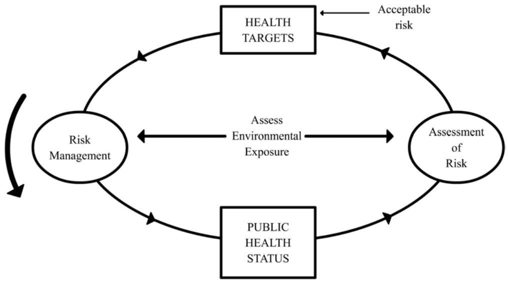

12

Management strategies

Dan Deere, Melita Stevens, Annette Davison,
Greg Helm and Al Dufour

Beginning within the context of the classical risk assessment framework, this chapter discusses the origins of risks to microbiological water quality. The importance of a preventative multiple barrier approach is discussed and the advantages of controlling contamination as near to the source as possible are presented briefly. Practical, simple to use approaches are needed to identify risks and manage them at the day-to-day level. The hazard analysis and critical control points (HACCP) principles are used to illustrate such a process in relation to drinking water. Although the HACCP examples are drawn from drinking water the principles are equally applicable to the recreational water and wastewater reuse areas. A recently proposed management strategy for recreational water is also outlined.

Water Quality: Guidelines, Standards and Health. Edited by Lorna Fewtrell and Jamie Bartram. Published by IWA Publishing, London, UK. ISBN: 1 900222 28 0

12.1 WHAT IS RISK?

Risk is a component of everybody's lives. All activities that we are involved in carry some degree of risk. Risks can either be voluntary, such as cigarette smoking, or involuntary, such as breathing air polluted with car emissions or drinking water containing carcinogenic chemicals. There are many definitions of risk that range from broad definitions such as: 'risk is the probability of injury, disease, or death under specific circumstances' (Raman 1990) to more specific definitions such as: 'risk is the probability that an adverse outcome will occur in an individual or a group that is exposed to a particular dose or concentration of the hazardous agent' (Langley and Van Alphen 1993).

Risk Assessment is the process undertaken to evaluate whether there is a risk and, if so, how severe it is. Risk Management incorporates understanding, evaluating and prioritising risks for a given system and then implementing appropriate risk reduction strategies. In drinking-water supplies, risk assessment and risk management are essential components of ensuring the public health of consumers. Generally, risk cannot be measured accurately and is described using qualitative terms such as high, medium or low. In some instances risks can be estimated and expressed quantitatively, albeit within an uncertainty interval or probability distribution (see Chapter 8).

12.1.1 Classical risk assessment framework

Classical risk assessment involves four conceptual steps. These have already been outlined in Chapter 8, but will be revisited here taking a risk management perspective.

12.1.1.1 Hazard identification

Hazard analysis is a key component of both qualitative and quantitative risk assessment and risk management. Hazard identification is the identification of the constituents of drinking water, recreational water, wastewater reuse or whatever that may have the potential to cause harm to the user. The source of the hazard is also determined. The term hazard is usually used to refer to agents that can cause harm. An example of a microbiological hazard is the bacterium responsible for causing cholera, *Vibrio cholerae,* and the source of the hazard is faecal material from individuals infected with this agent. In terms of risk management, hazards need to be considered along with the events that result in the introduction of contamination. These event-hazards in terms of drinking water supply include storms, pipe breaks, treatment plant or disinfection plant failure.

12.1.1.2 Exposure assessment

The components of exposure assessment are:

- Identifying how and where the hazard enters the system;
- Determining who is going to be exposed to the hazard, how the hazard will reach them and what acts on the hazard within the system;
- Estimation of the concentration of the hazard that will reach the consumer; and
- The quantity and timeframe of hazard exposure.

12.1.1.3 Dose–response assessment

Dose–response assessment determines the impact that a hazard has on the population, given the concentration that the population is exposed to. Dose–response factors are calculated for many chemicals (such as lead and arsenic) and some micro-organisms based on animal and human feeding studies and studies of waterborne disease outbreaks. The results of these studies provide information on the severity of the health effects from exposure to different amounts of a given hazard.

12.1.1.4 Risk characterisation

Risk characterisation is the consolidation of information from exposure assessment and dose–response assessment. Characterising risk is determining the likelihood of an adverse effect from exposure to the specific hazard. For drinking water systems, risk characterisation has been carried out mainly for chemical contaminants. For example, for arsenic, the toxicological data is combined with the estimation of intake of water with a measured arsenic concentration to determine the risk of skin cancer and to give an acceptable ‘guideline’ concentration for this hazard in potable water (WHO 1993).

Risk characterisation also involves considering the uncertainty involved in each risk assessment step, for example, the extrapolation of results from animal feeding studies to humans. Other issues considered in risk characterisation include assessing the significance of the risk and whether it is acceptable, determining if action is required to reduce or eliminate the risk, and whether risk reduction can be carried out in a cost-effective manner (see Chapter 10).

A quantitative risk assessment programme is both time-consuming and subject to uncertainty. It may take years to develop a reasonable quantitative risk estimate for any particular hazard. Therefore, the management of risk should not necessarily await the outcomes of such an assessment. Instead, a more simplistic judgement-based assessment of risk would form the first action in a risk management programme, with detailed risk analyses being performed as a separate exercise (Bell 1999).

12.2 ORIGINS OF RISK

Risk management activities draw from all aspects of the classical risk assessment framework particularly the exposure assessment, which considers how it is that a person may become exposed to a contaminant. Any attempt at managing risk within a system, such as a drinking water supply system or a recreational water body, needs to start by asking what the origins of risk are within that specific system.

12.2.1 Chemical versus microbiological risk

Although this book focuses on microbiological risk it is important to note that there is a fundamental difference in the way that chemical and microbiological contamination (and therefore risks) arises, which leads to the adoption of different management strategies. Using a drinking water context the distinction is as follows:

(1) Microbiological Risk: the risk or probability of illness associated with the contamination of water supplies with bacteria, viruses, protozoa and so on. Symptoms of microbiological illness can be acute or chronic and there may also be delayed sequelae. However, in risk management terms microbiological risks are considered to have arisen from acute exposures – either an infection occurred or it did not when contaminated water was consumed.

(2) Chemical Risk: the risk of illness from chemical pollution of drinking water, or from chemicals, such as disinfection by-products that are formed within a water supply as a result of water treatment. Once again, health effects attributed to chemicals in drinking water can be acute (generally resulting from short-term exposure to high concentrations of chemical) or chronic (resulting from long-term exposure to low levels of chemical contaminant). However, due to the huge dilution factors involved, few chemicals are likely to reach concentrations in water that would result in discernible health effects due to a short period of exposure (where they do reach high concentrations, the water is generally likely to be undrinkable due to foul taste). Therefore, in risk management terms, chemical risks tend to be considered to have arisen from long-term, even lifetime, exposures.

In practice, as the above paragraphs illustrate, the picture is not black and white. However, for the purposes of this chapter we shall focus on microbiological risks due to acute exposures. As will become clear, this distinction is not academic and has significant implications in terms of risk management.

12.3 ORIGINS OF MICROBIOLOGICAL RISK

Using drinking water as an example, microbiological contamination can arise at many points in the catchment to tap supply chain. Figure 12.1 gives a generic catchment to tap flow diagram for microbiological risk that illustrates points that have been well established as sources of risk in many systems.

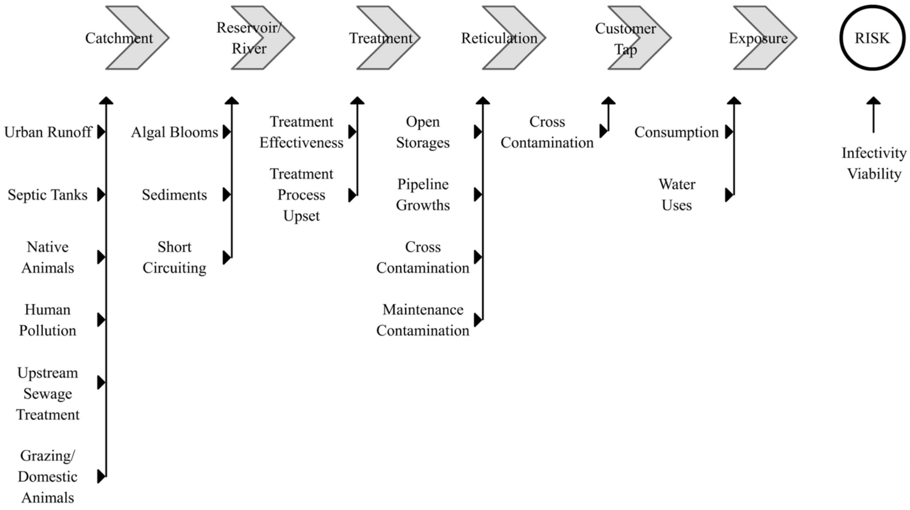

Figure 12.1. Generic flow diagram for sources of microbiological risk in a drinking water context (adapted from Stevens *et al.* 1995).

We have already discussed key terms such as hazard and exposure. Two additional terms and concepts will now be introduced. The first is *events*; this term will be used to describe an occurrence that leads to an increase in the risk of exposure. An example might be a storm in the catchment of a water supply system that leads to increased faecal material being washed into a reservoir (or equally a storm that leads to discharge of faecal material into a bathing area).

The second important concept related to events is that events need to be considered together as scenarios – *the fault-tree concept*. As can be seen by considering Figure 12.1, an event such as a storm is only likely to lead to a health risk to a community if other events occur as well. For example, there would first need to be significant levels of infectious pathogens in faeces in the catchment. Second, the storm would need to be severe enough to wash significant levels of contamination into the source water. Furthermore, water would need to be abstracted before significant levels of pathogens have lost viability and/or settled from the water body. Finally, an appropriate treatment barrier would either need to be absent or overwhelmed by the pathogen load. Such an example illustrates that in most cases events should not be considered in isolation but as part of a chain of events. A simple diagram illustrating this is given in Figure 12.2 (Stevens *et al.* 1995).

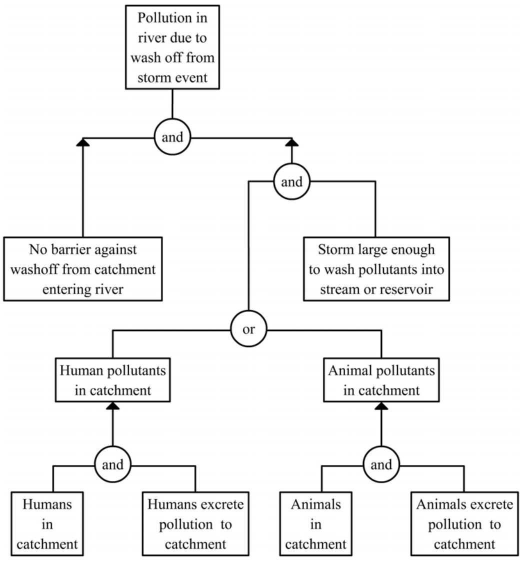

Figure 12.2. Generic fault tree for storm runoff polluting a drinking water source (adapted from Stevens *et al.* 1995).

12.3.1 Multiple barriers

Drawing from the above basic concepts it is important to move on to consider magnitudes of effect and probabilities of occurrence rather than simply presence or absence of risk or occurrence or otherwise of events. For example, animal faeces containing pathogens are not best considered as being either present or absent in significant amounts, but rather they are present at a range of contamination levels distributed in time. Equally, storms can have a range of severities and treatment barriers a range of capabilities or degrees of failure. Thus, the objective of risk management is to consider the events that contribute to risk and to focus on mitigating factors – barriers to risk. The objective is to reduce the risk to an acceptable level and/or to minimise risk by optimising the risk reduction throughout the system and by optimising the available barriers.

The use of multiple barriers works at two levels. First, in most cases, barriers act to reduce rather than completely eliminate risk. Therefore, since events are linked, the use of multiple barriers provides multiple levels of protection that act together to reduce the total risk by more than the reduction achieved by any one barrier. Second, where a barrier is reduced in its effectiveness, the presence of other barriers helps to maintain a reduced level of risk throughout the failure. This is the first of several reasons why the acute nature of the exposure timeframes relevant to microbiological risk is important. Even a short barrier failure where that barrier is a major factor in risk reduction could lead to unacceptable levels of risk exposure – maybe even a disease outbreak. However, where there are multiple barriers that are each capable of giving major risk reductions, failure of any one barrier is less significant. To give an advanced theoretical drinking water example, in a detailed assessment of microbiological risk, Teunis *et al*. (1997) considered the microbiological risk exposure for a population depending on a single high efficiency barrier for protection (filtration plant). The authors illustrated that in such scenarios, almost all the risk to the consumers during any one-year time period arises during the summation of the very brief periods, perhaps less than one day in total during that year, when the treatment barrier is operating poorly.

Another implication of the need for multiple barriers is that barriers need to be effective when they are most needed. For example, if most septic tanks in a catchment overflow during storms, and most treatment plant failures also occur during storms due to overloading, how well the treatment plant and septic tanks work most of the time becomes relatively unimportant if most of the risk exposure occurs during these occasional storms. Thus, another implication of the acute exposure of relevance to microbiological risk is the need for barriers to be effective during the short exposure to extreme event periods.

12.3.2 Outbreaks don’t just happen

So far we have taken a theoretical perspective. We have considered microbiological risk from first principles by going through the thinking associated with predicting and understanding exposure pathways, sources of contaminants, events that lead to increased risk and the use of multiple barriers and the multiple benefits associated with these. It is also useful to take a practical perspective and look at the types of events and scenarios of linked events that have led to actual disease outbreaks, these being extreme examples of microbiological risk exposure. Table 12.1 (Davison *et al.* 1999) illustrates deficiencies in system operation, management or risk identification that were responsible for outbreaks of cryptosporidiosis from drinking water supplies in the US (Rose *et al.* 1997).

Table 12.1. Some shortcomings identified in some cryptosporidiosis outbreaks in the US

Deficiency	Comment
Monitoring equipment for filtration optimisation during periods of rapid change in source water.	Equipment was improperly installed, poorly maintained, turned off, ignored or temporarily inoperable.
Treatment plant personnel did not respond to faulty or inoperable monitoring equipment.	Deficiencies in the equipment were not compensated for by increasing the type and frequency of monitoring.
Filter backwash was returned to the head of the treatment process.	This process results in the possibility of concentrating oocysts, which may be put back into the system during a filtration breach.
Sources of high contamination were found near the treatment facility.	No mitigating barriers were in place to protect against introduction of oocysts into receiving waters (streams and groundwater) during periods of high runoff.
Sources of *Cryptosporidium* were unknown in the catchment prior to the outbreak event.	Knowledge of the sources of *Cryptosporidium* could have facilitated mitigation of the risk.
Natural events may have been instrumental in flushing areas of high oocyst concentrations into receiving waters.	Heavy rain can flush/carry oocysts into waters upstream of the treatment plant.
Filtration processes were inadequate or altered.	During periods of high turbidity, altered or suboptimal filtration resulted in turbidity spikes and increased turbidity levels being noted in the finished water.

Similar observations were made regarding the UK outbreaks reviewed by the UK Group of Experts (McCann 1999). Table 12.2 gives examples of disease outbreaks and their causes grouped according to cause to show the variety of scenarios that can lead to disease outbreaks.

Table 12.2. Scenarios affecting municipal drinking water implicated as causes of disease outbreaks

Causal event(s)	Aetiology	Water type	Cases	Reference
Pre abstraction and treatment				
Surface run off from contaminated catchment after heavy rain. Increased Cl demand due to turbidity.	*Campylobacter*	Chlorinated surface water	3000	Vogt *et al.* 1982
Contaminated surface run off from meltwater and heavy rain entering municipal wells.	*Campylobacter*	Untreated groundwater	241	Millson *et al.* 1991
Drought followed by heavy rain agricultural surface run off and poor coagulation and mixing.	*Cryptosporidium*	Cl'ed + package filtered river water	34	Leland *et al.* 1993
Poor mixing and flocculation with filters started up without backwashing.	*Cryptosporidium*	Surface water (CT)	13,000	Rose *et al.* 1997
Increase in turbidity, poor coagulation and backwash recycling.	*Cryptosporidium*	Surface water (CT)	403,000	Rose *et al.* 1997
Catchment contaminated by higher than realised population, Cl dosage too low.	*Giardia*	Cl'ed surface water	350	Shaw *et al.* 1977
Post abstraction and treatment				
Backflow of farm-contaminated river water due to low mains pressure.	*Campylobacter*	Sand filtered groundwater	2000	Mentzing 1981
Switch to unchlorinated stagnant reservoir subject to animal contamination.	*Campylobacter*	Untreated tank water	150	
Agricultural runoff entering unsealed supply.	*Cryptosporidium*	Surface water (CT)	27	Badenoch 1990
Deliberate contamination of water storage tank.	*Giardia*	Municipal supply	9	Ramsay and Marsh 1990
Cross-connection between pressure dropped potable and wastewater lines at pump wash.	*Giardia* & *Entamoeba*	Surface water (CT)	304	Kramer *et al.* 1996
Sewage overflow entering pipes after repairs of ice breaks made without post chlorination.	*E coli* O157	Municipal supply	243	Swerdlow *et al.* 1992
Birds entering water storage tank.	*Salmonella*	Untreated groundwater	650	Angulo *et al.* 1997

CT: Conventionally treated Cl: Chlorine Cl'ed: chlorinated

These scenarios are similar to the ones identified in Sweden (Chapter 6). They also represent the 'tip of the iceberg', as outbreak detection is notoriously difficult, as outlined in Chapters 4 and 6. Thus, given the problems of under-reporting and outbreak detection it is useful that we learn about the source of microbiological risk from detected outbreaks. This can then be extrapolated to sub-detectable-outbreak scenarios. The study of outbreaks provides useful insights into the origins of waterborne disease risks in total and illustrates that events and scenarios or chains of events involving barrier failures and/or other unusual events are the key risk sources and, therefore, targets for risk management.

12.4 MANAGING RISK

At its most simple, waterborne disease risk management involves:

- identifying potential sources of contamination; and
- managing barriers to prevent contamination reaching end-users.

In an ideal system this would be satisfactory since:

- all scenarios by which contamination could enter would be understood;
- barriers would be effective at eliminating the risk from these sources;
- any barrier failure would be detected and corrective actions taken; and
- individuals with the power to manage risk would have this as their primary interest and would behave appropriately.

In reality:

- the arrangement of waterborne contamination sources and barriers is very complex and is never perfectly understood;
- barriers are rarely absolute barriers and function primarily to reduce risk, not eliminate it;
- finite resources limit the ability of contamination sources to be controlled at source or via barriers; and
- individuals with the power to manage risk may have conflicting interests and people cannot be controlled and relied upon totally.

This detail and complexity prevents an individual from fully understanding and managing the risks to waterborne contamination, and means that simplistic approaches to risk management will be ineffective. In reality, arrangements are complicated and multiple individuals and stakeholders are required to be involved both for identifying contamination scenarios and managing barriers. This complexity necessitates the use of systems to manage risk.

12.4.1 A systems approach

Managing risk in real systems requires a systems approach. This section provides a checklist of steps used in managing risk in a water supply and in producing a risk management plan. The terminology used is kept consistent with that of Hazard Analysis and Critical Control Points (HACCP). This has been found to be an acceptable framework for guiding the process of risk management in water supplies (Barry *et al.* 1998; Deere and Davison 1998; Gray and Morain 2000; Havelaar 1994). There are a number of other frameworks that are similar and many factors (Davison *et al.* 1999), such as the practical experience with, and widespread knowledge about, HACCP that make it a potential model of choice. The principles of HACCP are shown in Figure 12.3.

HACCP has, as its basis, a focus on controlling hazards as close to their source as possible. It has been described as a ‘space age’ system for assuring food safety due to its development during the 1960s US Space Program for protecting astronauts from unsafe food and beverages. An effective quality assurance system that addresses these principles has become the benchmark means to assure food and beverage safety since its codification in 1993 by the United Nations Food and Agricultural Organization (FAO) and World Health Organization (WHO) Codex Alimentarius Commission.

12.4.1.1 Assemble team and resources

Complex systems cannot be understood and managed by any one person. A team of individuals needs to be identified that will have the collective responsibility for identifying risks and barriers from contamination source to the point of exposure. This team needs to be made up of individuals with the skill required to identify risks and barriers as well as the authority to ensure barrier management is developed. Experts, not normally associated with the system in question, may need to be brought into the team as the occasion arises.

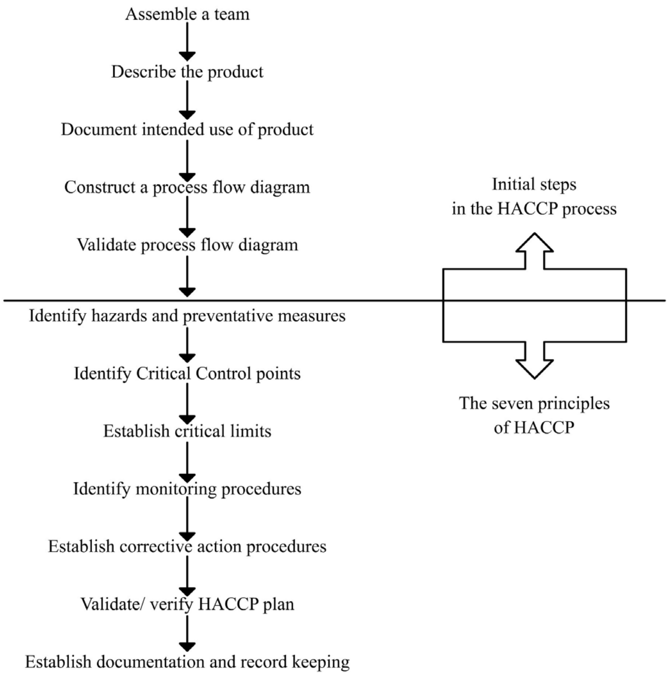

Figure 12.3. Principles of HACCP.

This could include veterinary and human infectious disease specialists, scientists, engineers or an independent team facilitator. For example, the catchment HACCP plan described by Barry *et al.* (1998) involved such a multi-disciplinary team. The team needs to have the resources, in terms of time and equipment, to perform the task.

12.4.1.2 Flow chart and flow chart verification

Complex systems cannot easily be visualised. A working representation, such as a hierarchical series of flow charts, needs to be produced describing possible sources of contamination, transfer pathways by which contamination can reach end-users, and barriers. Representations of systems can be inaccurate. Verification of the representation could involve field audits and cross-checking by others with specific system knowledge.

12.4.1.3 Describe the water and its use

Risks cannot be completely eliminated. There needs to be an understanding of the health status of the exposed population and the level of risk to which they can acceptably be exposed. This enables the most relevant contaminants to be identified and, in some cases, their allowable concentrations to be determined. This equates to a description of the nature of the water at the point of exposure. It is important to be realistic about the communities' likely uses of the water. Thus, if drinking water is intended only for consumption by healthy adults with all others required to boil their water, is this understood by these end-users? Is this in fact likely? If not, unboiled water consumption among these other groups needs to be considered as a likely end-use. Once these foundation steps have been performed, a logical process for identifying risks and barriers should be followed.

12.4.1.4 Hazard analysis

Using the systematic representation (e.g. flow chart) as a guide, hazards, their sources and scenarios by which they could contaminate the water need to be identified. Ideally, some assessment of the risk from each of these hazards and events needs to be made. This is useful because priorities can be assigned to each potential risk. Some can simply be ignored, making the overall job of risk management simpler. Others can be assigned as important in terms of aesthetics and quality but not necessarily of public health significance. Finally, those that are of public health significance can be focused on as the first priority. Two examples of approaches used for assigning risks to hazards are given in Table 12.3 and Figure 12.4.

Table 12.3. Example of a common, simple risk assessment framework as used in South East Water (Melbourne, Australia) HACCP plan (Risk Factor = Likelihood × Severity of Consequences. If a risk factor is 6 or greater, the hazard is to be considered further in the HACCP plan and monitoring and corrective actions should be devised.)

	Severity of Consequences				
Risk Factor Matrix **Likelihood**	Insignificant No impact or not detectable	Minor Significant impact	Moderate Impact of target levels	Major Impact on franchise levels	Catastrophic Public health risk
Almost certain (daily)	5	10	15	20	25
Likely (weekly)	4	8	12	16	20
Moderate (monthly)	3	6	9	12	15
Unlikely (annually)	2	4	6	8	10
Rare (every five years)	1	2	3	4	5

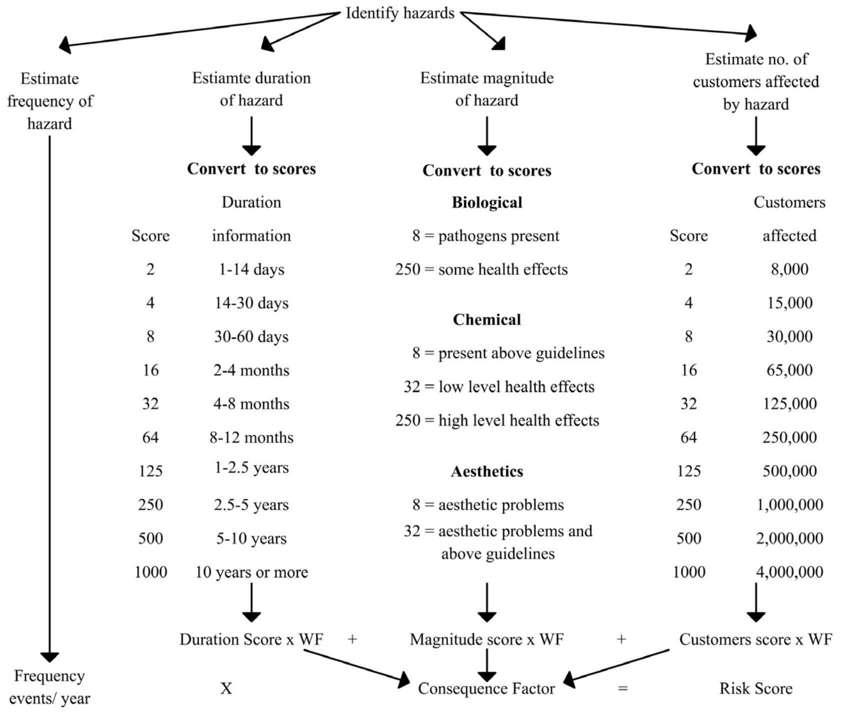

Figure 12.4. Methodology for scoring risks used in the Sydney Water hazard analysis developed by Parametrix/AWT (courtesy of Carl Stivers, Parametrix, Australia).

12.4.1.5 Critical control points

The identification of barriers to contamination and preventative measures is the first step in managing risk. Generally, microbiological risks are best controlled at or as near as possible to the source of contamination, because multiple benefits arise from control at source that do not arise from control once systems are already contaminated (end of pipe treatments). These are as follows:

- Amplification: once released into the aquatic environment, microbiological contaminants can cause infections and multiply. This can have detrimental effects by increasing the pathogen load on end of pipe barriers as well as leading to increased prevalence of pathogens in the environment generally. This contamination also reduces the value of the water upstream of the end-of-pipe treatment point.

- Multiple barrier protection: reliance on end-of-pipe treatments can lead to almost total reliance on a single barrier for protection. Unless this barrier is extremely reliable and effective, this will expose end-users to risk during barrier failure.
- Polluter pays: an emphasis on controlling pollution at source reduces the cost transfer from the polluter to the end-user of the water. Instead, the polluter is more likely to bear a greater share of the cost of preventing contamination or of cleaning it up. As well as being ethically attractive, prevention of contamination and treatment at source may in fact turn out to be the lowest community-cost solution for some contaminants.

Barriers are Control Points (CP), that is, points that control the risk by reducing or eliminating the transfer of pathogens to end-users. To ensure an appropriate prioritisation some of these points can be singled out as the most significant and can be termed Critical Control Points (CCP). These are points at which barrier effectiveness is essential for safe water use. Some barriers are involved in control of aesthetics; these can be termed Quality Control Points (QCP). These points are important or even critical for acceptable quality, but not necessarily for safety.

Critical control points identified in recently produced HACCP plans cover a variety of areas from the consumers' properties (e.g. fitting of backflow prevention devices) to disinfection and raw material control at treatment plants and control of catchment animals (Barry *et al.* 1998; Gray and Morain 2000). Note that some activities are not designated as critical control points but are instead delegated to the status of supporting programmes. An example would be the use of best practice management in catchments (Ashendorff *et al.* 1997) or the procedure used for repairing burst water mains. This is discussed further below.

12.4.1.6 Critical limits

Risk management activities should be focused on control points. Procedures and targets need to be determined such that control activities can meet an appropriate specification. This specification might refer to a measurable physical property of the water, such as turbidity, or to an observable property in a catchment area. These measurable/observable factors can have limits assigned to them such that provided the control point is operating within these prescribed limits, the hazards can be taken as being under control. This is an important concept. The hazards themselves usually are not the measurable factor. Instead, some feature of the barrier that can be observed or measured is chosen that can act as a surrogate for control of the hazard. This is important for several reasons:

- Hazards are often not practically measurable at concentrations that represent an acceptable risk. This makes the use of surrogates more protective.
- Hazards are generally not measurable in real-time or on a continuous basis. Ideally, limits such as observations or measurable properties of water will be available at the time and point of inspection. This permits rapid interrogation and response, which is more protective and preventative.
- There are numerous possible hazards that may vary rapidly in both time and space. Such hazards are likely to be present as a result of a scenario of particular events. They may not be present in a relatively steady-state situation. As a result, the absence of detectable concentrations of hazards at one point in time does not necessarily provide assurance of its absence later. The use of surrogates is, therefore, more conservative.

The limits set will usually be grouped at two levels. Operational limits may be set at a point where a response is required, for example as an early warning, but where water quality is not likely to be significantly compromised. Critical limits will be set at points where urgent action is required to ensure that water quality and safety remains acceptable.

12.4.1.7 Monitoring and corrective actions

Managing risks at control points requires the detection of control point failures. Monitoring is required to pick up operational and critical limit exceedances. The nature and frequency of this monitoring will depend on what is being monitored. Thus, when selecting and setting operational and critical limits it is important to consider the practicalities of monitoring these. If they can’t be monitored with sufficient frequency and practicality to reveal barrier failures in good time, there is little point setting them. In some cases, a combination of observations and/or measurables may together constitute what is taken as a limit (e.g. a critical disinfection envelope may consist of a combination of pH, chlorine concentration, temperature and time and be determined using an appropriate algorithm; Smith *et al.* 1995). The frequency of monitoring depends on the speed at which barrier failure can occur and the rate at which contamination can build up after failure. For example, it may take only a matter of hours for source water turbidity levels to change and increase beyond acceptable levels such that this parameter may need to be checked at intervals of minutes. In contrast, the density of feral mammals present in a catchment area could take five years to change significantly and this density could, therefore, be checked at intervals of years.

When exceedances to limits are detected by monitoring activities some action needs to be taken to bring the control point back into specification. Ideally this action will be predetermined and will be tested for its effectiveness.

12.4.1.8 Record keeping, validation and verification

Documenting the key aspects of the plan is in itself a useful discipline to ensure clarity and completion. It also provides a written record of the plan for use by others and as a basis for updating. Recording monitoring activities and significant events provides a body of information for long-term trend analysis and auditing.

The complete plan (hazards, control points, limits, monitoring and corrective actions) becomes a guide on how to operate a specific water supply system for a safe, high-quality water supply. To be relied upon this plan needs to be supported by accurate technical information. Assumptions about sources and barriers need to be checked to validate this accuracy. Validation combines system-specific information with published scientific information. In many cases there will be generic or system-specific unknowns and professional judgement will need to be applied. In the longer term, research can be used to fill these data gaps. There is a need to pick up and incorporate new information as it becomes available to ensure that the plan remains valid. Collating, synthesising and disseminating such information could be a potentially important role of international organisations (such as the WHO).

Once a plan is implemented, there needs to be some verification that it is being followed in practice. Furthermore, there needs to be some verification that the water reaching consumers, or the bathing water (and so on) is in fact of an appropriate quality.

12.4.2 Managing people and processes

The development of a realistic plan describing how things should operate is only the first step in managing risk. If the plan is to work it must be followed in practice. There needs to be a supporting programme of good operating practice. Furthermore, the people and processes responsible for managing risk need to follow the plan as intended. To achieve this involves leaving the realm of hard science and HACCP theory and entering the world of quality management systems – systems for gaining control of people and processes to ensure the desired outcome. The importance of this control of day-to-day activities cannot be overstated and it is worth noting that the organisations that have implemented HACCP plans, be they food, drink or tap-water suppliers, have seen it as essential to underpin the process with a quality management approach. Key elements of a supporting quality management programme are:

- Strong commitment at all organisational levels;
- Good operational practices described in standard operating procedures for repair, maintenance and operation;
- Ongoing education and training of employees in good operational practices;
- Product and raw material traceability;
- Control and use of key documents, checklists and data records; and
- A compliance culture with strong auditing to ensure procedures are followed.

In Europe and Australia the standard approach to drinking water quality management, ISO 9000, is appropriate and is by far the most commonly used model. In the US, where ISO systems have not been widely adopted, an alternative system is under development building on a treatment plant control system termed Partnerships for Safe Water (Pizzi *et al.* 1997). Simpler HACCP/ISO 9000-based quality assurance systems have been developed for small food and beverage organisations. It is anticipated that such systems could also be applied to smaller water authorities, which might not have the resources to implement a full ISO 9000 and HACCP system but would nevertheless benefit from these systems being in place.

12.5 DRINKING WATER CASE STUDIES

In 1996, the Australian Drinking Water Guidelines (NHMRC/ARMCANZ 1996) stated the need to follow a quality system and multiple barrier approach. To enable water suppliers to adopt the system most consistent with their organisational practices, the guidelines did not single out any particular system. Australian water companies have responded to these guidelines by undergoing HACCP-type risk assessment processes and implementing quality management systems to control their processes and people. Example case studies could be drawn from most of Australia's major cities (such as Brisbane Water (Gray and Morain 2000), Sydney Water, Melbourne Water and South East Water in Melbourne) as well as a number of rural supplies (DLWC 1999).

12.5.1 Sydney Water, Sydney, New South Wales, Australia

Over a period of approximately a year, hazard assessment and management workshops were carried out by Sydney Water to evaluate the risks to each of its 14 water supply systems. Various stakeholders (including State Health Officials) and Sydney Water employees were invited to the workshops and asked to contribute their knowledge in ascertaining the hazards (from catchment to customer) that had happened to or were likely to happen to Sydney's water. The team was divided into groups that concentrated on the various aspects of the water supply system including catchment, storage, treatment and distribution. The identified hazards were then scored based on the methodology given in Figure 12.4, which was developed by a consultant team of risk assessment and water quality specialists (with inputs from Sydney Water) for Sydney Water. This methodology is very flexible as it can be adapted to specific systems (based on number of customers for instance) and provides a more sophisticated approach to hazard assessment when compared to risk assessment matrices often quoted in HACCP methodologies. An example of the generic types of hazards and the scoring results is given in Table 12.4.

Table 12.4. Example hazards and ranking scheme based on Sydney Water hazard assessment methodology. For weighting factors, see Figure 12.4

Hazard	Dur.	Mag.	Cust.	Conseq factor	Freq.	Risk score	Total risk
	Weighting factors						
	0.24	0.47	0.29				
Filter breakthrough	2	250	16	122.6	3.50	429	11.5
Pathogen ingress through mains breaks	2	8	2	4.8	60.0	289	19.2
Incorrect dam screen filters	2	250	16	122.6	2.00	245	25.7
Flushing causing resuspension of sediment in pipes	2	32	4	16.7	12.0	200	31.1
Backwash supernatant returning to treatment system	2	250	16	122.6	1.50	184	36.0
Inappropriate treatment train for high pathogen contamination	8	250	16	124.1	1.20	149	40.0

Dur. - duration; Mag. - magnitude; Cust. - customers affected; Conseq. - consequence; Freq. - frequency (events/year).

Those hazards that were identified as posing approximately 80% of the cumulative risk were chosen for hazard management. It should be noted that the hazards in Table 12.4 are example hazards only and are not exhaustive. It should also be noted that, based on the concept of multiple barriers, the absence of a barrier or management option constitutes a hazard to water quality in its own right.

The same workshop participants were then asked to revise the chosen hazards to make sure that important ones had not been missed. This process is vital as it, again, utilises the knowledge and intuition of the people who operate the water systems on a day-to-day basis rather than relying purely on a ‘numbers approach’. Participants were also asked to provide information on the management options in place or those required.

12.5.2 South East Water, Melbourne, Victoria, Australia.

Over a period of around nine months, South East Water implemented an ISO 9000 quality management system across the whole business. This included all aspects of operational practice affecting water quality. After this system had become established, South East Water implemented a HACCP system over a four-month period. Both systems are externally audited and have been certified to international standards (in the case of HACCP this is the National Sanitation Foundation standard).

Representatives from internal operational areas, health authorities, other water companies and consultants were included in HACCP teams. In total, six relatively small teams developed plans relevant to their specialist areas, such as ‘backflow prevention’ or ‘disinfection’. One of the most commonly used risk assessment matrices, given in Table 12.3, was applied. This approach is simpler than that used by Sydney Water, reflecting the relatively simpler water supply system. An example worksheet illustrating the level of detail adopted for the HACCP plan is given in Table 12.5. In essence, any operational aspect thought to have an impact on public health was considered significant and underwent the HACCP process.

A number of studies were undertaken to validate that particular operational practices were effective at maintaining safe water. Some of these were very specific. For example, South East Water repairs around 1500 burst water mains per year. A detailed follow-up of the water quality after a number of these burst main repairs was used to validate the mains burst repair procedure. In a more comprehensive validation exercise, a study similar to the epidemiological studies described by Payment (1997) was performed using epidemiologists from Monash University Medical School. Around 600 houses receiving water supplied by South East Water were selected and half were fitted with water filter/UV units and the other half with sham units.

Table 12.5. Example based upon a HACCP worksheet for a hazard-event (South East Water HACCP plan)

Step	Hazard	Preventative measures	Risk	CCP/ QCP/ CP	Target level	Action level	Monitoring procedure	Corrective action
Storages	Pathogen contamination of closed storages	Scheduled maintenance program. Cleaning of storages Bird proofing Roofing of open storages	Unlikely/ catastrophic 10	CCP	Intact bird proofing mesh	Any breach in bird proofing	Water Operations field technicians carry out inspections during site visits. These inspections occur on average fortnightly with reports being recorded in personal diaries or rung in immediately.	Any breaches are notified to Water Operations engineers who repair bird proofing and undertake any or all of the following actions: Scour contaminated water Drain and clear storage Flush affected area Increase disinfection dosing Bypass storage Alternative supply Actions undertaken are recorded

This double-blinded randomised clinical trial study design was used to follow the health status of these 600 families for 18 months (Hellard *et al.* submitted) to look for the effect of filtering/disinfecting water as a means of validating the normal water delivery process.

12.6 A NEW APPROACH FOR MONITORING AND ASSESSING RECREATIONAL WATER QUALITY

The traditional management approach to maintaining the safety of bathing beach waters has been to sample the water on a routine basis to determine if the microbiological quality meets certain predetermined limits. This approach has several shortcomings, some of which are directly related to the analytical methods used to measure water quality. Currently used methods involve the measurement of micro-organisms commonly associated with excreta from the intestinal tract of warm-blooded animals (see Chapter 13). The measurement of indicator bacteria provide a retrospective assessment of water quality. Usually 24 hours are required before the density of indicator bacteria in the water sample can be determined. Under these circumstances the hazard associated with the excreta-contaminated water may no longer be present by the time the indicator bacteria are detected. This type of temporal delay in detecting hazards in water is not effective for managing risks associated with beach waters. A second shortcoming of indicator bacteria is that some of the micro-organisms used to measure water quality may have extra-enteral sources. Industrial wastes are known to provide an environment that can produce coliforms and faecal coliforms. These shortcomings mean that the organisms do not adequately provide warning of potential risk from enteric pathogens and may serve to confuse the picture.

Although these shortcomings are not catastrophic, they do present a situation where frequent routine sampling may not be economically effective when compared to the benefits that may accrue with regard to maintaining minimum health risks for swimmers. The costs of frequent routine monitoring can be burdensome to small communities and currently there is no acceptable alternative to the traditional approach.

In 1998, a tentative alternative approach to the testing currently used was proposed at an expert consultation that was co-sponsored by the World Health Organization and the United States Environmental Protection Agency (Bartram and Rees 2000; WHO 1999). The approach (which requires filed testing and possibly further adaptation) is ideally suited to amendment to account for specific local circumstances, and leads to a classification scheme based upon health risk. It presents two significant elements, namely:

- A classification scheme based on an inspection of various sources of faecal contamination (i.e. a sanitary survey), the extent to which faeces affect beach waters and the density of faecal indicator bacteria in beach water samples.
- The possibility of reclassifying a beach to a higher class if effective management interventions are instituted to reduce exposure and thereby lower the risk of swimming-associated illness.

The elements of the proposed scheme are illustrated in Figure 12.5. The advantage of the classification scheme, as opposed to the usual pass/fail approach, lies in its flexibility. A large number of factors can influence the condition of a beach and the classification system reflects this, allowing regulators to invoke mitigating approaches for beach management.

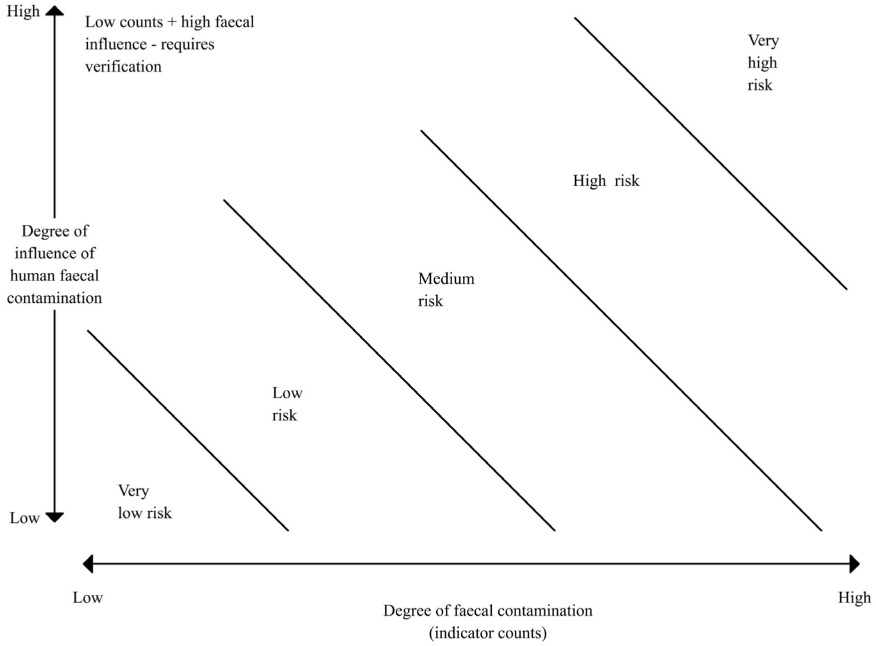

Figure 12.5. Schematic representation of classes of health risk (reproduced with permission from WHO 1999).

The horizontal axis of the figure shows the degree of faecal contamination as measured with indicator bacteria. The vertical axis shows the degree of influence of human faecal contamination. The degree of faecal contamination has a direct influence on the classification of risk and the indicator densities provide a means of monitoring beach waters to determine changes in classification.

12.6.1 Principle sources of human faecal contamination

The most important sources of human faecal contamination that affect bathing beaches are:

- discharges from sewage treatment plants including those from combined sewer overflows;
- riverine sources, where rivers receive sewage discharges, and the river is used directly for recreation or it flows to coastal or lake areas used for recreation; and
- contamination from bathers themselves.

The faecal contaminants from these sources can be graded based on either the distance from the beach of the discharge outfall, the distance of travel or travel time to the beach in river systems or the density of swimmers at beaches.

12.6.1.1 Sewage discharges

The risk potential associated with sewage discharges can be estimated if information regarding the length of the outfall and the degree of treatment of the wastewater is available. For example, raw untreated sewage discharged directly on to the beach would carry a very high risk potential. If the discharge is carried far from the beach through a long distance outfall, the risk potential would become negligible. At the opposite end of the risk gradient, a very low risk potential results if the sewage receives tertiary treatment plus disinfection even if the treated sewage is discharged directly on to the beach. The matrix of the degree sewage treatment and the outfall distance from the beach is a key element in determining the influence of faecal contamination as it relates to risk classification. The risk potential is outlined in Table 12.6.

Table 12.6. Risk potential to human health through exposure to sewage (reproduced with permission from WHO 1999)

Treatment	Discharge type		
	Directly on beach	Short outfall[1]	Effective outfall[2]
None[3]	Very high	High	Not applicable
Preliminary	Very high	High	Low
Primary (inc. septic tanks)	Very high	High	Low
Secondary	High	High	Low
Secondary + disinfection	Medium	Medium	Very low
Tertiary	Medium	Medium	Very low
Tertiary + disinfection	Very low	Very low	Very low
Lagoons	High	High	Low

[1] The relative risk is modified by population size. Relative risk is increased for discharges from large populations and decreased for discharges from small populations.
[2] This assumes that the design capacity has not been exceeded and that climatic and oceanic extreme conditions are considered in the design objective (i.e. no sewage on the beach).
[3] Includes combined sewer overflows.

12.6.1.2 Riverine discharges

Riverine and estuarine beaches and beaches near the mouth of rivers can be affected by faecal contamination from point sources, such as sewage treatment plants which discharge into the river. The risk potential associated with discharges of sewage into rivers can be estimated by determining the size of the discharging population and the flow rate of the river receiving the sewage. The flow rate influences the dilution of the sewage as it enters the river. The dilution effect is related to dry weather and wet weather flow. Dry weather flow is associated with low dilution and this usually occurs during the bathing season. Low flow rivers provide very little dilution effect and, therefore, the size of the discharging population takes on increased significance because of the high volume of waste produced. Under all conditions plug flow with no dispersion is assumed. To form a data set from which risk potential can be estimated, various combinations of population size and river flow rate are used in conjunction with the type of treatment applied to the sewage influent. These estimates can be used to classify beaches on rivers or near coastal waters affected by riverborne faecal contamination.

The risk potential classification system for riverine systems is similar to that used for ocean outfalls. The dilution effect gradient runs from a high population density with low river flow to a medium population density with a medium flow river to a low population density with a high river flow. The risk potential is greatest with high population and low river flow, and the lowest risk potential with low population and high river flow. This pattern of risk holds for effluents of all types of treatment. The type of treatment does affect the risk potential. As the treatment process becomes more complex, the risk potential for each dilution effect decreases. In practice several discharges into a single river are likely to occur and where larger discharges are treated to a higher level, then smaller sources (including septic tank discharges) and combined sewer overflows may represent the principal source of concern.

The classification system can be used directly for freshwater river beaches and for beaches in estuarine areas. The system may also be appropriate for beaches near the mouth of rivers contaminated with faecal wastes.

12.6.1.3 Bather shedding

Bathers have been shown to shed high densities of *E. coli*, enterococci and *Pseudomonas aeruginosa* in tank studies where total body immersion was examined under controlled conditions (Breittmayer and Gauthier 1978; Smith and Dufour 1993). Other studies have demonstrated the accumulation of faecal indicator bacteria over the course of a day at populated beaches (Cheng *et al.* 1991). Two elements, bather density and water bodies with very little water movement contribute to bather-to-bather transmission of illness. These two elements can be used to develop a risk potential matrix which lists low risk for high bather density and high dilution, and a very low risk in the case of low bather density and high dilution. Medium risk results from high bather density and low dilution, which becomes low risk if both the bather density and dilution are low. These risks may be higher if the beach is populated with high numbers of young children or if no sanitary facilities are available.

12.6.2 Assessing microbiological quality

Sewage and faeces contain a number of harmless bacteria, such as enterococci and some types of *E. coli*, and chemicals, such as coprostanol, which can be used to detect the presence of faecal material in water (see Chapter 13). These indicator bacteria or chemicals can be used to quantify the amount of faeces at a beach. They have been used to show the relationship between beach water quality and swimming-associated illness (WHO 1998). Primary indicators, such as *E. coli*, faecal streptococci and enterococci have been used for years as measures of faecal contamination. Other micro-organisms, such as clostridia or coliphage, are also associated with faecal contamination but have not received broad acceptance as traditional indicator bacteria. These organisms are designated as secondary indicators and they are used mainly for follow-up analyses or for their instructive value.

Faecal streptococci or enterococci are used as marine water quality indicators in temperate climates. These micro-organisms can be placed in categories that describe percentiles of water quality densities that are associated with health effects. These bacteria are considered primary indicators and they have been used on a routine basis for many years. It has been suggested that these indicators have sources other than the gut of warm-blooded animals, such as soil or plants, in tropical environments. In this situation sulphite-reducing clostridia or Clostridium perfringens have been proposed as secondary indicators.

In temperate freshwater environments, *E. coli* is an effective indicator of faecal contamination, in addition to faecal streptococci and enterococci. Secondary indicators such as clostridia are suggested for use in freshwater tropical climates. The percentile values associated with health effects in swimmers would not necessarily be the same in marine and in fresh waters.

The percentiles can be categorised based on the relationship to illness. For instance, five categories (labelled A to E) could be segregated based on upper 95 percentile values of <10, 11–50, 51–200, 201–1000 and >1000 for faecal streptococci or enterococci, where all categories above 50 are associated with swimmer illness. The use of these categories is advantageous for classifying risks and for reclassifying risks associated with faecal contamination.

12.6.3 Primary classification of beaches

Primary classification of a beach involves conducting a sanitary inspection of potential pollution sources to determine the susceptibility of the beach to faecal influence and a microbiological assessment of beach waters using primary indicators. Once the appropriate categories are determined by sanitary inspection and microbiological assessment they can be fitted into a table, such as Table 12.7, to determine the primary classification for a beach. For example, if the microbiological quality of beach water, as indexed by faecal streptococci or enterococci, is in the 11–50 indicator density range (category B) and the faecal influence category was found to be moderate then the particular beach would be classified as ‘good’.

Reclassification of a beach to a higher or lower level might result from a number of events, such as a major break in an outfall pipe or a significant modification of the treatment process. Either one of these events could dramatically affect the quality of the bathing water with respect to faecal contamination of a beach. A break in an outfall pipe could deliver much higher levels of faecal contamination to a beach and thereby increase the risk of swimming-associated illness over a potentially long time period until the break is repaired. This condition would necessarily change the microbiological assessment category and the sanitary inspection category with a resultant change to a lower classification. Similarly, an improvement in the treatment process, wherein a primary treatment process was upgraded to a secondary treatment process, would improve the quality of the water reaching a beach. This would not only affect the sanitary inspection category, but also the microbiological assessment category. The long-term effect of changing these two categories would be to change the classification of a beach to a higher, more desirable level.

Table 12.7. Primary classification matrix (reproduced with permission from WHO 1999)

Sanitary Inspection Category[#]	Microbiological Assessment Category (indicator counts)				
	A	B	C	D	E
Very low	Excellent	excellent	good	good[+]	fair[+]
Low	Excellent	good	good	fair	fair[+]
Moderate	good*	good	fair	fair	poor
High	good*	fair*	fair	poor	very poor
Very High	fair*	fair*	poor*	very poor	very poor

[#] = susceptibility to faecal influence; [+] implies non-sewage sources of faecal indicators (e.g. livestock) and this should be verified; * indicates unexpected results requiring verification.

Some events are much more variable than intervention measures or system breakdowns. Rain events are situations where the sanitary inspection categories and the microbiological assessment category can be significantly modified. Sewage treatment plant effluents can bypass the treatment system because wastewater sewage drains are frequently also used for stormwater. Under heavy rain conditions the combined system can overwhelm the treatment regime and effluents are discharged without treatment. Combined sewer overflows to riverine environments affect the categorisation of potential risk associated with the treatment category. The overflows will change the category from treated to untreated sewage and will lead to an increase in the risk potential. Although rainfall events are not predictable, the effect of these events on beaches are predictable. For example, it can be determined that the microbiological assessment category may increase to the 101 to 200 indicator density range from the 51 to 100 range with a half-inch of rainfall. This change, along with the faecal influence category change, might lower the beach classification from good to poor. Since this change can be predicted based on the amount of rainfall, a temporary management action would be appropriate at the beach.

12.6.4 Management actions

Routine monitoring may be a key element in maintaining the safety of bathing waters. It is a direct measure of microbial quality of beach waters and closely related to beach classification. It is also a means of measuring beach change in status over time. If the beach has been properly classified and the faecal influence is fairly constant, it should be possible to substantially reduce the monitoring requirements.

Direct action should be a principal management approach. Improvement of the treatment process or other remedial actions such as diversion of the sewage discharges away from a beach by constructing long-distance outfalls will significantly lower the potential risk associated with human excreta. The retention of wastewater combined with stormwater so that it can be treated later rather than discharged to receiving waters untreated, would also significantly lower risks at bathing beaches.

The management of intermittent events, such as stormwater runoff, can usually be addressed by informing the public, either through the media or by posting signs at the beach, that a short-term health hazard exists. Other means of dissuading the public from exposure to contaminated water may be to close nearby car parks or not to provide public transport to the bathing beach.

Under the proposed classification scheme, routine monitoring would always require that some type of annual sanitary inspection be performed. The monitoring scheme would be variable, with those beaches classified as 'excellent' or 'very poor' requiring the least amount of monitoring, whereas beaches classified as 'good', 'fair' or 'poor' might require more frequent sampling because their quality would be most likely to change with small changes in faecal influence.

Although many of these management options are practised to some extent, their use with the proposed scheme for beach classification has not been implemented. The value of the suggested scheme for classifying beach waters is that it may lead to a number of activities that will decrease the risk of exposure to faeces-contaminated bathing waters. It will allow individuals to make informed choices about their personal risks. It will encourage local risk management because the system is simple and economically feasible. It will minimise the monitoring effort and thereby minimise costs. It will encourage local decision-making with regard to public health actions. Lastly, it will encourage incremental improvement in local water quality management because the categories and the priorities for improving public health are well defined.

The validity and value of the proposed risk classification scheme should be evaluated through extensive field testing to verify the scientific soundness of the approach.

12.7 IMPLICATIONS FOR INTERNATIONAL GUIDELINES AND NATIONAL REGULATIONS

Management frameworks such as those outlined in this chapter can be generalised and, as such, are amenable to incorporation into international guidelines. It is increasingly being recognised that management through the use of end product standards only, while still important, is limited. Complementing end product standards with measures and indicators of safe process and practice, as outlined here, is a powerful tool in health protection. Many management strategies represent common sense and good housekeeping. They are relatively easy to implement, are cost-effective and can be especially valuable, in national terms, where the cost of water testing is a major impediment to the adoption of local standards.

12.8 REFERENCES

Angulo, F.J., Tippen, S., Sharp, D.J., Payne, B.J., Collier, C., Hill, J.E., Barrett, T.J., Clark, R.M., Gelreich, E.E., Donnell, H.D. and Swerlow, D.L. (1997) A community waterborne outbreak of salmonellosis and the effectiveness of a boil water order. *American Journal of Public Health* **87**(4), 580–584.

Ashendorff, A., Principe, M.A., Seeley, A., LaDuca, J., Beckhardt, L., Faber Jr, W. and Mantus, J. (1997) Watershed protection for New York City’s supply. *Journal of the American Water Works Association* **89**, 75–88.

Badenoch, J. (1990) *Cryptosporidium* in water supplies. Report of the Group of Experts. Department of the Environment, Department of Health. HMSO.

Barry, S.J., Atwill, E.R., Tate, K.W., Koopman, T.S., Cullor, J. and Huff, T. (1998) Developing and Implementing a HACCP-Based Programme to Control *Cryptosporidium* and Other Waterborne Pathogens in the Alameda Creek Watershed: Case Study. American Water Works Association Annual Conference, 21–25 June 1998, Dallas, Texas.

Bartram, J. and Rees, G. (2000) *Monitoring Bathing Waters,* E & FN Spon, London.

Bell, G. (1999) Managing food safety: HACCP and risk analysis. *The New Zealand Food Journal* **29**(4), 133–136.

Breittmayer, J.P. and Gauthier, M.J. (1978) Contamination, bacterium d’une zone balneaire liee a sa frequentation. *Water Research* **12**, 193–197. (In French.)

Cheng, W.H.S., Chang, K.C.K. and Hung, R.P.S. (1991) Variations in microbial indicator densities in beach waters and health-related assessment. *Epidemiology and Infection* **106**, 329–344.

Davison A, Davis, S. and Deere, D. (1999) Quality assurance and due diligence for water – Can HACCP deliver?. Paper presented AWWA/WMAA Cleaner Production in the Food and Beverage Industries Conference, Hobart, 1–3 September.

Deere, D.A. and Davison, A.D. (1998) Safe drinking water. Are food guidelines the answer? *Water* November/December: 21–24.

DLWC (1999) The management of *Giardia* and *Cryptosporidium* in town water supplies: Protocols for local government councils. NSW Department of Land and Water Conservation, Australia.

Gray, R. and Morain, M. (2000) HACCP application to Brisbane water. *Water* **27**, January/February, 41–42.

Havelaar, A.H. (1994) Application of HACCP to drinking water supply. *Food Control* **5**, 145–152.

Hellard, E., Sinclair, M., Forbes, A. and Fairley, C. (submitted) A randomized controlled trial investigating the gastrointestinal effects of drinking water. *American Journal of Public Health.*

Kramer, M.H., Herwaldt, B.L., Craun, G.F., Calderon, R.L. and Juranek, D.D. (1996) Waterborne disease – 1993 and 1994. *Journal American Water Works Association* **88**(3), 66–80.

Langley, A. and van Alphen, M. (eds) (1993) *Proc. 2nd National Workshop on the Health Risk Assessment and Management of Contaminated Sites*, South Australian Health Commission, Adelaide.

Leland. D., Mcanulty. J., Keene. W., and Stevens. G. (1993) A cryptosporidiosis outbreak in a filtered-water supply. *Journal American Water Works Association* **85**(6), 34–42.

McCann, B. (1999) UK counts cost of Crypto protection. *Water Quality International* May/June: 4.

Mentzing, L.O. (1981) Waterborne outbreaks of *Campylobacter* enteritis in central Sweden. *Lancet* **ii**, 352–354.

Millson, M., Bokhout, M., Carlson, J., Speilberg, L., Aldis, R., Borczyk, AZ. and Lior, H. (1991) An outbreak of *Campylobacter jejuni* gastroenteritis linked to meltwater contamination of a municipal well. *Canadian Journal of Public Health* **82**, 27–31.

NHMRC/ARMCANZ (1996) Australian Drinking Water Guidelines. National Health and Medical Research Council and Agriculture and Resource Management Council of Australia and New Zealand.

Payment, P. (1997) Epidemiology of endemic gastrointestinal and respiratory diseases – incidence, fraction attributable to tap water and costs to society. *Water Science & Technology* **35**, 7–10.

Pizzi, N., Rexing, D., Visintainer, D., Paris, D. and Pickel, M. (1997) Results and Observations from the Partnership Self Assessment. Proceedings 1997 Water Quality Technology Conference, Denver, Colorado, 9–12 November.

Raman, R. (1990) Risk perceptions and problems in interpreting risk results. Paper presented at the 18th Australasian Chemical Engineering Conference CHEMECA '90. Auckland, New Zealand, August.

Ramsay, C.N. and Marsh, J. (1990) Giardiasis due to deliberate contamination of water supply. *Lancet* **336**, 880–881.

Rose, J.B., Lisle, J.T. and LeChevallier, M. (1997) Waterborne Cryptosporidiosis: Incidence, outbreaks and treatment strategies. In *Cryptosporidium* and Cryptosporidiosis (ed. R. Fayer), CRC Press, Boca Raton, FL.

Shaw, P.K., Brodsky, R.E., Lyman, D.O., Wood, B.T., Hibler, C.P., Healy, G.R., Macleod, K.I., Stahl, W., and Schultz, M.G. (1977) A community-wide outbreak of giardiasis with evidence of transmission by a municipal water supply. *Annals of Internal Medicine* **87**, 426–432.

Smith, B.G. and Dufour, A.P. (1993) *Effects of Human Shedding on the Quality of Recreational Water,* American Society of Microbiology, Atlanta, Georgia.

Smith, D. B., Clark, R. M., Pierce, B. K. and Regli, S. (1995) An empirical model for interpolating C*t* values for chlorine inactivation of *Giardia lamblia*. *Aqua* **44**, 203–211.

Stevens, M., McConnell, S., Nadebaum, P. R., Chapman, M., Ananthakumar, S. and McNeil, J. (1995) Drinking water quality and treatment requirements: A risk-based approach. *Water* **22**, November/December 12–16.

Swerdlow, D.L., Mintz, E.D., Rodriguez, M. *et al.* (1992) Severe life-threatening cholera in Peru: predisposition for persons with blood group O. Abstract 941. Program, 32nd Interscience Antimicrobial Agents Chemotherapy conference, 267.

Teunis, P.F.M., Medema, G.H. and Havelaar, A.H. (1997) Assessment of the risk of infection by *Cryptosporidium* or *Giardia* in drinking water from a surface water source. *Water Research* **31**, 1333–1346.

Vogt, R.L., Sours, H.E., Barrett, T., Feldman, R.A., Dickinson, R.J. and Witherell. L. (1982) *Campylobacter* enteritis associated with contaminated water. *Annals of Internal Medicine* **96**, 292–296.

WHO (1993) Guidelines for drinking-water quality. Volume 1. Recommendations. World Health Organization, Geneva.

WHO (1998) Guidelines for safe recreational-water environments: coastal and freshwaters. Consultation Draft, World Health Organization, Geneva.

WHO (1999) Health-based monitoring of recreational water: the feasibility of a new approach (the 'Annapolis protocol'). Protection of the Human Environment. Water, Sanitation and Health Series, World Health Organization, Geneva.