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Introduction

1.1 PURPOSE AND SCOPE

This publication is a critical review of removal and inactivation of microbial pathogens by drinking-water treatment processes. Chapters 2 and 3 focus on removal and inactivation processes respectively, in terms of their operational principles, mechanisms and efficiency. Chapter 4 presents performance models for granular filtration and disinfection, two of the most important barriers for microbes, and illustrates how these models can be used to determine the effects of process variables on treatment efficiency. Chapter 5 looks at measures of process variation, including uncertainty in treatment effects and problems associated with the use of surrogates. Finally, Chapter 6 illustrates how an approach based on a water safety framework can be used to minimize microbial hazards in water.

The review focuses on bacteria, viruses, protozoan parasites and microbial toxins, and their removal from source water by various treatment processes. The aim is help water utilities to:

- choose appropriate treatment in relation to raw water quality
- estimate pathogen concentrations in drinking-water
- assess the ability of treatment processes to achieve health-based water safety targets
- identify control measures in process operation.

This review does not attempt to cite all the relevant literature; rather, it highlights information that illustrates the performance of each treatment process. Where possible, it provides quantitative information on the removal or inactivation of pathogenic microorganisms and toxins. Also, it considers (and, where possible, quantifies) interactions between the effects of different treatment processes.

The information is given at different levels of detail:

- The first level estimates the order of magnitude of the expected effect under typical process conditions and proper operating conditions. This level of detail allows simple decision trees for the choice of a treatment chain to be constructed.
- The second level identifies the process parameters (both design and monitoring) that are most relevant to the treatment effect, and quantifies the effect of these parameters. Where possible, mathematical models are used to describe these relations. This level of detail allows control measures and their operational limits to be identified. There is an emphasis on physical and chemical parameters; microbiological indicators are discussed in a separate review (Dufour et al., 2003).
- The third level identifies and quantifies any variability and uncertainty in the treatment effect that is not explained by the process parameters. This level of detail allows exposure to pathogens to be assessed within the framework of a formal risk assessment procedure.

1.2 MULTIPLE BARRIERS

For centuries, the process of providing safe drinking-water has relied on the application of the 'multiple barrier concept'. Hippocrates (460–354 B.C.), writes in *Air, Water and Places* — the first treatise on public hygiene, that 'qualities of the waters differ from one another in taste and weight'. One should 'consider the waters which the inhabitants use, whether they be marshy and soft, or hard and running from elevated and rocky situations, and then if saltish and unfit for cooking for water contributes much to health' (Baker, 1948).

The concept of multiple barriers for water treatment is the cornerstone of safe drinking-water production. The barriers are selected so that the removal capabilities of different steps in the treatment process are duplicated. This approach provides sufficient backup to allow continuous operation in the face of normal fluctuations in performance, which will typically include periods of ineffectiveness. Having multiple barriers means that a failure of one barrier can be compensated for by effective operation of the remaining barriers, minimizing the likelihood that contaminants will pass through the treatment system and harm consumers. Traditionally, the barriers have included:

- protection of source water (water used for drinking-water should originate from the highest quality source possible);
- coagulation, flocculation and sedimentation;
- filtration;
- disinfection;
- protection of the distribution system.

If these conventional barriers are thought to be inadequate, it may be advisable to consider adding multiple stages of filtration or disinfection.

The benefit of multiple treatment barriers is illustrated by a recent epidemiological study of a karstic groundwater system where one well was filtered and chlorinated while a second was only chlorinated (Beaudeau et al., 1999). Increases in sales of antidiarrheal drugs correlated strongly with lapses in chlorination of the well that had disinfection as the only treatment. In contrast, no effect could be traced to lapses in chlorination of the filtered well. The combination of filtration and chlorination appeared to provide sufficient duplication in removal of contaminants that temporary lapses in disinfection did not generate a measurable adverse outcome (Beaudeau et al., 1999).

1.3 PROCESS CONTROL MEASURES

There are many different microbes that may be of concern in source waters or within the distribution system. Developing a monitoring scheme for each would be an impossible task; therefore, another approach is needed. The food and beverage industry has used the “hazard analysis critical control point” (HACCP) approach to determine the key points within the manufacturing chain where contamination can be measured and prevented. A similar concept can be used by water utilities, to prioritize the key contamination points within the treatment and distribution system (Bryan, 1993; Sobsey et al., 1993). This approach allows utilities to focus their resources on monitoring these points and correcting any deviations from acceptable limits. The latest edition of the World Health Organization (WHO) *Guidelines for Drinking-Water Quality* (WHO,

2004) incorporates such an approach, providing guidance on the development of a water safety plan. The plan is developed using a water safety framework, which combines HACCP principles with water quality management and the multiple barrier concept.

Most microbiological monitoring programs for drinking-water have not been designed using such a framework. However, many of the relevant concepts are found in the overall process control of water treatment plants and distribution systems. For example, maintaining a disinfectant residual within the distribution system can be considered a control procedure.

The water safety framework is not only applicable to microbial monitoring of drinking-water treatment; it can also be applied to aspects such as turbidity, disinfectant residuals, pressure and particle counts. A strength of the framework is that it allows water utilities to allocate limited laboratory resources to monitoring points within the water supply process where the results will provide the greatest information and benefit.