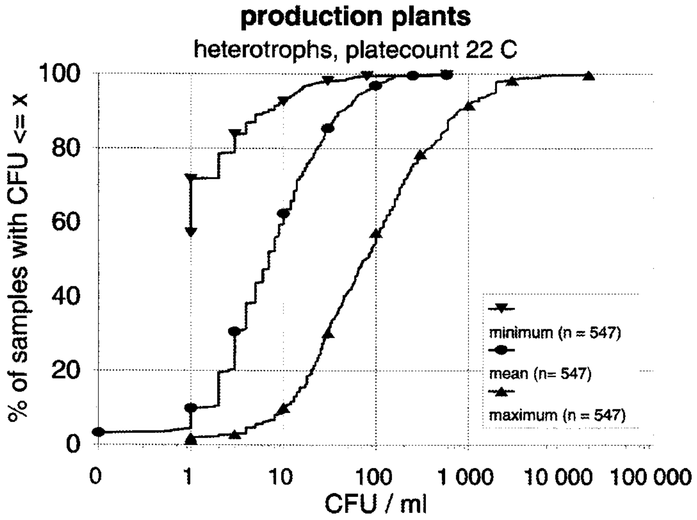

Figure 10 *HC22 in finished water (national data)*

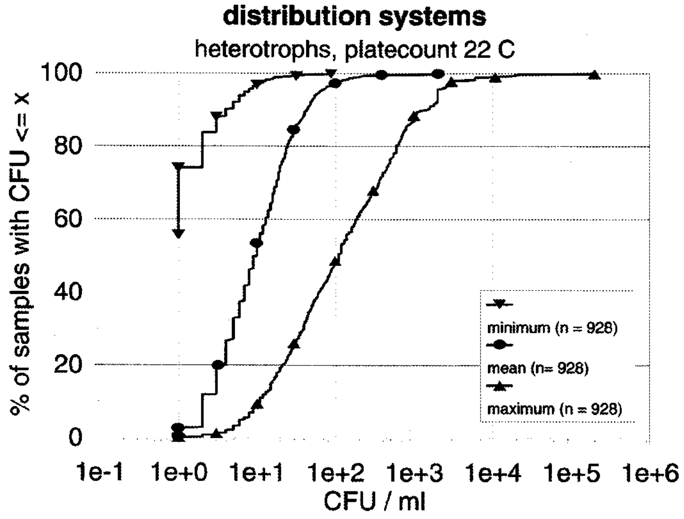

Figure 11 *HC22 in distributed water (national data)*

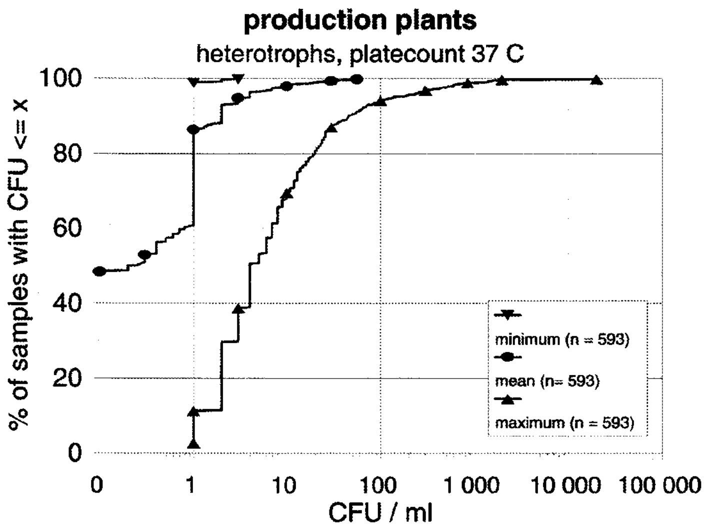

Figure 12 *HC37 in finished water (national data)*

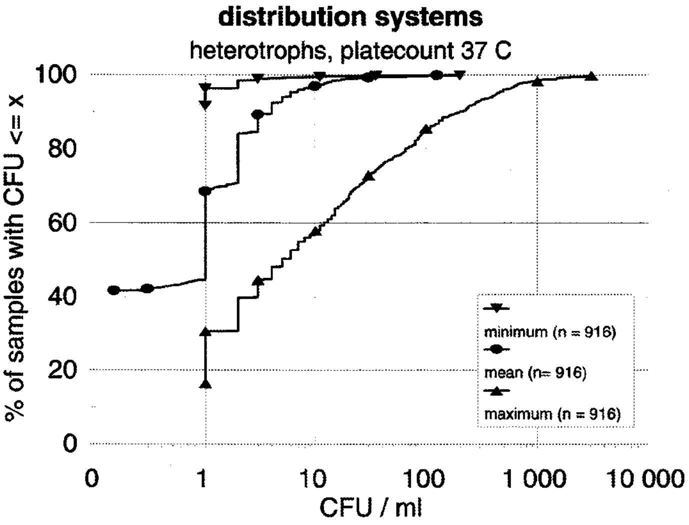

Figure 13 *HC37 in distributed water (national data)*

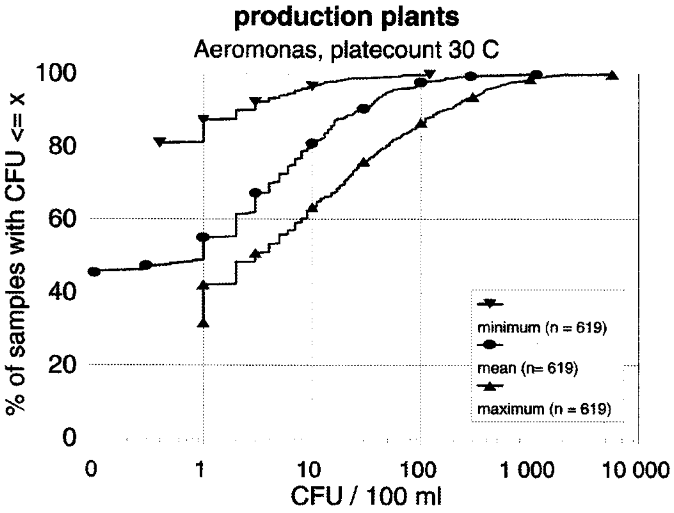

Figure 14 *Aeromonas in finished water*

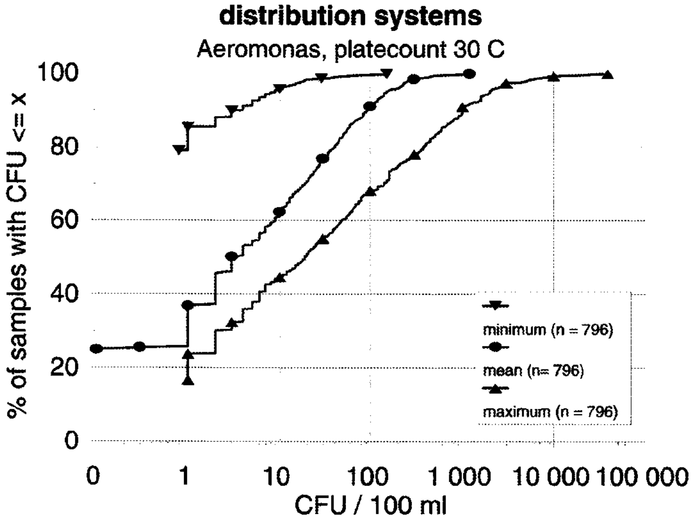

Figure 15 *Aeromonas in distributed water*

ANNEX 5 - Additional data on drinking water quality in the Netherlands

This paragraphs presents the values of water quality determinands in the finished and distributed water of the 9 selected treatment plants (see paragraph 3.4.2).

Contents

Disinfection by-products......185
Temperature......190
Acidity......191
DOC......191
Dissolved Oxygen......192
Turbidity......193

Disinfection by-products

In the graphs with DBP-concentrations guideline levels are mentioned:

WLB: levels proposed for the Netherlands legislation
EU: levels proposed for the EU guidelines
WHO: WHO guidelines 1993
US: US = USEPA Health Advisory (Office of Water) 1994.

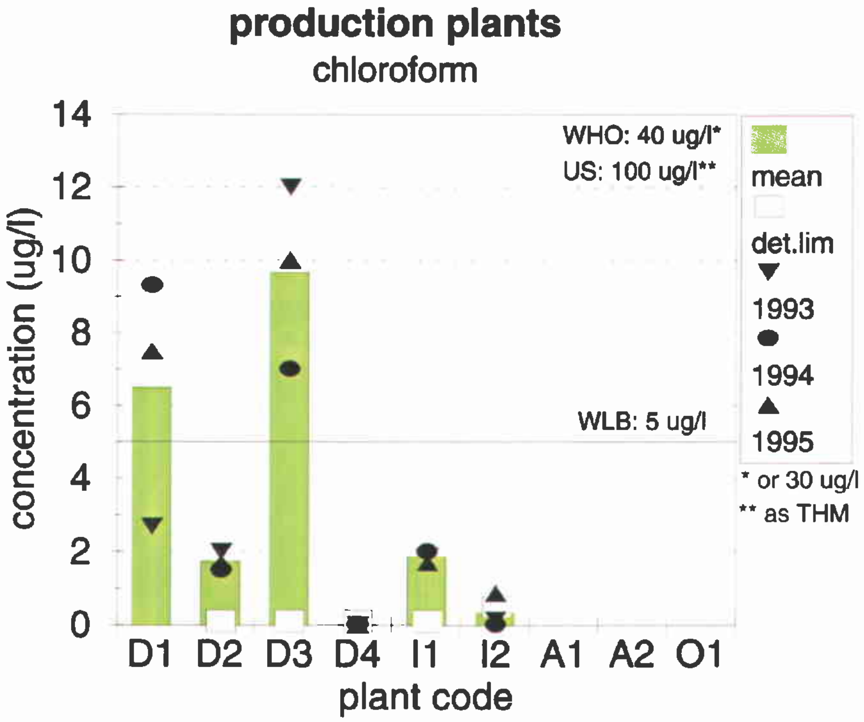

Figure 16 *Chloroform in finished water*

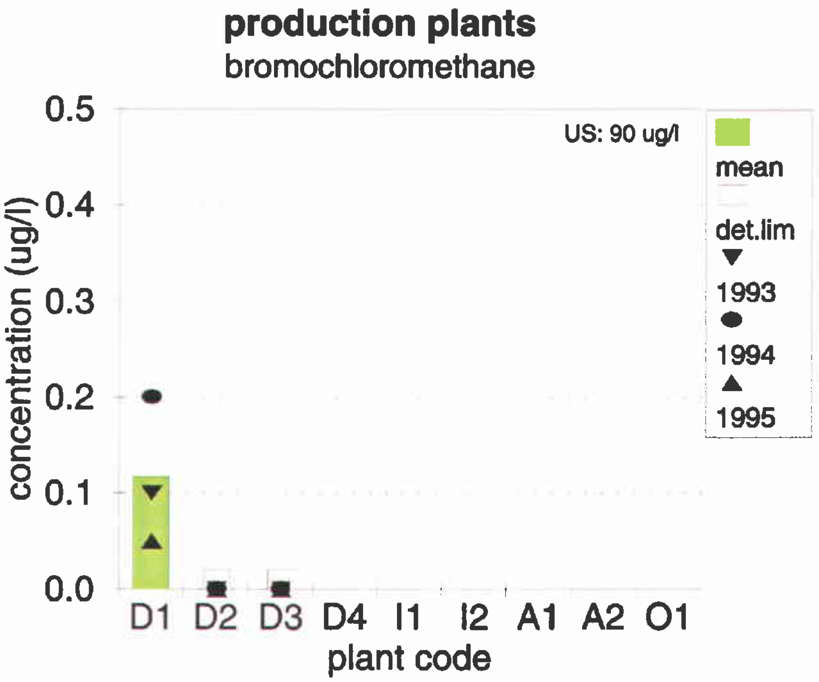

Figure 17 *Bromochloromethane in finished water*

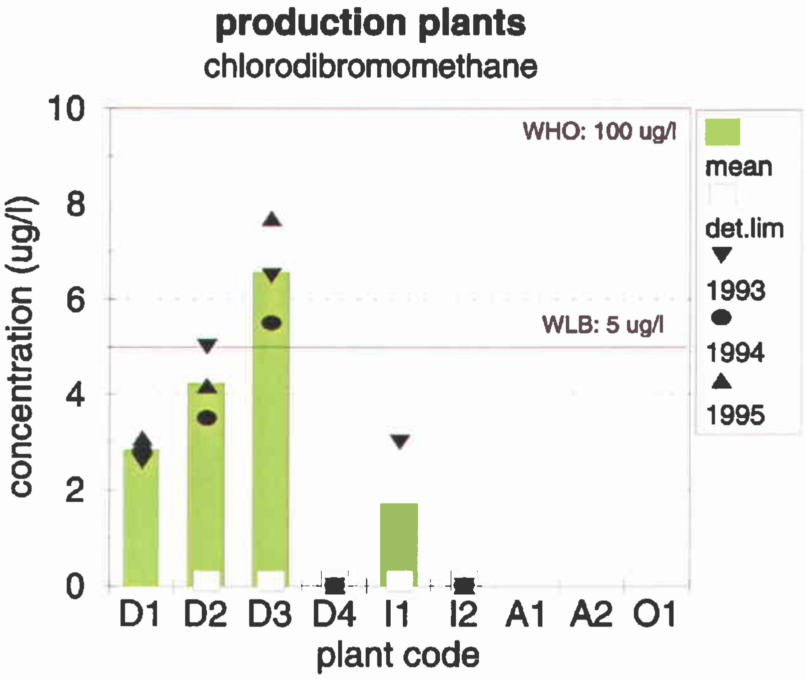

Figure 18 *Chlorodibromomethane in finished water*

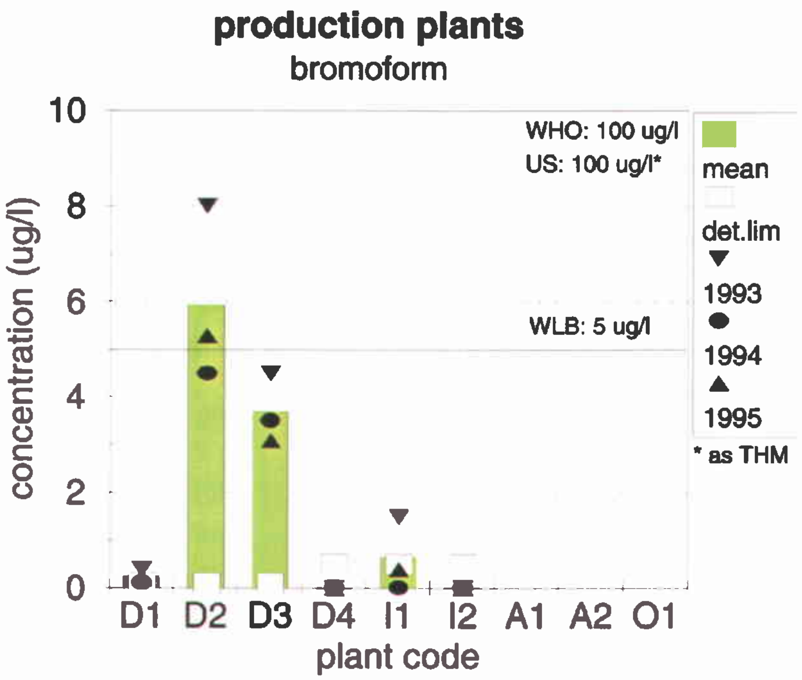

Figure 19 *Bromoform in finished water*

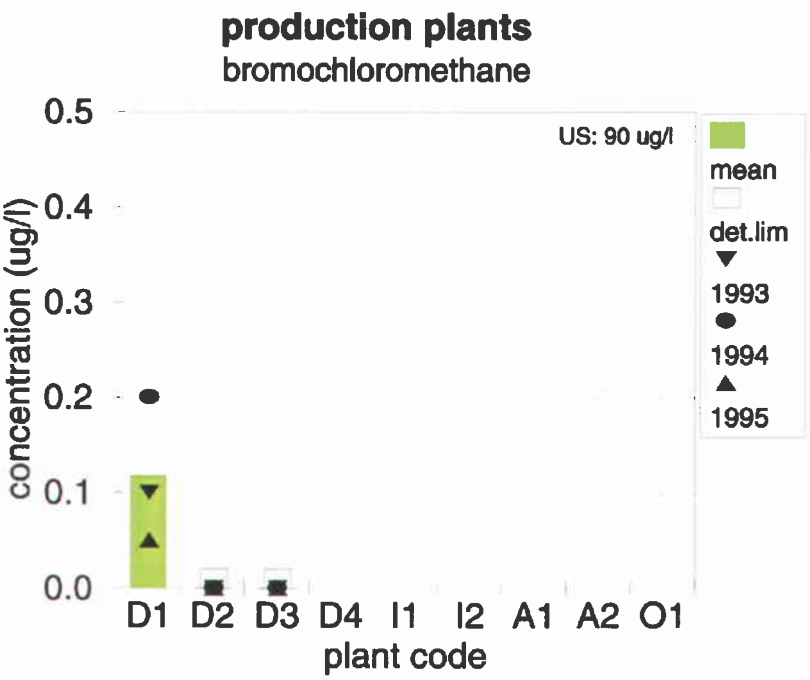

Figure 20 *Bromochloromethane in finished water*

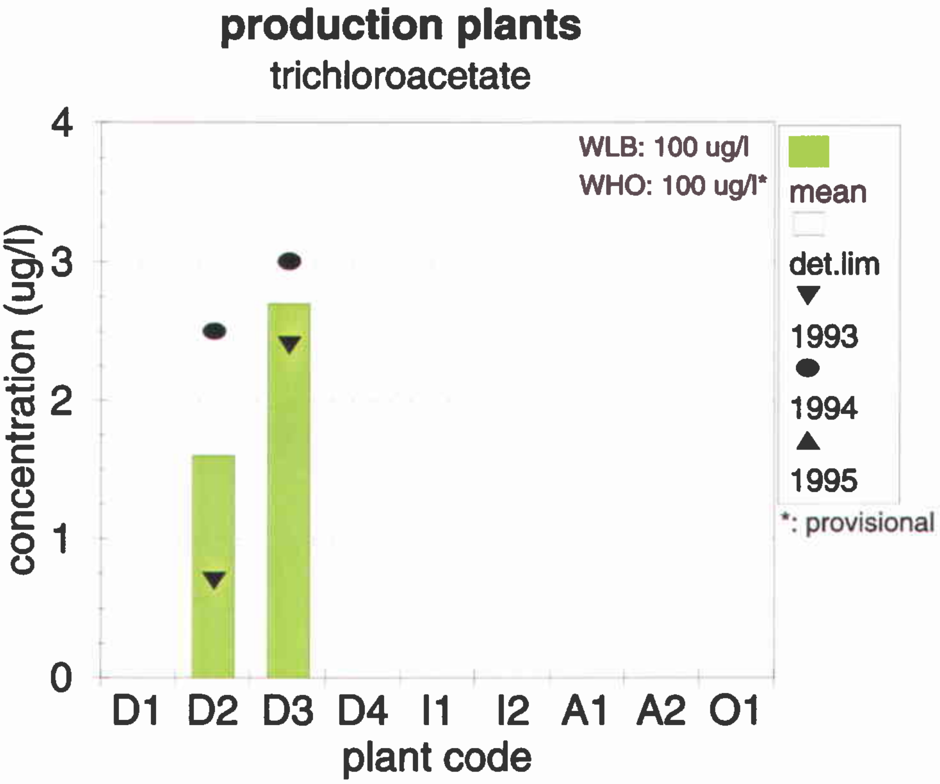

Figure 21 *Trichloacetate in finished water*

Figure 22 *Trichloroacetonitril in finished water*

Figure 23 *Dicloroacetonirtil in finished water*

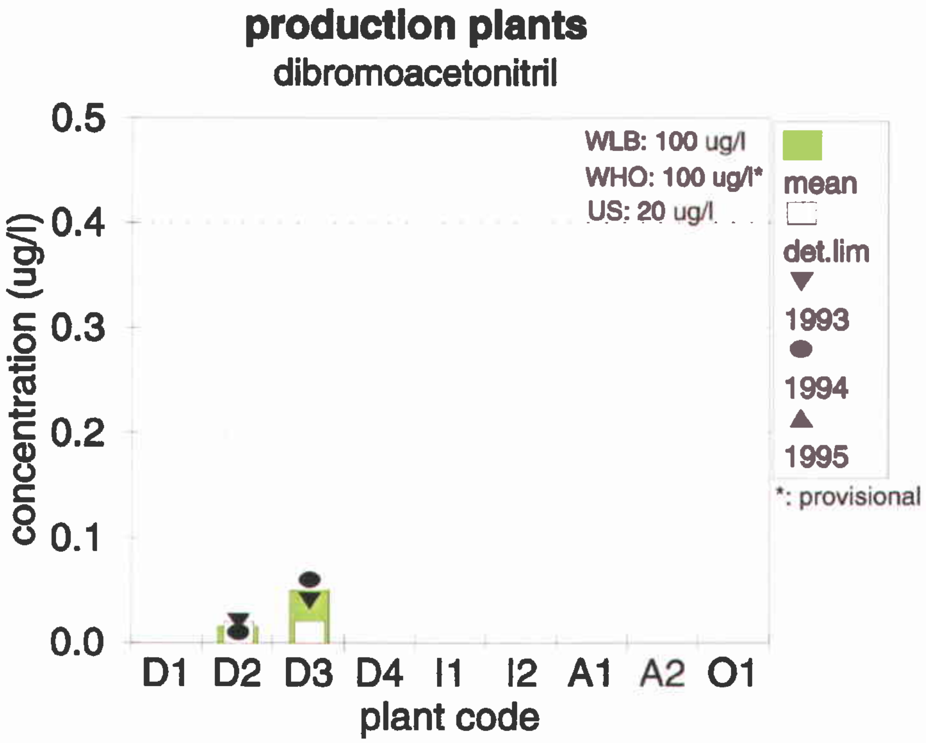

Figure 24 *Dibromoacetonitril in finished water*

Temperature

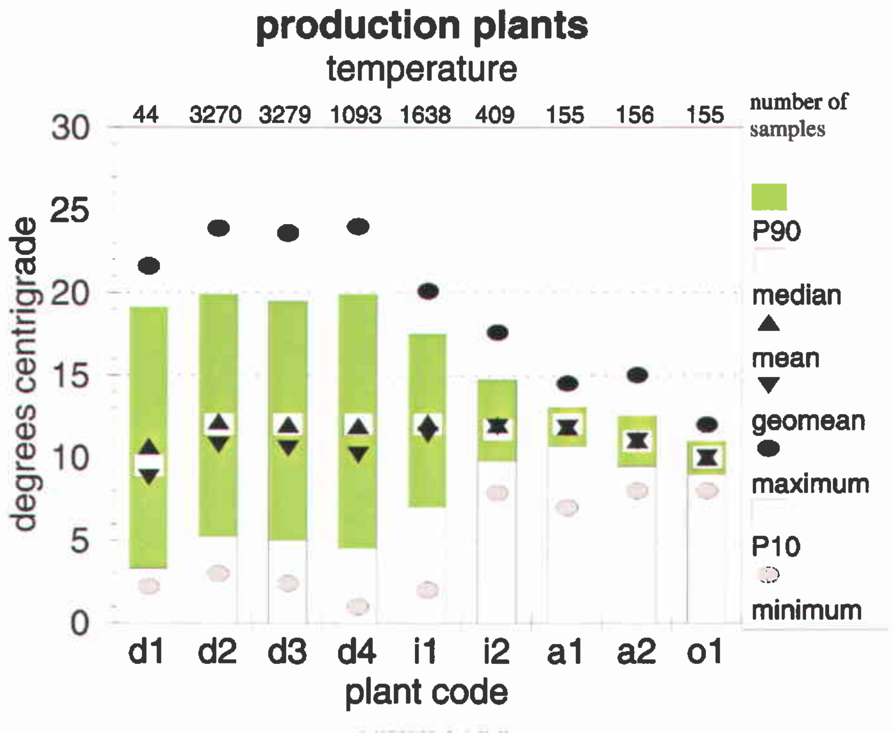

Figure 25 *Temperature in finished water*

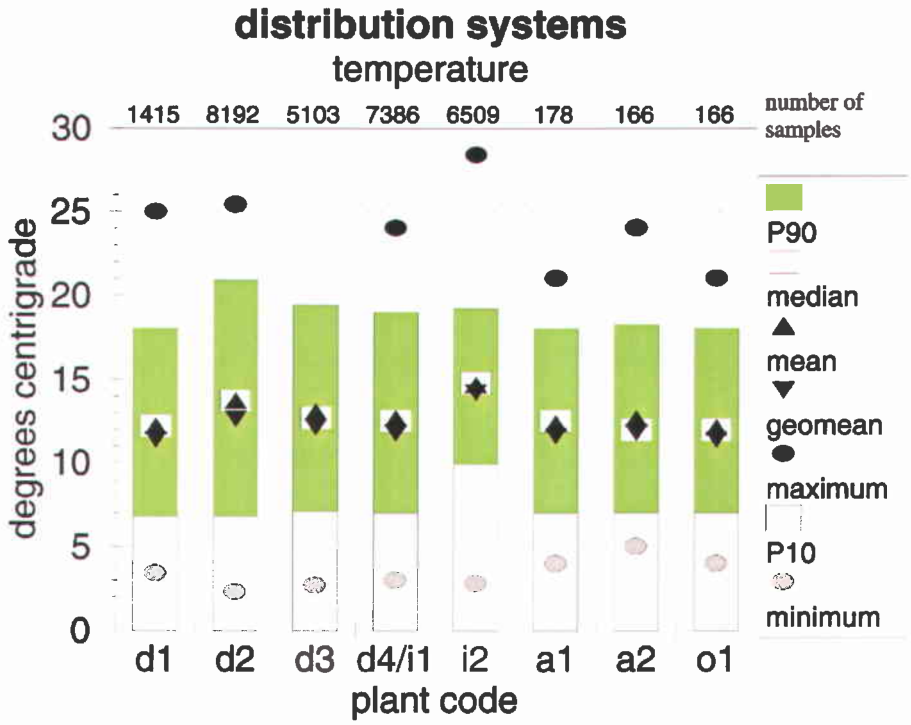

Figure 26 Temperature in distributed water

Acidity

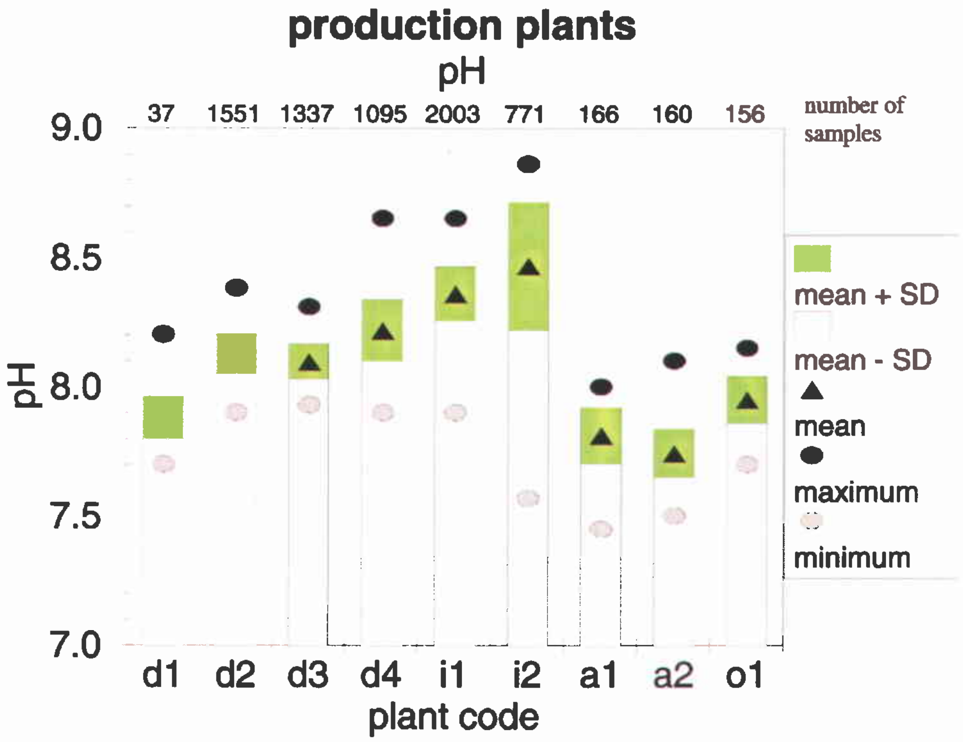

Figure 27 *Acidity in finished water*

DOC

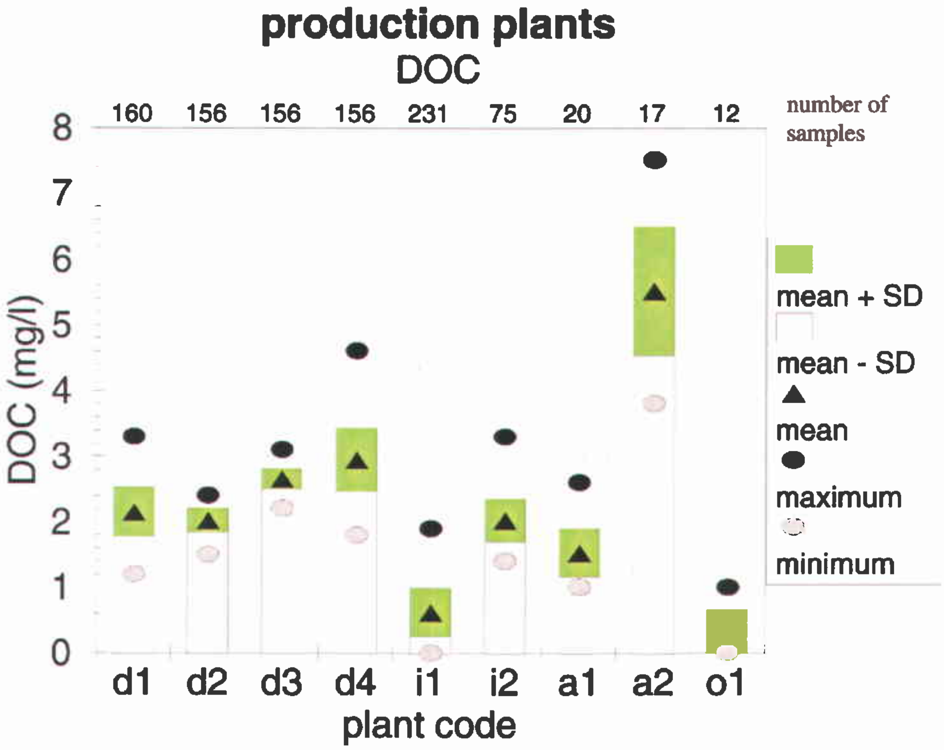

Figure 28 *DOC in finished water*

Dissolved Oxygen

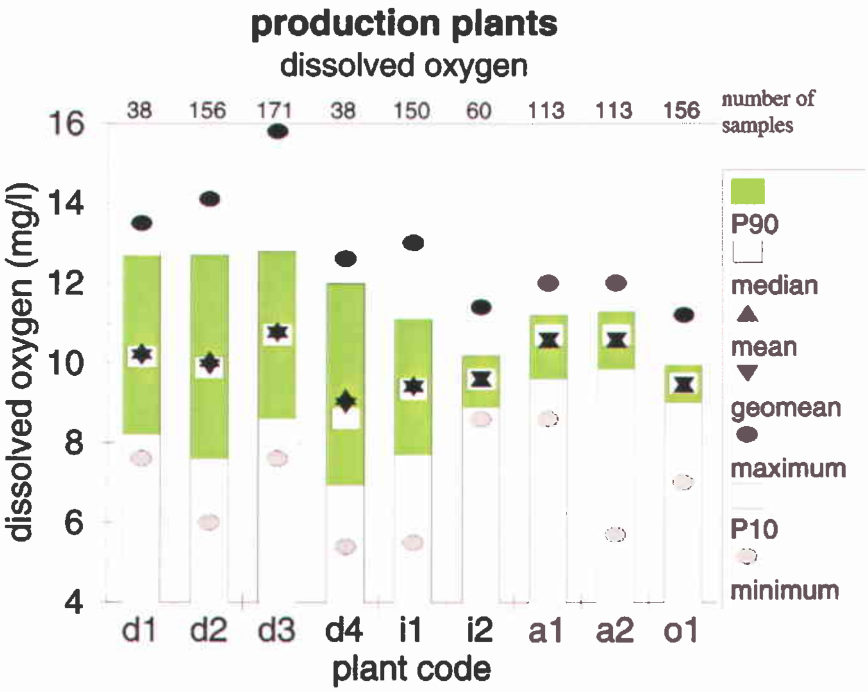

Figure 29 *Dissolved oxygen* in *finished water*

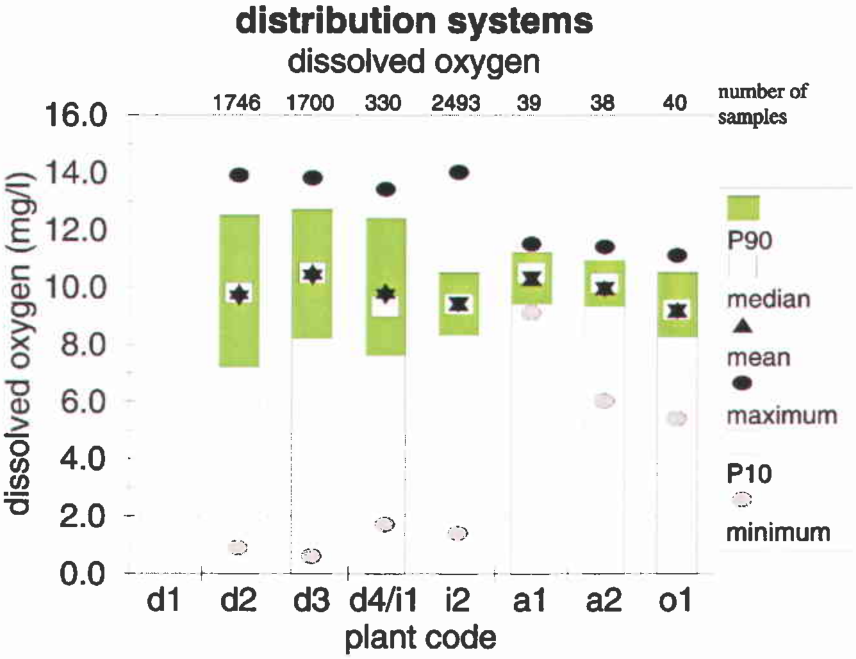

Figure 30 *Disolved oxygen in distributed water*

Turbidity

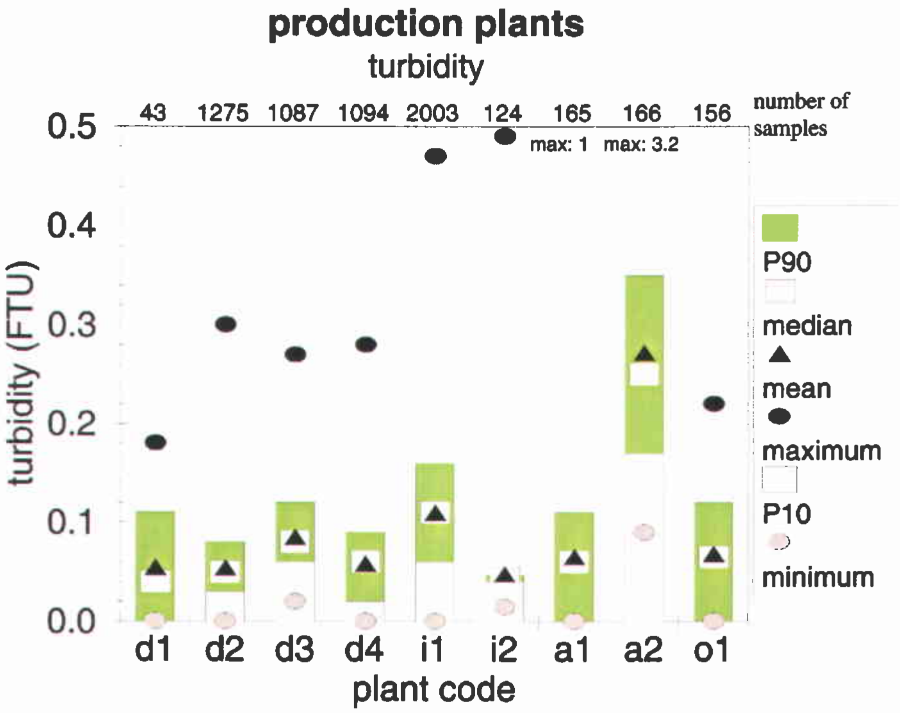

Figure 31 *Turbidity in finished water*

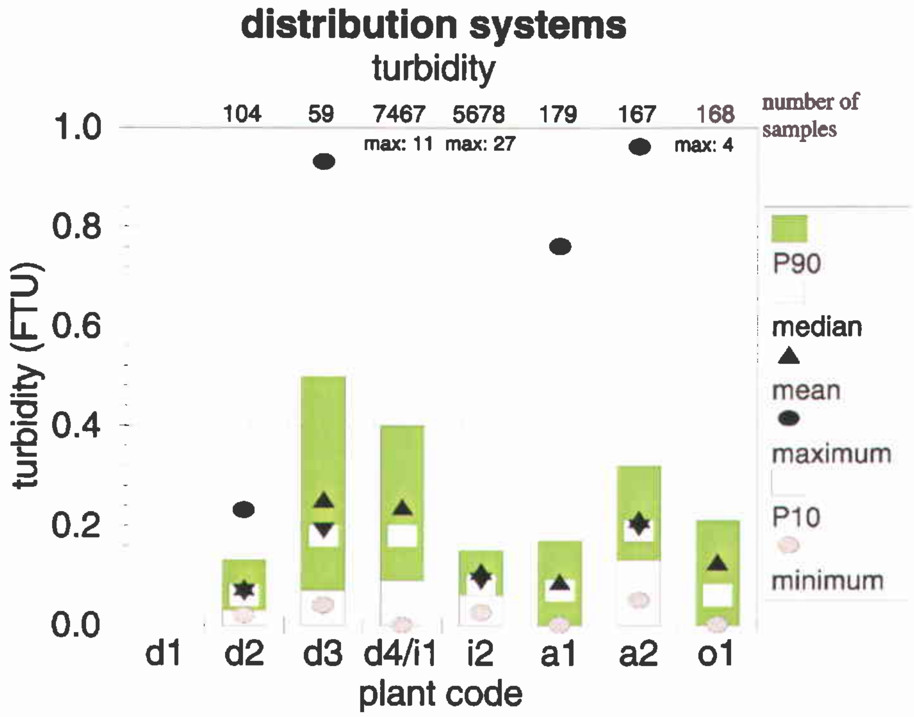

Figure 32 *Turbidity in distributed water*

ANNEX 6 - Characteristics of selected treatment plants in the United Kingdom

Water Treatment Works A1

A schematic diagram for Works A1 is shown in figure 1.

Water Treatment Works A2

A schematic diagram for Works A2 is shown in figure 2.

Water Treatment Works A3

This is comprised of nine boreholes, some of which have GAC filtration for pesticide removal. Final disinfection is with free chlorine.

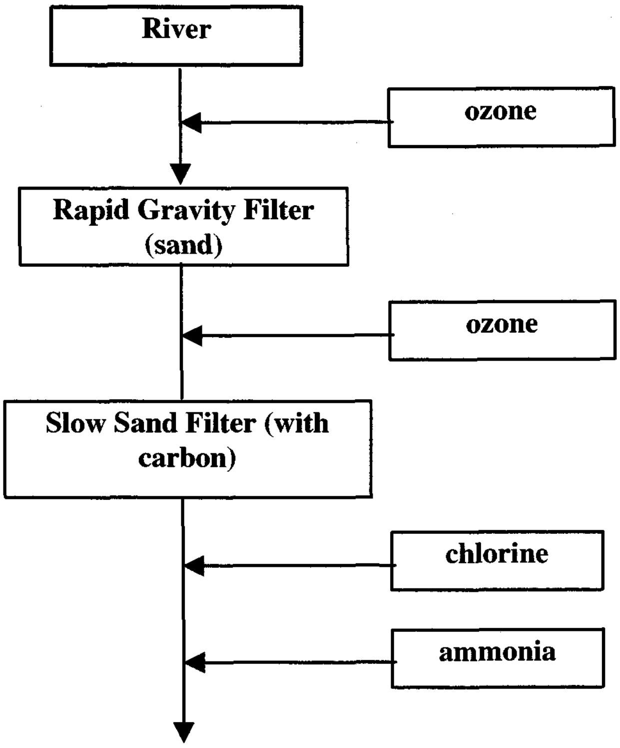

Figure 1 *Schematic Diagram of Water Treatment Works A1*

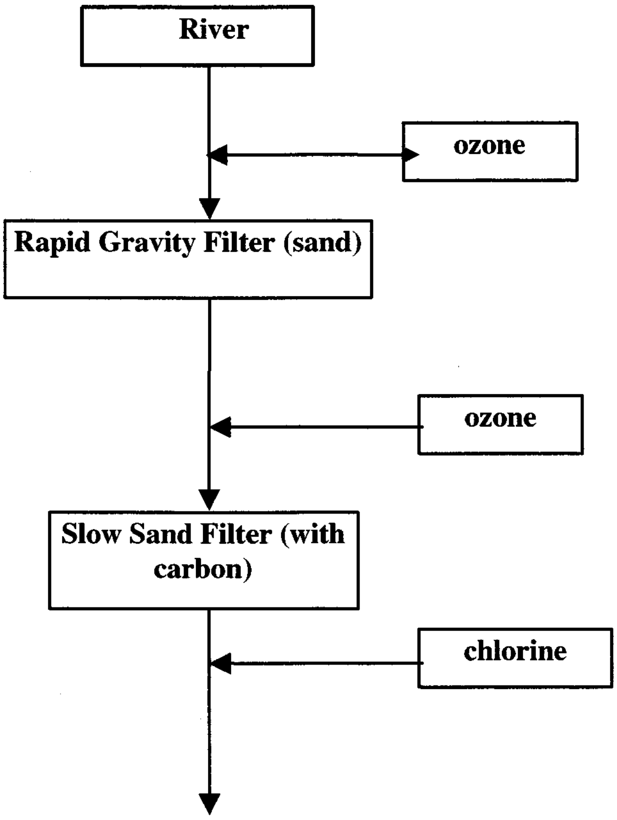

Figure 2 *Schematic Diagram of Water Treatment Works A2*

Water Treatment Works C1

A schematic diagram of Treatment Works C1 is shown in figure 3.

The water is abstracted directly from a river via three intakes which are processed as two separate streams. On some occasions one of these streams is supplemented with water from a number of boreholes located on the site of the treatment works.

Stream One (41Ml/d)
Direct river abstraction
Coarse screens.
Turbidity and pH monitoring equipment has been installed to measure the acidity of the river water.
Sedimentation Tanks and Accentifloc Clarifiers with Aluminium Sulphate coagulant
Chlorine addition to 1.7-2.7 mgl^{-1}
Rapid Gravity Filtration (5.8m/h)
Dechlorination (SO_2)
*Ozone (CT approx 12 mins)
GAC Filtration (EBCT 10 mins)*
Chlorine addition 1.5 mgl^{-1}
Contact Tank (10-12h), pH correction (NaOH), chorine residual adjustment (SO_2)

Stream Two (34Ml/d)
Direct river abstraction
Coarse Screening, Band screens
Flat Bottom Clarifiers with Aluminium Sulphate coagulant and polyelectrolyte aid
Chlorine addition (1.7-2.7 mgl^{-1})
Introduction of Borehole water which is aerated by forced air, chlorinated for iron removal (1.7-2.7 mgl^{-1}). Combines with river water treatment stream on to -
Rapid Gravity Filtration (4.8m/h)
Dechlorination(SO_2)
*Ozone (CT approx 12)
*GAC Filtration (EBCT 10min)
Chlorine addition (1.5 mgl^{-1})
Contact Tank (10-12h)
pH correction (NaOH)
Chlorine residual adjustment (SO_2)

* * Treatments added after 1995 and so effect not reflected in data collected for the study (92-94) Similarly microfiltration and recirculation of washwater and sludge from both streams was introduced in 1995.

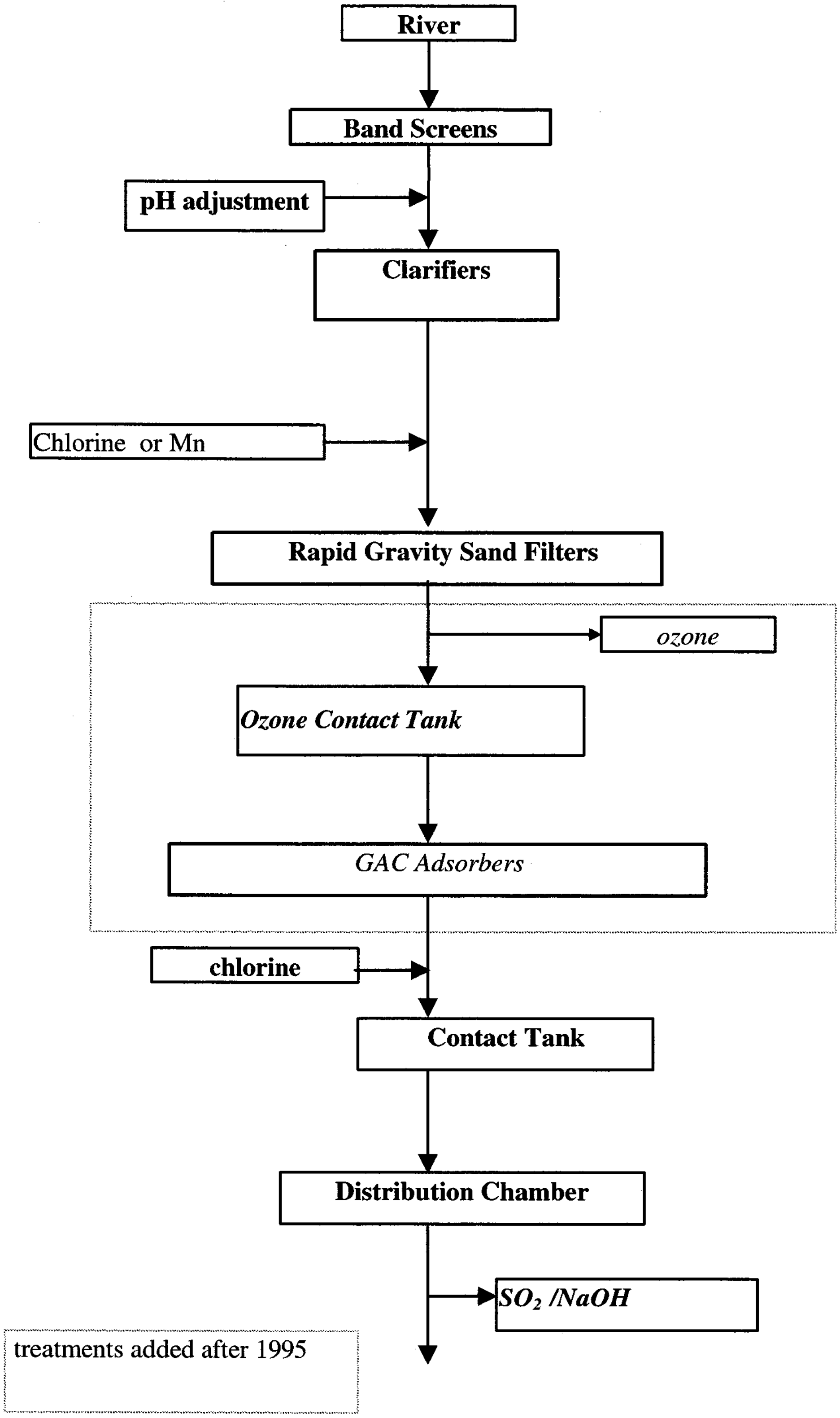

Figure 3 *Schematic Diagram of Treatment Works C1*

Water Treatment Works C2

A schematic diagram of Treatment Works C2 is shown in figure 4.

Work Output (111Ml/d maximum)

Coagulation with Ferric Chloride (NaOH added when required at pH 7.4-7.6)

Intermittent addition of Powdered Carbon (pesticides)

Addition Polyelectrolyte

Clarification (Flat Bottomed, Accentrifloc and Accelerator)

Chlorination free residual of 1.8 mgl^{-1}

Rapid Gravity filtration (anthracite/sand)

Rechlorination at outlet of "open filters"

Contact in potable reservoir (>2h)

Dechlorination of part of stream to 0.6 mgl^{-1} (SO_2) Remainder leaves at 1.0 mgl^{-1}

Since 1995, phosphoric acid has been added to part of the works final water.

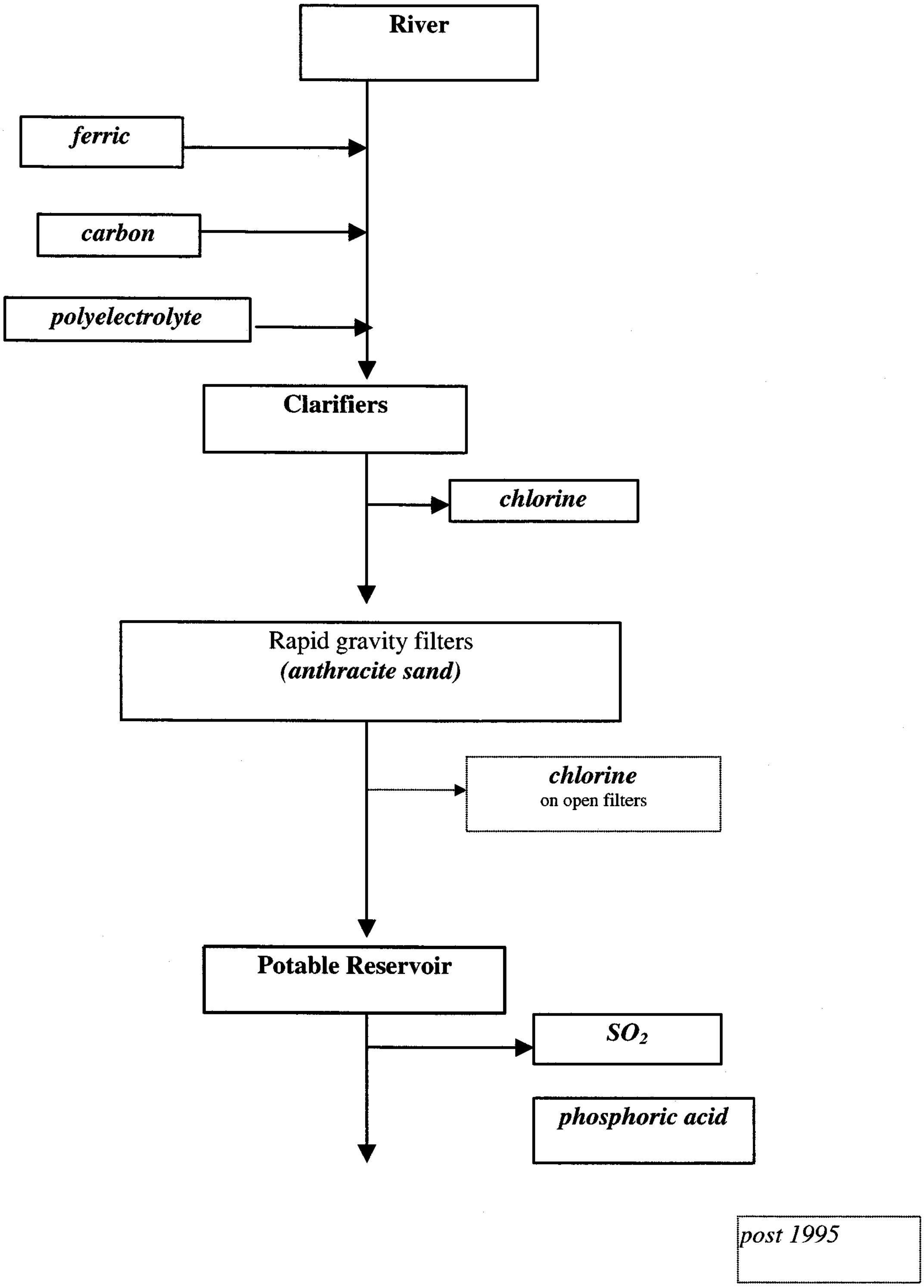

Figure 4 *Schematic Diagram of Water Treatment Works C2*

Treatment Works D1

A schematic diagram for Works D1 is shown in figure 5.

Treatment Works D2

Deep groundwater with simple chlorination. Serves a small geographically remote area, but is also blended into a bulk supply for a wider area. Chlorine levels are set for the bulk supply. High combined chlorine residuals are formed with the background ammonia at about 0.16mg/l

Treatment Works M1

A schematic diagram for Treatment works M1 is shown in figure 6.

Under normal conditions, water is abstracted from the River at the rate of ten million gallons per day (45.4 $M\lambda d^{-1}$). The water is carried along a Canal some (64 km) to a 90 410 $M\lambda$ reservoir. The time of travel in the canal is 4-6 days, dependent upon the abstraction rate.

Water is pumped from the raw water storage reservoir via a band screen and up to seven pumps to the treatment works which is situated adjacent. Aluminium sulphate and polyelectrolyte coagulants are added before the water passes forward to six sedimentation tanks and seven rapid gravity sand filters. Fluoridation is practiced at this works using hexafluorosilicic acid, and pH correction is with lime. The free chlorine dose leaving the works is trimmed to a target of between 0.40 and 0.46 $mg\lambda^{-1}$ with sulphur dioxide. *(NB Data for 1992-94 suggest a more realistic mean value of 0.33 free, 0.41 total).*

This water supplies two nearby towns and is also mixed with other sources to serve several surrounding more rural water supply zones.

Sludge is drawn continuously from the sedimentation tanks and, together with the filter wash-water, passes to three settling tanks which allow the sludge to be settled, again with the help of a polyelectrolyte coagulant. The supernatant from these tanks is returned to the head of the works. Settled sludge is pumped to a wastewater treatment works

Details of Treatment works M2

A schematic diagram for Treatment works M2 is shown in figure 7.

A 600mm borehole drilled to a depth of 106.68 m into red sandstone 3.18Mld^{-1} abstracted and pumped to a reservoir (3.4 Ml capacity). Treatment is chlorination only.

Supplied to a population of 10,000 via a 300mm PVC main. Supply zone was originally constructed out of cast iron and Asbestos cement, but this is being replaced.

Water Treatment Works D1

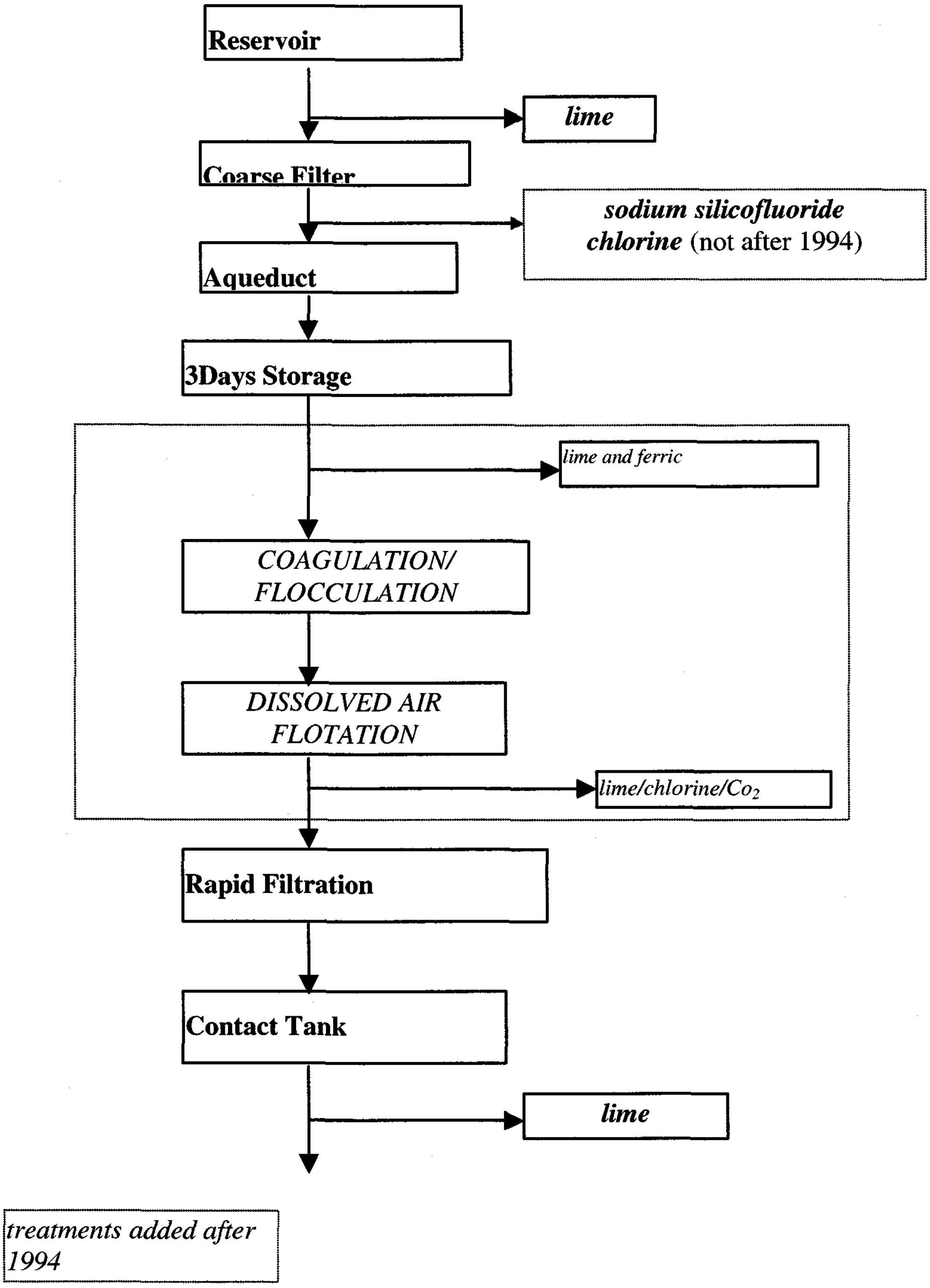

Figure 5 Schematic Diagram of Water Treatment Works D1

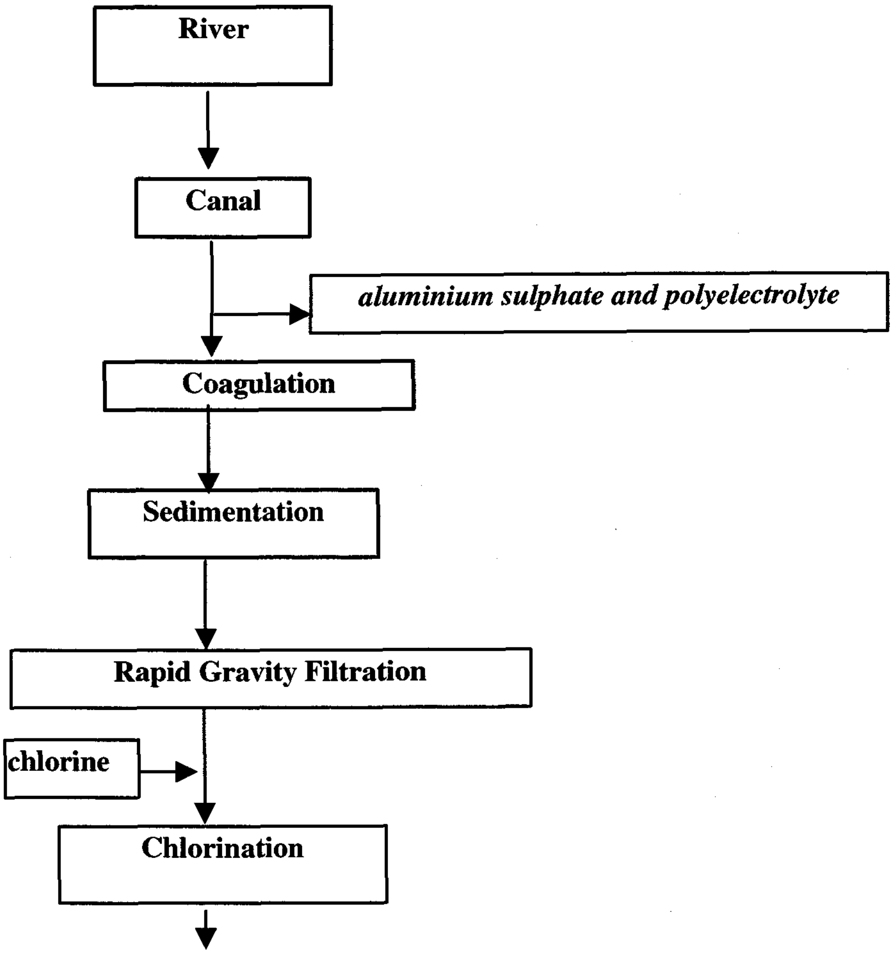

Figure 6 Schematic Diagram of Water Treatment Works M1

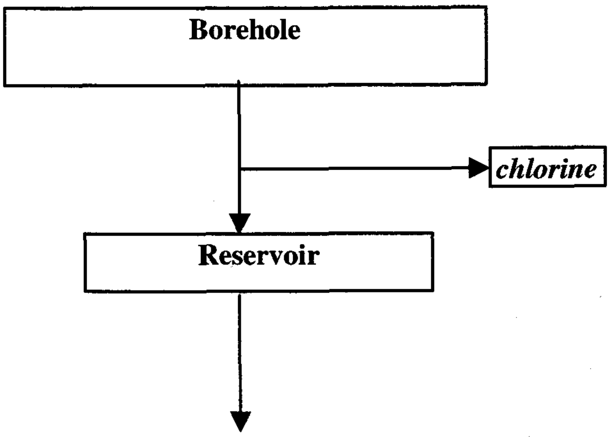

Figure 7 Schematic Diagram of Treatment Works M2