Application of HACCP to drinking water supply

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HACCP is a food safety management system that can also be applied to drinking water supply. It has not, as far as we know, been formally introduced for this purpose. However, concepts of total quality management and quantative risk assessment are increasingly being used to assure safe drinking water. In this paper the integration of these concepts is discussed. The major microbiological hazards in drinking water supply are pollution of raw water sources, recontamination of storage and distribution facilities for treated water and growth of pathogens in raw and treated waters. In ground water supply, protection of the aquifers is the essential critical control point (CCP); if this cannot be assured, additional disinfection of the abstracted water will be necessary. In surface water supply, several CCPs can be identified including coagulation/flocculation/sedimentation/ filtration and (chemical) disinfection. Recontamination of treated waters is also a major CCP. Several steps are important to assure the quality of the final water, but cannot be considered to be CCPs under the responsibility of the water producer because of a lack of a direct control. These include the quality of abstracted waters, the effect of raw water storage reservoirs and growth of microorganisms in the distribution or plumbing systems. Surveillance of these steps is, however, essential to properly define the critical limits for the above-mentioned CCPs.

INTRODUCTION

The hazard analysis critical control point (HACCP) system was developed in the 1970s as a universal, scientifically based framework to assure safe food production. It has been expanded and improved since then and has now become a universally accepted system which is increasingly being used for food producers, regulatory authorities and inspection services alike. This paper will examine the applicability of HACCP on drinking water supply, with main emphasis on microbial contaminants.

Although water is also considered as a food by many, there is surprisingly little contact between the domains of water and food production. Furthermore, regulations for drinking water quality are usually developed and enforced by other agencies than those responsible for food control. This is so at both supranational

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(WHO, EU) and national level. Hence, the application of HACCP on drinking water production has not been attempted before. Similar approaches to assure the quality of drinking water have been introduced, however, and these need to be taken into account when discussing the present subject. Relevant developments are the introduction of total quality management (TQM) on the basis of the ISO 9000 series of standards, and the use of quantitative risk assessment (QRA) to develop health-related standards for pathogenic micro-organisms in water. These will be discussed together with, HACCP, in the following paragraphs, and an attempt will be made to integrate the different approaches. Some attention is also given to describing the basic principles of HACCP, because it is considered desirable that this paper can be read and understood by those in drinking water supply with little background in HACCP. Full details of the HACCP procedure are given elsewhere (Codex, 1993; WHO, 1993). Some aspects (verification and documentation) are not extensively discussed here.

Drinking water is an important raw material for the

food industry and, as such, an item of concern in many HACCP studies. The quality standards for drinking water are not specifically designed for this purpose, however. The major consideration in defining drinking water is direct use of human consumption, and this will be the viewpoint taken in this paper. Food industries should decide if the control by the drinking water suppliers is sufficient for their specific purposes, or if additional treatment is required. Conversely, own supplies of food industries can be analysed and controlled according to the principles for public water supply as laid down here.

PREPARATORY STEPS OF THE APPLICATION OF HACCP TO DRINKING WATER SUPPLY

HACCP was originally described as a sequence of seven steps, but recent documents have added five activities which can be considered as preparatory activities. Step 1, the assembly of the HACCP team (and putting down its terms of reference), is necessary to assure that all relevant knowledge is available to perform the HACCP study, and that reporting to higher management is assured. Such a step could be discussed in the company conference which is considered an essential part of the introduction of TQM in water supply (Van der Zwan et al., 1992).

Step 2, describing the product, and Step 3, identifying its intended use, are highly relevant for food industry because of the great diversity of products. Drinking water production is more universal, as is its expected use. These steps are therefore not critical, although some attention should be paid to the pattern of drinking water consumption of the local population. Only the consumption of unheated drinking water causes microbiological risks. Data on consumption of unheated drinking water are not easily available, because risk assessments have mostly been carried out for chemicals, and these were normally based on total drinking water consumption. In a HACCP study, it could be useful to obtain data on the consumption of unheated drinking water in relation to age and for specific risk groups (immunocompromized, pregnant women etc.). Furthermore, it should be studied if certain persons are advised to consume large quantities of drinking water for medical reasons. These data will also be useful in the QRA process that will be described later.

Steps 4 and 5 of HACCP, construction and confirmation of a flow diagram, are likewise considered an essential part of the introduction of TQM (Van der Zwan et al., 1993). This makes documentation more accessible and makes it easier to introduce changes. A generalized flow sheet for drinking water production is given in Figure 1. The three fundamental stages in drinking water supply are abstraction, treatment and distribution. Drinking water may be produced from a variety of sources. Groundwater may be used as it is naturally available, or after it has been infiltrated into
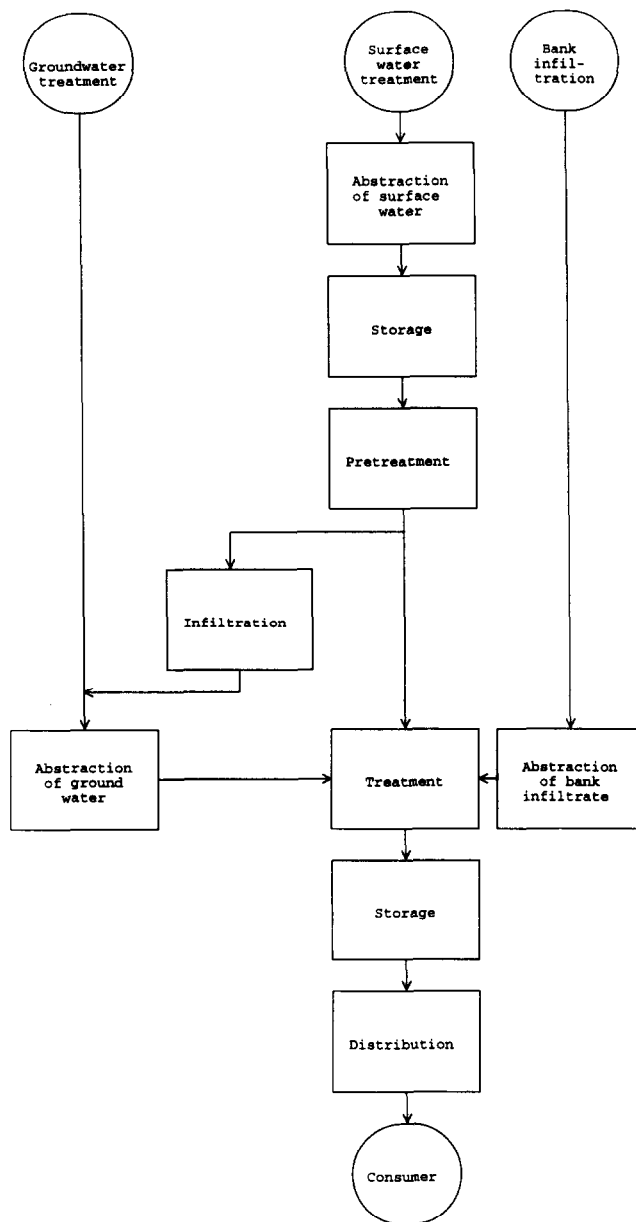

Figure 1 Generalized flow-sheet for drinking water supply (modified after van der Zwan et al., 1993)

river banks or dunes. Deep infiltration into aquifers is of growing interest. Directly abstracted surface water is usually stored in artificial reservoirs to improve quality and to bridge periods of poor source water quality. Each type of raw water has a characteristic pollution pattern, and treatment must be related to the source water quality and the desired end product standards. The challenge of the distribution process is to bring the treated water to the consumer in such a way that the quality does not deteriorate by chemical or biological processes in the complex distribution network, nor by extraneous pollution. The specific flow sheet for a particular supply will be a detailed elaboration of the above described general sequence.

HAZARD ANALYSIS

The objective of this step is to obtain a comprehensive

Table 1 Generalized HACCP analysis of drinking water production

Process step	Hazards	Preventive measures	CCP?	CCP parameters	Monitoring procedures	Corrective actions
Groundwater abstraction	Transport of pathogens to well-head	Define protection zone around well and restrict land-use	Yes	Travelling time	Tracer injection studies Specific pathogens Faecal index bacteria	Remove sources of pollution
	Ingress of pathogens through well-casing	Proper construction and maintenance	Yes	Adhere to good engineering practices	Inspection Faecal index bacteria	Instruction/ reconstruction
Bank infiltration	Transport of pathogens to well-head	Define minimum travelling time and/ or distance	Yes	Site-specific	Tracer injection studies Specific pathogens Faecal index bacteria	Replace abstraction wells Increase treatment
	Ingress of pathogens through well-casing	Proper construction and maintenance	Yes	Adhere to good engineering practices	Inspection Faecal index bacteria	Instruction/ reconstruction
Surface water abstraction	Contamination by faecal discharges	Reduce point and diffuse pollution sources Restrict water intake	No		Faecal index bacteria Specific pathogens Turbidity	Increase treatment
	Multiplication of pathogens	Control eutrophication, thermal discharges, residence time of water	No		Not applicable	
Storage of surface water in reservoirs	Short circuiting	Build reservoirs in series	No		Tracer studies Conservative parameters Faecal index bacteria	Increase treatment
	Recontamination by faeces of wild-living animals	Discourage presence of wild-living animals	No		Specific pathogens	
(Pre)Treatment (a) Coagulation/ flocculation/ sedimentation/ filtration	Poor floc formation Poor floc removal Filter defects	Increase coagulant dose, add coagulant aid Regular backwashing and cleaning First filtrate after backwash to waste	Yes	Turbidity Particle counts Pressure loss	On-line measurements	Increase disinfection
(b) Disinfection	Survival of pathogens	Optimize dose and contact time of disinfectant	Yes	Residual concentration of disinfectant (may vary during the year)	On-line monitoring	Automatic feedback system
	Formation of disinfection by-products			pH Temperature Bacteriological indicator organisms		Modify target dose/ residual
Storage of treated water	Recontamination	Integrity of construction	Yes	Total coliforms	Daily sample to lab	Isolate reservoir Rechlorination
		Hygiene during works	Yes	Adhere to hygiene protocols	Inspection, sample	
	Regrowth of opportunistic pathogens	Reduce residence time Fill–draw regime	No			
Distribution	Recontamination	Integrity of construction Positive pressure at all times	Yes	Total coliforms Pressure in system	Frequent samples	Isolate part of system Rechlorination
		Hygiene during works	Yes	Adhere to hygiene protocols	Inspection, sample	Flush
	Regrowth of opportunistic pathogens	Reduce residence time Reduce AOC and/ or biofilm potential	No			

list of all biological, chemical and physical agents or conditions which have the potential to cause harm. Some documents on HACCP (e.g. ICMSF, 1988; Bryan, 1992) also include the assessment and the severity of the risk associated with these hazards. Later documents (Codex, 1993; WHO, 1993) require possible control measures to be defined for each hazard. A control measure can be used to: 'eliminate hazards or to reduce their impact or occurrence to acceptable levels. More than one control measure may be required to control a specific hazard and more than one hazard may be controlled by a specified measure' (WHO, 1993). The latter statement is certainly true for drinking water supply. It is increasingly being recognized that safe drinking water supply should not be based on a single barrier such as disinfection, but that a multiple barrier approach is required to effectively eliminate and/or inactivate the various types of hazardous microorganisms. This will also provide an additional safety margin should one barrier temporarily fail. The proper design of barriers against pathogenic microorganisms is complicated by the fact that their use may lead to new hazards, such as the formation of disinfection by-products. It is therefore imperative that the treatment is designed to minimize the overall risk, and that the degree of treatment is related to the raw water quality (Craun, 1993).

For drinking water supply, three areas of hazardous situations are relevant:

(a) Pollution of raw water sources, mainly by human or animal faeces, introducing a variety of pathogens, including viruses, bacteria and protozoan (oo)cysts.

(b) Extraneous pollution of drinking water storage and distribution facilities by repair on installation works, back-siphonage, pressure drops, cracks or leaks in reservoir covers etc. Also, the air used for ventilation of storage reservoirs may cause hazards to occur.

(c) Growth of pathogenic bacteria or free-living amoebae in raw or treated waters, stimulated by eutrophication, thermal pollution etc.

A large variety of pathogenic microorganisms should be considered for each hazardous situation. Information to set up a list of microorganisms of concern can be derived from a variety of sources: outbreaks of drinking water related disease; outbreaks of diseases associated with recreational waters or shellfish consumption; foodborne or zoonotic disease outbreaks; laboratory studies on the occurrence of virulence factors (toxin-production, adherence to or invasion of mammalian cells, serotypic of genotypic similarities etc).

It is necessary to use all sources of information because the information derived from waterborne outbreaks alone is insufficient. In many outbreaks the causative agent is not identified. Moreover, low level endemic diseases are not recognized as an outbreak. To illustrate this point: the protozoan *Cryptosporodium* was recognized as a zoonosis in 1976 but a waterborne outbreak was not reported until 1984. However, the actual quantification of the risks associated with a particular microorganism will be more difficult if organisms are not known to have caused outbreaks. The universal nature of drinking water supply makes it possible to produce and update a list of microorganisms of concern at an international level (see e.g. WHO, in press). Local information will then be used to decide which organisms actually need to be considered for a particular treatment works.

A generalized hazard analysis of drinking water supply is given in *Table 1*, which also gives some general information on preventive measures. Specific details for each step in the process will be discussed later.

ESTABLISHMENT OF CCPs

The proper identification of CCPs is a key issue in HACCP, because the major efforts in process control will be directed towards these steps. In many food processing operations, a single step can be identified that is a major barrier to pathogens, e.g. heating. Chemical disinfection has served a similar role in drinking water production for a long time. Modern concepts in drinking water treatment have changed, however. The acceptable dose for chemical disinfectants is reduced as much as possible to minimize the formation of disinfection by-products. Newly recognized pathogens, such as viruses and protozoa, have a higher resistance to chemical disinfection. As a consequence, other steps are now considered equally important in achieving an acceptable drinking water quality, and the number of CCPs has increased (see *Table 1*).

Groundwater abstraction relies heavily on the ability of the soil to act as an effective barrier. Protection of the aquifers is therefore essential. This is usually reached by restricting land use around ground water abstraction sites. In the zone directly surrounding the well (protection zone), all activities such as agriculture, storage of chemicals, construction of septic tanks, laying of pipelines or sewers, etc, are normally hazardous. If the water producer owns the land in the protection zone, it is easier to control such activities. At larger distances, the activities will generally become less restricted, depending on the nature of possible pollutants and their stability and transport in the soil. A second aspect is well-head protection and integrity of the abstraction system, designed to prevent ingress of contamination alongside the shaft. Both aspects are CCPs, because usually groundwater treatment does not include any processes that significantly reduce the numbers of pathogens. In the USA, however, the Ground Water Disinfection Rule prescribes chlorination of all groundwater, unless it has been shown that soil passage is an adequate barrier. When chlorination is applied, the ground water protection may not be a CCP.

Surface water is subject to a diversity of pollutions, and it is necessary to control the extent to which this is taking place. This must be done by the competent authorities, at national or international level, because the water producer normally is not in direct control of pollution of its raw water sources. A preventive measure which can be taken by the producer is the restriction of water intake in periods of poor quality (e.g. after heavy rainfall). These control measures are often not sufficiently effective to call these steps CCPs, and further treatment is necessary in these cases. However, the producer should frequently survey the raw water to check the concentration of pathogens in order to decide whether the treatment is still adequate.

Storage in reservoirs is the first step that reduces the majority of pathogenic microorganisms in surface water treatment. The effect is related mainly to the residence time of the water, and possibilities for short-circuiting. Furthermore there is the possibility of recontamination by wildlife, or man if recreation on the reservoirs is allowed. Again, these are not CCPs in the classical sense because the pathogen reduction cannot adequately be controlled. The pollution of the storage reservoirs has to be taken into account when the subsequent treatment steps are designed (e.g. chemical disinfection). Surveillance is therefore necessary. The need to examine the raw water directly for pathogens, rather than for faecal indicator bacteria, is a novel aspect and an important consequence of the application of HACCP on drinking water supply.

A common step in all surface water treatment plants is coagulation/flocculation/sedimentation/filtration. By adsorption to and inclusion in flocs, microorganisms are removed from the water phase. This process has a 'broad-spectrum activity' and removes all types of microorganisms to a significant extent. It is thus a control measure that may partially control more than one hazard and an important CCP.

A second step which is almost invariably used in surface water treatment is chemical disinfection by addition of chlorine, ozone, chlorine dioxide etc. These agents have a very rapid inactivating effect on bacteria, a lesser but also important effect on viruses and, depending on dose and contact time, may also have an effect on protozoan (oo)cysts. The disinfection step obviously is a CCP. Modern waterworks will have additional treatment steps after major disinfection, such as activated carbon filtration. To inactivate bacteria growing in these filters, post-disinfection is applied. At this stage, the disinfectant does not provide an additional margin of safety, hence post-disinfection in this context is not a CCP. In many countries, post-disinfection is considered to be a preventive measure against recontamination of the distribution network. The effect, however is limited and also in this context, post-disinfection should not be considered as CCP.

The major hazard in storing the treated water and in the distribution system is recontamination. This must be prevented by adequate construction, by maintaining

positive hydrostatic pressure at all times, and by hygienic precautions when laying new mains or working on existing facilities. Another hazard associated with treated water is regrowth of possibly pathogenic bacteria or amoebae in the distribution or plumbing system. Regrowth is mainly dependent on three parameters: residence time, nutrient concentration and temperature. The latter can usually not be controlled by the drinking water producer but the first two parameters can. Prevention of recontamination is clearly a critical control measure and thus the storage and distribution system are CCPs for this hazard. If recontamination is adequately prevented, regrowth is not a major concern.

USING QRA FOR THE ESTABLISHMMENT OF CRITICAL LIMITS FOR EACH CCP

The traditional way of assuring the microbiological quality of drinking water is by monitoring for a series of bacterial indicator organisms in several stages of the treatment process, and taking corrective action if (legal) limits are not met. Recent epidemics of crypto-
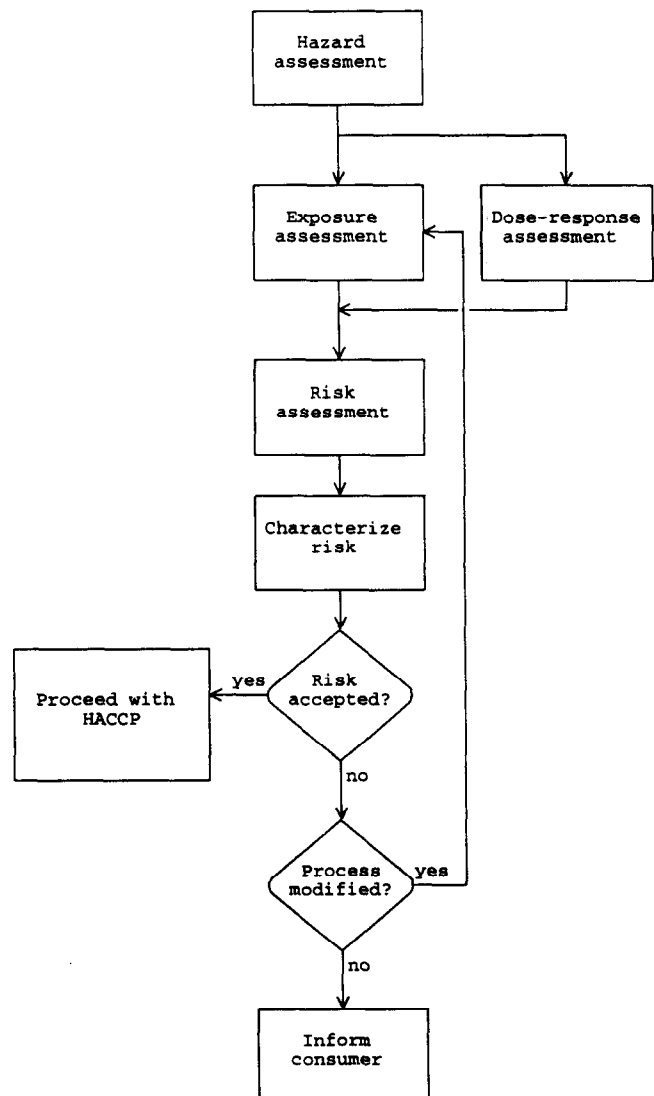

Figure 2 Generalized flow-sheet of quantative risk assessment

sporidiosis have painfully demonstrated that this approach is no longer valid, and a more comprehensive approach must be taken. The HACCP system is a useful framework. However, as presently used in food microbiology, the system is mainly qualitative and may be subjective, because the opinions of experts are relied upon when defining critical limits for CCPs. The use of QRA has been instrumental to make more rational decisions for drinking water supply, and might be of similar value for food production.

Common with HACCP, QRA starts with the production of a list of hazards (*Fiigure 2*). The list of microorganisms of concern, as produced in HACCP, can be used for this purpose. In principle, a risk assessment should be made for each identified pathogen. To reduce the work load, it should be attempted to select those agents with the highest priority, either because of their severe effects on human health or because of their resistance in water treatment.

The second step in QRA is exposure assessment. As will be seen, safe concentrations of pathogens in drinking water are usually far beyond the detection limits of current microbiological techniques. Direct measurements of exposure levels are therefore not possible and an indirect approach must be used (Havelaar, 1993). Such an approach can be based on actual measurements of the concentration of pathogens in the source water. Where possible, mathematical models and measurements of index organisms can be used to expand the available data. The data on raw water concentrations are then used as input for models describing the performancce of the treatment process, derived from actual field studies (usually only feasible in the first stages of production), pilot-scale studies with seeded microorganisms or extrapolation of laboratory studies. Additionally, data on indicator organisms or kinetic mathematical models (Rietveld *et al.*, 1994) can be used. When treatment models are combined with distribution models and actual drinking water consumption data, an estimate of the exposure to drinking water derived pathogens can be made. A mathematical model for the exposure of pathogens through drinking water can also be used to answer 'what-if' questions when defining the critical limits. What would be the effect on exposure if a certain limit would not be met? Would this effect be acceptable or not? If not, the limit has to be defined as critical.

The third step in QRA is the dose-response assessment. For this purpose, several studies in which volunteers were exposed to different concentrations of pathogens, are available. Haas (1983) has described methods to extrapolate these results at relatively high exposure levels to the levels normally occurring in drinking water. Results indicate that exposure to even a single organism may result in the possibility to cause infection. However, the probability of infection by a single organism varies from 30% for the highly infectious rotavirus to 0.0007% for *Vibrio cholerae* (Rose and Gerba, 1991). At low doses, the probability of infection increases approximately linearly with the dose. Infection may or may not result in clinically manifest disease, sometimes followed by death or chronic complications such as arthroid rheumatitis. There is little information on the chance for each of these events to occur, but it is generally assumed that they are not strongly related to the initial dose, but more to factors associated with the host. A specific aspect of microbiological risk assessment is the possibility of secondary infection, i.e. the spread of disease from the person initially infected by the drinking water to other persons through direct contact or contamination of the personal environment.

The results of exposure assessment and dose-response assessment are combined in the risk assessment stage, where the likelihood of unwanted consequences associated with each hazard are described, preferably in quantitative terms. The results of the risk assessment procedure are placed into perspective in the risk characterization step. They can be related to regulatory decisions on risk acceptance. For example, the US Environmental Protection Agency has postulated an acceptable risk of infection of 10^{-4} per person per year for any microbial contaminant of drinking water (Regli *et al.*, 1991). This leads to maximum tolerable concentrations of viruses and protozoa in drinking water of 10^{-6} to 10^{-8} per litre. A more general definition of acceptable risk has been given by the Dutch Directorate General for Environmental Protection: an individual risk of death of less than 10^{-8} per person per year (pppy) is considered negligible, whereas at a risk greater than 10^{-6} pppy, risk reduction measures must be taken (Anon, 1988). This general approach has not yet been applied to microbiological risks. This appears to be complicated because of the lack of reliable data on the relation between infection, disease and death. A second possibility to place the calculated risks into perspective is to look at relative risks. For pathogenic microorganisms this would imply that the contribution of drinking water to the total incidence of a particular disease is estimated. It must be decided what percentage of actual disease is acceptable to be transmitted through drinking water. In view of the widespread use of drinking water, also by high risk groups, it may be expected that risk acceptance of pathogens in drinking water will be low.

The final stage of the QRA procedure is the decision of the acceptability of the calculated risks. If the risks are not acceptable, risk reduction needs to be considered. With regard to drinking water supply, the possible modifications depend on the type of hazard that is not sufficiently controlled. If the origin is the source water, additional treatment steps or alternative sources need to be considered. If recontamination of the treated water may occur, additional hygienic precautions should be[d] considered. If the problem is aftergrowth, it should be considered whether the treatment process can be modified to reduce nutrient concentrations in the water, to change materials in contact with the water and/or residence times of the

water in the distribution mains. After successful identification of modifications in the process, the risk assessment tree should be passed once more to estimate possible improvements. If no changes are feasible, or if the implementation of changes requires several years, the consumer should be informed so that additional measures at the individual level may be taken to prevent exposure. Such measures may be the advice to boil the water or to recommend particular risk groups not to consume the water. Normally, such measures are only necessary in emergency situations, and will last a few weeks at most. It is however, possible that longer periods may be required to reduce the risk to acceptable levels. For example, new knowledge about the significance and great resistance of oocysts of *Cryptosporidium parvum* have shown that certain water supplies, currently fulfilling all requirements, do not reduce the hazards associated with this organism, to an acceptable level. Additional treatment, in particular ozonation, needs to be installed but this may take several years to realize. In the meantime, either a higher risk must be accepted, the consumer must be advised how to manage the additional risk (e.g. to boil the water) or alternatives must be offered (emergency supply, bottled water).

CURRENT STATUS OF CRITICAL LIMITS AND MONITORING PARAMETERS FOR CCPs IN DRINKING WATER SUPPLY

The above-described use of QRA to define critical limits has not been used systematically in drinking water supply, but important aspects have been incorporated into official regulations, particularly in the USA. Also critical limits have been defined in the past by applying a reasoning that fits very well into the HACCP system. The critical limits are usually site-specific and will not be discussed in detail here. Some parameters to define critical limits are given in *Table 1* and some numerical values are given below.

The critical limits for groundwater abstraction are usually expressed in terms of minimum travelling time of the water from the point of possible pollution to the production well. The process is highly complex and mathematical models, although available, do not yet have adequate predictive capability. At specific sites, tracer injection studies (preferably biological agents, such as bacteriophages) can be used for an empirical approach to reduce the uncertainty. Furthermore, bacteriological monitoring of the abstracted water for faecal index bacteria remains important to safeguard the water quality. However, the presently used protection zones (e.g. 60 days travelling time in The Netherlands) have originally been based on studies with bacteria. It is now known that viruses and possibly also protozoa may survive longer and/or travel faster in the subsoil than bacteria, so that the adequacy of the 60-day limits and bacteriological criteria are seriously questioned.

Treatment processes are the major CCPs in surface water supply. The effect of coagulation/flocculation/sedimentation/filtration is usually monitored by measuring the turbidity of the filtrate. Recent experience with waterborne outbreaks of cryptosporidiosis has shown that very low values should be aimed for, e.g. <0.25 nephelometric turbidity units (NTU). A novel approach is the use of particle counters, preferably after each individual filter. The effect of the disinfection process in properly filtered water is primarily a function of the product of the concentration of the disinfectant and the contact time (Ct-product). The temperature of the water and the pH are important additional variables. The necessary Ct-product depends on the water quality, the effect of previous steps and the accepted risk. Usually, the pathogen concentrations in the raw water are higher in winter, and the effect of treatment processes, including disinfection are less. Consequently, the necessary Ct-product is higher in winter than in summer. The disinfection process can be monitored on-line by measurements of residual disinfectant, pH and temperature; a direct feedback system can be included. Off-line checking for bacteriological indicator organisms (directly after disinfection and/or in the treated water) continues to be important, particularly for verification purposes.

The protection against recontamination during storage and distribution of treated water can only be monitored indirectly, and conventional bacteriogical methods appear to be adequate. Preventive measures related to keeping adequate hygiene during new works and maintenance, and to preventing malconnections to the mains, are important. Regular instruction of all workers and inspection of in-house installations should be used to control the points. Furthermore, the effectiveness of the programme should be evaluated frequently.

ACKNOWLEDGEMENTS

REFERENCES

Anon. (1988) *Premises for Risk Management*. Annex to the Dutch National Enviromental Policy Plan, Second Chamber of the States General, 1988–89 session, 21137, nos. 1–2. Ministry of Housing, Physical Planning and Environment, The Hague

Bryan, F.L. (1992). *Hazard Analysis and Critical Control Point System – A Guide to Identifying Hazards and Assessing Risks Associated with Food Preperation and Storage*. World Health Organization, Geneva

Codex (Codex Alimentarius Commission) (1993) *Guidelines for the Application of the Hazard Analysis Critical Control Point (HACCP) System*. ALINORM 93/13A, Appendix II. World Health Organization, Geneva

Craun, G.F (Ed.) (1993) *Safety of Drinking Water Disinfection: Balancing Chemical and Microbiological Risks*. ILSI Press,

Washington DC

Havelaar, A.H. (1993) The place of microbiological monitoring in the production of safe drinking water. In: (Ed. Craun, G.F.) *Safety of drinking water disinfection: balancing chemical and microbiological risks*. ILSI Press, Washington DC, pp. 127–141

Haas, C.N (1983) Estimation of risk due to low doses of micro-organisms: a comparison of alternative methodologies. *Am. J. Epidemiol.* **118**, 573–582

ICMSF (1988) *Micro-organisms in Food. 4. Application of the Hazard Analysis Critical Control Point (HACCP) System to Ensure Microbiological Safety and Quality*. Blackwell Scientific Publications, Oxford

Regli, S., Rose, J.B., Haas, C.N. and Gerba, C.P. (1991) Modelling the risk from *Giardia* and viruses in water. *J. Am. Water Works Assoc.* **83**, 76–84

Rietveld, L.C., Van Dijk, J.C. and Medema, G.J. (1994) Modelling of the elimination of pathogenic micro-organisms in the floccula-

tion process. In: *Proceedings of the International Specialized Conference on Disinfection of Potable Water: the Total Spectrum*. International Water Supply Association, London, pp. 13.1–13.17

Rose, J.B. and Gerba, C.P. (1991) Use of risk assessment for development of microbial standards. *Water Sci. Technol* **24**, 29–34

Van der Zwan, J.T., Hoekstra, A.C. and Van Bavel, A.H.M. (1992) Van projectplan naar uitvoering: de bedrijfsconferentie. *H_2O* **25**, 711–715

Van der Zwan, J.T., Hoekstra, A.C. and Van Bavel, A.H.M. (1993) Het zorgsysteem: opzet en beschrijving van de bedrijfsprocessen. *H_2O* **26**, 715–721

WHO (1993) *Training considerations for the Hazard Analysis Critical Control Point System*. WHO/HPP/FOS 93.3. World Health Organization, Geneva

WHO (in press) *Guidelines for Drinking Water Quality* Vol. 2 World Health Organization, Geneva