Preface

Water quality and safety are issues that increasingly attract the attention of public health authorities and engage the energies of microbiologists, engineers, and epidemiologists. The increase in waterborne outbreaks, both in frequency and severity, has raised the visibility of water microbiology in the public domain. Unfortunately, funding for research in the areas of water microbiology and public health has been declining at this time of pressing need for information to underpin decision-making and response to emergency events.

Recognizing that the issues associated with water and public health are of significant impact, the American Academy of Microbiology convened a colloquium of experts in microbiology, engineering, epidemiology, and risk assessment in Guayaquil, Ecuador, April 4-6, 1995. Topics of intense discussion included identification of the current extent of waterborne disease outbreaks and the future threat of waterborne disease and epidemics traceable to water sources within both developed and developing countries. A plan of action to mitigate the problems associated with microbiologically unsafe drinking water was developed, emphasizing resource management, behavioral patterns, and related human factors contributing to waterborne infections. Education at all levels—professional and public—was emphasized. Climatological and political factors were also considered and are noted in the plan of action.

In developing countries, treatment of water and domestic and industrial wastes is nonexistent or grossly inadequate. Until sanitation practices are improved, elimination of waterborne disease is impossible. In developed countries, deficiencies in treatment and delivery, especially those due to an aging and deteriorating infrastructure, pose serious threats to human health. Crucial questions were identified concerning disinfection-resistant microbial populations, emergence of antibiotic resistance, transfer of virulence factors among microorganisms, and the need to minimize anthropogenic impact on source waters. The colloquium brought together a total of 65 scientists from 12 countries. Thus, a truly global perspective was offered on these issues.

The Academy is grateful to the colloquium participants who shared so generously their expertise, perspective, and time and provided wise counsel, and the Steering Committee—Timothy Ford (Chair), Erich Bretthauer, Jorge Calderon, Charles Gerba, James Shapiro, and Mary Wilson—who spent many long hours organizing this highly successful meeting and preparing the final report.

All of us acknowledge, with sincere gratitude, the excellent staff support and attention to detail provided by Carol Colgan, Director, and Peggy McNult, Manager, American Academy of Microbiology. J.P. Shine and Suzanne Michaud provided editorial assistance.

The subject of microbiological safety of water will very soon become an international priority as travel across national boundaries and the sheer numbers of human citizens increase in the decade ahead, placing Promethean demands on water resources. The issues presented in this document merit very serious attention. If ignored, the consequences will be unavoidable.

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Executive Summary

Increases in population over the past century have placed tremendous pressures on water resources of both the developed and developing world. These pressures include direct contamination from domestic, industrial, and agricultural wastes and less direct effects caused by climate change and other ecological disturbances. The result is a contaminated and often increasingly scarce global resource, which in turn is contributing to a rise in waterborne disease outbreaks worldwide. Population projections for the next century suggest that these pressures can only increase. Without appropriate intervention, waterborne disease outbreaks/epidemics/pandemics are also expected to increase dramatically.

Waterborne disease cannot be eradicated, as was smallpox, because of the variety of disease agents transmitted by water. Trade and travel are too extensive; border closures have not proved effective. On the contrary, they are more often destructive to both the economy and the culture of a region. Risks of disease must, therefore, be controlled at the community level by basic sanitation and availability of uncontaminated water. A systems approach is needed for water management, including watershed protection, drinking water treatment and distribution, and wastewater collection and treatment.

Control of waterborne disease is dependent on education at every level—from household to government. Solutions to the problem of waterborne disease vary, depending on regional economy and climate. For developing countries, a low technology approach—i.e., education and minimal treatment—may dramatically reduce incidence of waterborne disease, which, as an immediate consequence, will significantly effect the economy of that region. Industrial productivity, including tourism, depends on a disease-free environment. To induce governments to invest in water quality improvements, emphasis needs to be placed on economic benefits.

Developed countries face the very real demands of existing infrastructures, emergence of pathogens resistant to water treatment and disinfection, and increasing numbers of immuno-compromised individuals. In addition, poorly defined risks from toxicity of disinfection byproducts need to be considered. Clearly, education is critical, from the level of the average citizen to water utility personnel, professional organizations, and universities conducting research. One area of notable concern involves use of indicator organisms. Dependence on traditional indicators, such as coliforms, can be misleading, particularly when viral and/or protozoal contamination is suspected. There is a critical need for the immediate future to identify more appropriate indicators for both temperate and tropical regions and/or to validate/modify the use of current indicators. In the long run, however, direct detection and enumeration of pathogens must be accomplished.

In summary, the quality of global water supplies cannot continue to deteriorate without serious consequences to global distribution, incidence, and severity of waterborne disease. Accurate risk analysis and global public education at all levels are critical. Although application of advanced technologies can improve water quality, massive investment is required. Low technology options, coupled with appropriate education, can provide dramatic improvements in human health in even the least developed countries. Ideally, a multidisciplinary approach would be undertaken internationally, with both developed and developing nations working in unison to address water quality issues. Sanitary engineers, microbiologists, epidemiologists, and public health officials working as a team to address the health risks posed by microbial pathogens should be the highest priority, nationally and internationally.

Conclusions and recommendations of the colloquium:

- The list of potentially pathogenic microorganisms transmitted by water is increasing significantly each year. Newer methods, especially molecular genetic-based methods, must be used to detect these pathogens.
- Development, implementation, and maintenance of low cost, low technology water treatment systems are critical for reduction of global morbidity and mortality associated with waterborne disease.
- Waterborne disease must be made reportable and active surveillance implemented, both nationally and internationally.
- Improved risk assessment methodology and database development are needed for waterborne diseases.
- Governments, non-governmental organizations, institutions, and individuals with influence to effect public opinion must be educated about the social and economic burden of waterborne diseases.
- Policies related to waterborne disease are needed to integrate the concerns and enable implementation of water treatment in both developed and developing countries.
- Training, education, technology transfer, and communication with the public through television, radio, and print on subjects relevant to microbiological safety of water must be undertaken immediately.

1. Introduction

There is growing concern about the general failure of authorities to understand the public health and associated socio-economic impact of waterborne and related infectious diseases. The benefits of investment in research and technology aimed at the control of these diseases tend to be underestimated. The American Academy of Microbiology convened a colloquium of invited experts to define the problem, formulate research needs and priorities, and decide on a strategy for action at the global level. The colloquium, entitled "Global Issues in Microbiological Water Quality for the Next Century," held April 4-6, 1995 in Guayaquil, Ecuador, was attended by approximately 65 scientists from 12 different countries having national and international expertise. The individuals attending the colloquium represented a variety of disciplines, including public health microbiology, ecology, economics, microbial methods (including molecular biology methods), epidemiology, and journalism. Some of these individuals have worked in the field of water microbiology and related disciplines for more than 20 years. There were also representatives from agencies involved in the development of health and environmental policies (e.g., the U.S. Environmental Protection Agency (EPA), the Centers for Disease Control and Prevention (CDC), the World Health Organization (WHO), and the World Bank) who were active participants in the colloquium.

The goal of the colloquium was to develop a report on needs, from policy and scientific viewpoints, concerning microbial risks in drinking water. During the colloquium, six groups were formed to address questions on what is and what is not known about global waterborne disease, how the risks should be described, assessed, and prioritized, and recommended actions. What emerged was a striking commonality of problems hindering access to microbiologically-safe water in both developed and developing parts of the world. Bottled water and/or home treatment provides the best short-term solution to decreasing the risk of waterborne disease. From this and other information arising from the colloquium, it was clear that the distribution of safe water to the home can no longer be taken for granted, not even in the United States or Western Europe.

1.1 PRIMARY GOAL

Agencies, policy makers, and individuals responsible for providing water to communities have failed to recognize that a large proportion of the world's population continues to lack access to microbiologically-safe drinking water. This may be largely due to the deficiencies in understanding, not only by the public, but also by policy and decision makers and the scientific community, that the problem is severe and immediate.

The primary goal of this report is to raise awareness among individuals, households, professionals, politicians, community leaders, organizations, and institutions of the quintessential importance of microbiological quality of water, its rational use and conservation, and the impact of waterborne disease on society. Microbiological safety of drinking water is predicted to be a major concern in the 21st century and already is a cause of global conflict.

1.2 BACKGROUND

The spread of cholera in tropical nations and cryptosporidiosis outbreaks in temperate regions have awakened new interest in waterborne diseases. The dramatic nature of these outbreaks, especially their severity in terms of morbidity and mortality, caught public attention, at least transiently, during and immediately after public reporting of the outbreaks.

Recorded epidemics of cholera have devastated Europe and North America since the early 1800s. For example, cholera was estimated to have infected 440,000 and killed more than 110,000 people in the United Kingdom in 1849 (Longmate 1966). Cholera occurs in epidemic form when there is rapid urbanization without adequate sanitation and access to clean drinking water. Hence, the focus of epidemics/pandemics has shifted to developing countries over the last century. The first pandemic was recorded in 1817, and we are now well into the seventh cholera pandemic, which started in Indonesia in 1961, reaching South America in 1991. A total of 1,076,372 cases and 10,098 deaths were reported in the region of the Americas by June 1995, according to the Pan American Health Organization (PAHO). Reported numbers are only a fraction of actual cases, and the epidemics do not appear to be transient, but rather to be settling into an endemicity, with epidemic "flare ups" predicted.

Table 1

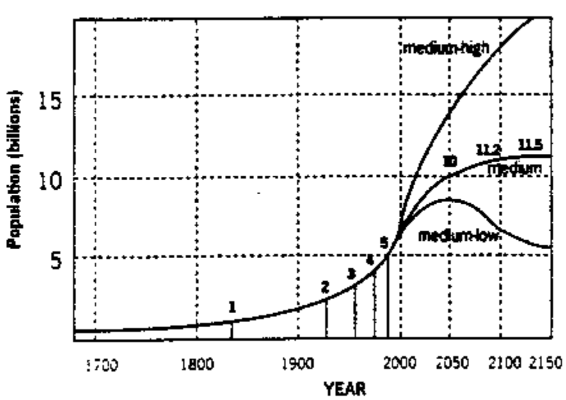
Cryptosporidiosis

1976 -	First human case diagnosed
1984 -	First well water outbreak
1987 -	First river water outbreak
1992 -	Multiple municipal water supply outbreaks
1993 -	Largest recorded waterborne outbreak in U.S. history (Milwaukee, Wisconsin)

(Source: CDC)

Figure 1

Recent increase in world population and UN projections to 2150. (Data source: UN, 1992-ref. 6)



From: UN Dept. of International Economic and Social Affairs. *Long-range World Projections: Two Centuries of Population Growth—1950–2150.* ST/ESA/SER.A/125. New York: United Nations. 1992.

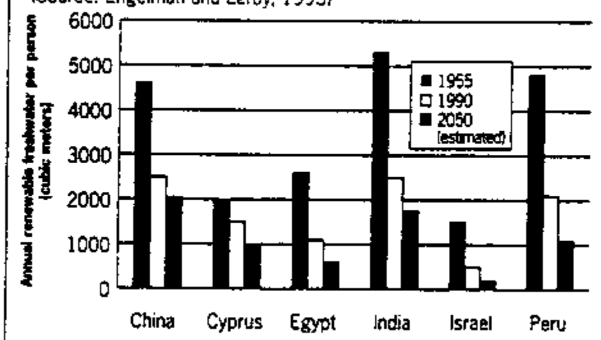
In developed countries, major outbreaks of cryptosporidiosis in the United Kingdom, United States, and Canada are beginning to change public health perspectives on risks of waterborne infectious diseases. The estimates were 400,000 people infected in Milwaukee, Wisconsin, in early spring 1993, i.e., approximately 25% of the total population of that city (MacKenzie, Hoxie, Proctor, et al. 1994). As a result of this and other outbreaks recently, confidence in the purity of public drinking water supplies, i.e., free of risk, is no longer widely shared by the U.S. public. The significant increase in sales of bottled water in the U.S. is clear evidence of this significant change in public perception and opinion.

Water use is directly related to population growth and development. (Figure 1 presents U.N. population projections to 2150.) There are significant disparities in water availability, water withdrawal per capita, and burden of disease when developed and developing countries are compared. (Figures 2 and 3 illustrate some of these disparities.) Despite differences, commonalities of the problems for both the developed and developing world are also striking. Large, widespread epidemics of waterborne disease are occurring in urban communities. Deaths are being reported as a result of water-acquired infections. Small communities are struggling with the problems associated with providing safe drinking water to their inhabitants. Increasingly, bottled water or home treatments are being suggested as stopgap solutions to contaminated tap water in developed countries, having long been employed in developing countries by those able to afford it.

It is important to remember that differentiation between developed and developing countries is an arbitrary process when drinking water safety is considered. There are continuous scales of development both within and between countries. For example, intra-urban health differentials can be at least as extreme as those between countries (Bradley, et al. 1991). However, problems and solutions vary from country to country, a fact that must be taken into account when formulating solutions. For example, one factor considered by some authorities to have been instrumental in the spread of cholera in Peru was inadequate disinfection of water supplies. Disinfection may have been abandoned or reduced in response to the report from the U.S. EPA on risk assessment of the carcinogenic potential of disinfection byproducts (DBP) (Anderson 1991). However, it is more probable and generally accepted that economics was the prevailing factor. Whatever the primary reason, this highlights the importance of comparative risk assessment and relative emphasis on DBP in developed countries vs. infectious disease, compared to developing countries. Integrated policies that address basic requirements for safety of water supplies and water quality that cross international boundaries need to be adopted. The single, most important requirement that must be emphasized is that disinfection of a public water supply should not be compromised.

Figure 2

Growing demand for water in selected countries 1955–2025
(Source: Engelman and Leroy, 1993)



The following thresholds of water stress have been suggested: when annual renewable fresh water per capita falls below 1,667 cubic meters, a country experiences water stress, below 1,000 cubic meters, water scarcity, and below 500 cubic meters, absolute scarcity (Falkenmark and Widstrand, 1992)

References

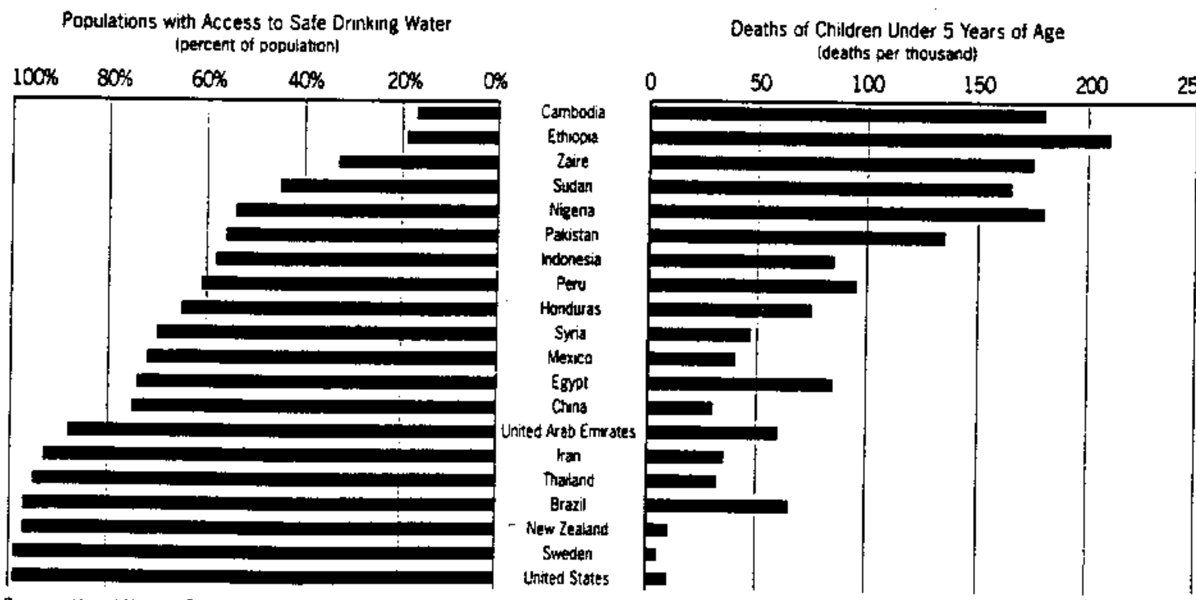
Engelman, R. and P. Leroy. 1993. Sustaining Water. Washington, DC, Population Services International.

Falkenmark, M and C. Widstrand, 1992. Population and water resources: a delicate balance. Population Bulletin, Population Reference Bureau.

1.3 SCOPE OF THE PROBLEM

It is ironic that successes in the control of infectious disease made early- and mid-20th century have resulted in decreased research, education, and funding in this area of public health. Fortunately, with realization that many control strategies have failed, evidenced by a resurgence in infectious diseases and pathogens becoming increasingly resistant to multiple antibiotics (Levins, et al. 1995), national priori-

Figure 3 **Water quality and child survival**



Sources: United Nations Children's Fund, *The State of the World's Children 1993*; Worldwatch Institute, *Worldwatch Paper 64: Investing in Children*, June 1985 ties are changing. The WHO reported that, of the 51 million deaths worldwide in 1993, approximately one third (16.4 million) were caused by infectious and parasitic diseases. In developing countries, infectious and parasitic diseases account for 44% of all deaths and 71% of deaths in children (World Development Report 1993). There is insufficient data to attribute a percentage of global infectious disease to water, although estimates of up to 80% have been given, when all water-related diseases are considered (Clarke 1993). A recent World Development Report estimates that diarrheal diseases traceable to contaminated water kill about 2 million children (about 10 million infants die each year in developing countries from all causes) and cause about 900 million episodes of illness each year (World Development Report 1992). The picture these data frame is stark indeed, especially since the trend is unequivocally an increase in infectious disease attributable to microbiologically unsafe water.

Water quality and quality of life are intimately intertwined. Exposure to infectious agents and toxic chemicals may occur through direct ingestion of water, ingestion of shellfish and other foods harvested in contaminated waters, ingestion of foods irrigated, washed or prepared with contaminated water, contact with water during bathing or recreational activities, and poor hygiene practices that are unavoidable in the absence of adequate quantities of clean water. In addition, a typically large and widely disseminated waterborne outbreak may result in many secondary cases not directly related to contaminated water, but that would not have occurred in its absence.

In many developing countries, water source quality shows continued deterioration (World Development Report 1992). In both developed and developing countries, ground waters are becoming increasingly contaminated and, in many cases, depleted as renewal rates are often only a fraction of withdrawal (Lewis 1990). These effects are a function of increasing population pressure, agricultural misuse, mining practices (acid runoff and erosion), pollution of groundwater, and the inability to keep pace with increasing demands on the resource. In addition to dependence on clean water for drinking and hygiene, competing uses for water for industry, agriculture, recreation, and energy place tremendous demands on an increasingly polluted global resource.

Urbanization affects water availability, quality, and waterborne disease transmission. At the turn of the century, in Europe and the U.S., typhoid fever was an emerging disease. It was controlled only when communities provided treatment of their public water supplies, first by filtration and then by the addition of chlorination. Many diarrheal diseases were reduced simultaneously (Fair, Geyer, and Okun 1968). As municipal infrastructures deteriorate or are stressed by increasing demand in developed or industrialized nations, an obvious outcome is increasingly severe epidemics of waterborne diseases. For example, the decline of urban infrastructure in the former Soviet Union resulted in recurrence of cholera in many cities (Ingram 1995).

In developed countries, chemical pollution of water has been the focus of attention paid to drinking water safety in recent years (Farland and Gibb 1993), due in part to the extraordinary sensitivity now possible in measuring chemical pollutants. Furthermore, the association of chemical pollutants with cancer evokes powerful images of a frequently fatal disease becoming ever more prevalent as population longevity increases. In contrast, the first image that comes to mind with water of poor microbiological quality is that of diarrheal disease, which everyone experiences at some time and from which the majority of people will recover. However, even in healthy individuals, recovery may be associated with chronic effects persisting for varying lengths of time. Although mortality of many waterborne infections is generally low, their socioeconomic impact in both the developed and developing world is severe; the impact is devastating in pandemics (Payment 1993). Thus, the morbidity and mortality associated with diarrheal diseases do not fully convey the severity of the problems caused by microbiologically poor water nor is the potentially fatal nature of diarrheal disease appreciated, especially for infants, children, the elderly, and the immunologically compromised, the latter including individuals undergoing chemotherapy, an increasingly large category of individuals. In reality, the consequences of poor water quality can extend far beyond diarrheal diseases (see Appendix 1).

Special areas of concern include:

Pathogens

- Conventional water treatment processes may not reliably prevent diseases caused by newly recognized agents, e.g., *Cryptosporidium*.
- Microorganisms with a higher level of resistance to chemicals used in water treatment and disinfection than expected have been recently recognized, including *Cryptosporidium, Giardia, Cyclospora,* and the mycobacteria (Ford 1993; Soave and Johnson 1995).
- Pathogens possess survival mechanisms that protect them from disinfection, such as the rugose form of *Vibrio cholerae* (Morris, Johnson, Rice, et al. 1993) (wrinkled, dwarf forms on culture plates that retain full virulence) or *Legionella pneumophila* that multiplies in amoebae where it lies protected from disinfection (Kilvington and Price 1990).
- As further research is done on transmission routes of infectious diseases, particularly for an increasingly large immunologically compromised population, many other infectious agents will be discovered to be transmissible by water.
- Declining immunities to many pathogens, mainly due to better sanitary conditions, increases the susceptibility and risk of disease during system failures.
- Development of antibiotic resistant strains of waterborne pathogens.

Climate change

- Water scarcity compromises hygiene as dwindling resources become increasingly polluted. In addition, reduced water pressure in distribution systems increases the risk of back siphoning of contaminated water.
- Floods can lead to breaching of barriers between sewage and water systems.
- Warming (or cooling) trends result in changes in the distribution of pathogens and disease vectors, e.g., the coastal algal blooms that precede cholera epidemics in Bangladesh (McMichael 1993; Garrett 1994; Huq, West, Small, et al., 1984).
- Increased exposure to ultraviolet rays (UV) may result in increased susceptibility to disease (Chapman, Cooper, Defabo, et al. 1995), and in increased mutation rates, with unpredictable effects on the ecosystem as a whole and on pathogen development specifically.

Anthropogenic pressures

- Complex water developments have resulted in increases in breeding sites for vector-borne diseases (e.g., construction of the Aswan High Dam in Egypt and subsequent dramatic increase in schistosomiasis) (Nash 1993).
- Destruction of wetlands has caused a reduction in the capacity of ecosystems to absorb nutrients (Epstein, Ford, Puccia, et al. 1994).
- Deforestation has resulted in decreased retention of water in the soil and decreased infiltration which replenishes groundwaters while increasing the extent of flooding, thereby reducing the overall freshwater resource (Clarke 1993).
- Decreased freshwater and marine fish populations have contributed to changes in food chain structure, resulting in unrestricted growth of "nuisance species" (Todd 1994).

Water uses other than a source for drinking, e.g., recreation, agriculture, and aquaculture, are contributing significantly to eutrophication and introduction of infectious agents. Contamination of water by these uses presents major human health hazards. For example, seafood contamination is a major cause of cholera in coastal regions of developing countries where eutrophication is rampant. The human health and economic costs of contaminated seafood worldwide are enormous.

2. Transmission and Control of Waterborne Diseases

2.1 TRANSMISSION AND CONTROL

Most waterborne disease outbreaks are localized—that is, they are usually confined to a particular city, village or province. However, national and international epidemics do occur, triggered and/or facilitated by international travel, bilge water discharge, animal export, cross-border water flow, food importation, and other means. There is no effective mechanism yet available to prevent intercontinental spread of waterborne pathogens, although vigilance at the potential receiving end can provide a partial barrier. Trade barriers that will stop a microbe cannot be instituted, and attempts to do so can be phenomenally disruptive. For cholera, supplying populations with safe water and sanitation has worked to reduce the incidence, where trade barriers, quarantine, antibiotic prophylaxis, and ineffective vaccines have failed (Barua and Merson 1992). Fortunately, even if a pathogen gains entry into a new community, it may not necessarily spread into the local water supply or survive there if the management system is adequate.

Transmission of pathogens by the water route can be reduced by watershed protection, proper handling of wastewater, and drinking water treatment that removes and inactivates the pathogens. A variety of methods have been established to achieve these objectives. The most significant are:

- establishment of watershed protection programs;
- construction and/or upgrade of wastewater collection and treatment systems, coupled with a higher level of education for the operators of the systems;
- construction and/or upgrade of potable water supply systems, including treatment, distribution, and control of water losses; and
- education of authorities and commercial providers on the regulations and risks associated with commerce, i.e., untreated wastewater discharge from ships, and the need to enact and implement such regulations.

There are a number of approaches that can be taken to ensure that the methods are adopted. Most important is providing information about watershed protection and the risks arising from travel and trade activities that affect water supply and safety. Information on efficacy of various water treatments in removing and inactivating pathogens, as well as the appropriate indicators of efficacy, is not universally available, as well as the economic value of water losses and risks associated with potential contamination of the distribution system. Critical points in water treatment and distribution need to be brought to the attention of the authorities responsible for the safety of public water supplies.

If circumstances, e.g., flooding and other such disasters, are such that it is no longer feasible to provide populations with tap water that is safe to drink, other measures can be used. These measures include educating the population widely and effectively on the fact that bringing water to a rolling boil or treatment with a chemical disinfectant, such as sodium or calcium hypochlorite, are the only direct means of reducing risk of contracting waterborne illnesses. The possibility of using pilot-scale technologies for water purification in countries with sufficient financial resources (microfiltration, nanofiltration, reverse osmosis, etc.) should be pursued. Cheap, effective, and practical technologies that enable water reuse and desalination need to be applied in the future, and research on such technological advances is badly needed (solar distillation and pasteurization are particularly attractive options) (Bailey, Forrest, and Snow 1991).

In developing as well as developed countries, the sanitary survey is an effective means for assessing sources of contamination or problem areas (Geldreich 1990). For example, an unprotected well may yield satisfactory water quality during dry spells, but heavy contamination may occur after rains. That information can be used effectively to mitigate the impact of direct or indirect sources of contamination, even in developed countries, since a decrease in contaminants in source water will likely result in a decrease in endemic illness, regardless of treatment used. Also, sanitary surveys can help anticipate and be used to relieve stress situations for water treatment plants (Okun 1994). The results of these surveys may also lead to a decrease in operating costs and possibly provide a safety factor for plants already operating with conventional treatment. In addition, seasonal and climatic fluctuations in pathogen ecology need to be brought into consideration in water treatment. Only by measuring the difference between what went into the system and what comes out of the tap can engineers determine the efficacy of their treatment systems.

Resource management practices in both developing and developed countries require a multidisciplinary approach. A key component is education of all entities involved as to the importance of good management of water resources. Resource management is incomplete without some emphasis on the importance of controlling microbial disease agents, developing good sanitation practices, and evaluating how agricultural practices contribute to degradation of water quality and cycle disease agents back into the human population. Long-term control of waterborne diseases requires parsimonious use of high quality water resources (e.g., groundwaters) and greater use of marginal quality water (e.g., rivers, treated wastewaters) for less quality demanding uses and for agricultural irrigation (United Nations 1985).

Global transmission of disease is more difficult to control if it is due to the mutation of already existing strains or emergence of new strains of microorganisms. However, it should be recognized that many recent outbreaks of "emerging pathogens" have been caused by a change in the ecological relationship between humans and animals or their ecosystems, rather than representing mutant or new organisms (Wilson 1994). By incorporating knowledge of the ecology of the natural environment into public health training, when such factors are the cause of a disease outbreak, it will be possible to catch the new disease early. Education and readiness of physicians and public health officials is key to prevention of further spread of waterborne disease, but education should include the disciplines of ecology and ecosystems to be effective in the global environment of the 21st century.

It is valuable to understand better the relevant environmental factors, such as climatological events associated with global warming and algal blooms. Algal blooms, for example, can be used as indicators for potential appearance of certain bacterial species (pathogens) in a specific part of the world (see Section 3.7). If conditions for waterborne disease outbreaks can be predicted, interim prevention measures can be instituted in those areas susceptible to the epidemic agent(s). Climatological information can be used also to prepare for disaster conditions, such as monsoons, typhoons, etc., which are linked to degradation of water quality and ensuing risk of waterborne outbreaks. Monitoring of infectious disease-associated parameters by satellite imagery may provide another tool for the public health worker.

2.2 WATER TREATMENT AND SANITATION

Current water treatment technologies for both wastewater and drinking water are adequate, but are often not applied, are poorly applied or are not sufficiently monitored and controlled. Water treatment practices certainly can be improved in most locales, provided that water consumers are made aware of the need, are shown how to accomplish the improvement, and have the financial resources to do so. In developing countries, the use of the simplest type of treatment (e.g., filtration or disinfection or a combination of both) will result in significant improvements in human health if those responsible are educated in the operation and maintenance of the treatment processes and financially enabled to implement them on a wide scale. A key factor to success is the involvement of local inhabitants in the process, including discussion of the cost of water provided by treatment, the benefits of the water treatment, and the need to maintain the treatment process. They must also be educated as to the absolute need to use good sanitation practices to prevent or reduce contamination of their water source.

In developed countries, the range of treatment options is generally more diverse than for developing countries. Treatment processes must still be properly maintained, monitored, and continuously operated to assure their performance. Inadequate, interrupted or intermittent treatment has repeatedly been associated with waterborne disease outbreaks (Moore, Herwaldt, Craun, et al. 1994). Advanced water treatment practices can be improved above conventional pathogen removal and inactivation, but at sharply increased cost. The combined use of disinfectants may be a reasonably economical way to achieve better inactivation of pathogens. Ozone is a potent disinfectant, but the capital costs, as well as cost of operation and maintenance, are far higher than for chlorine. In addition, ozonation still requires post-disinfection to establish a residual in the distribution network, and its byproducts are less well-characterized than those for chlorination (Singer 1993).

New methods of desalination and wastewater reuse provide a major growth area for the future, particularly in semi-arid areas, for irrigation-based agriculture, and for drought-stricken regions. A note of caution, however, is that the fate and pathway of pathogens within such systems are not fully understood, especially helminth eggs, viruses, and protozoa. Epidemiological studies will have to be done before these methods are applied on a mass scale. Acceptability of reuse depends to a large extent on confirmed microbial safety of the reused water and/or the agricultural product. Where water is in short supply, communities may reclaim sewage to use for nonpotable purposes, such as landscape irrigation, cooling, toilet flushing, car-washing, construction, and similar nondirect drinking water applications (EPA 1992). However, raising the background levels of microbial contamination, including parasites, must be prevented and effective monitoring established for the communities directly effected.

2.3 SELECTION OF TREATMENT REGIMES

Selection of a water treatment regime can be based on a multi-tiered approach, implying that there is a cumulative effect of treatment. No distinction is made between developed and developing countries, with the exception that appropriateness of a level depends on local needs, environment, economies, and available expertise:

- Minimum treatment, including large particle removal by sedimentation and subsequent disinfection. This may be an interim solution in a crisis situation. Additional considerations include provision and protection of wells and surface waters and education to raise public awareness.
- Slow sand filtration or other feasible low technology solutions, protection of the distribution network (if one exists), and education on operation and maintenance of systems.
- Replacement of some options with high technology, established methods that require extensive operator training and/or automated systems. These expensive options are appropriate for larger, more affluent communities that have the capacity to maintain and monitor distribution systems.
- Addition of optimized biological filtration, nanofiltration or reverse osmosis.

Drinking water treatment must also be viewed in the context of downstream communities using small or large amounts of raw wastewater for their water source, depending on the body of water from which they draw for drinking water. Treated or untreated wastewater discharged upstream *de facto* becomes the water source for the community downstream. A multi-tiered approach can also be considered for wastewater (National Academy of Sciences, National Research Council 1993):

Populations without collection systems

- For small communities and individual households in areas with low incidence of disease and large receiving areas that do not affect water supplies, wastewater treatment systems may be an inappropriate use of limited resources.
- For small populations, properly located latrines can reduce incidence of disease transmission. A higher technology approach is installation of septic tanks. However, septic system placement must not degrade the microbiological quality of groundwater, especially if it is the drinking water source.
- For larger populations, collection sites can be provided with transport to sewage lagoons or deep marine discharge sites.

Populations with collection systems

- For small populations, coarse screening and sedimentation may be sufficient before discharge.
- A more advanced approach involves lagoons or wetlands with conventional primary treatment, chemically enhanced coagulation with sedimentation, and disinfection of effluents.
- Secondary treatment methods include activated sludge and biological digesters.
- Tertiary treatment for removal of nitrogen, phosphorus, and heavy metals.

It should be emphasized that wastewater treatment results in the accumulation of sludge and pathogens that require proper handling and disposal. In addition, the quantity of sludge increases with treatment level.

Eliminating and preventing contamination of the water supply are two approaches that must be followed in tandem. Any of the above measures can result in significant improvements in public health, as long as the specific treatment is properly implemented and managed. Education of the public is critical to understanding and solving water quality problems, especially those unique to a given community (see Section 5.3).

2.4 TREATMENT COSTS

People will pay for quality and service. Therefore, money can be raised to improve water quality if the public is convinced genuine improvement in safety will be gained. For example, in most African countries, water supplies for rural communities are the responsibility of government, and newly independent governments invariably promise free water to these populations. Governments have had difficulty keeping these promises, and communities have been resistant to planning for themselves if government action is expected. More recently, rural communities in many African countries have, of necessity, taken up maintenance responsibilities themselves. Unserved and underserved urban communities are common. Water utilities are underfunded, usually government owned, and have little control over water pricing. A cycle of poor services, therefore, exists; there is difficulty collecting water revenues with subsequent even greater underfunding, leading to further poor services—a devastating cycle of events. Provision of safe and adequate water supplies at an affordable cost depends on recognition that communities are willing and should pay for the service they want, a service level that can only be reached by consultation with the beneficiary community. Recognition of the value of water, the cost of its extraction, treatment and delivery, and the cost of maintaining these services will result in a significant change in water development and management in the less developed countries. Water pricing based upon the above factors plus taking into account targeted subsidies, incentives, water scarcity, and competing interests could be a significant driving force for improving accountability of utilities, increasing the responsibility of consumers, and linking the quality of water to the demands of the consumer.

In the United States, the earliest water supply systems were built as private, for-profit enterprises. In most cases they were local monopolies and not well-regulated, so that in time their responsibilities were taken over by municipal agencies that were more responsive to consumer needs. An interesting example is in New York City where Aaron Burr, by establishing the Manhattan Company, ostensibly to provide water service, succeeded in his principal objective, the creation of a bank now know as the Chase Manhattan Bank. The quality of water service, both in insufficiency and offensive taste, was so bad that the city was obliged to take over responsibility for the water supply. The greater financial resources of the city were required to provide the first major upland supply from the Croton watershed, which brought water to the city by gravity in plentiful amounts in 1842. The level of investment required simply was not feasible for private enterprise (Blake 1956).

In the peri-urban areas of most large cities in the developing world, the poor are served by privately owned and operated vending organizations at rates to the consumer substantially greater per liter of water than to those who receive piped water. The poor apparently could pay for piped water, but it is the government that has failed to capitalize on the payments made by the poor for water they buy from vendors. This money could help pay back the government funds borrowed to build the pipelines to serve them. Government leadership is required in helping communities provide piped water to all people in a service area through loans which are then repaid by the users at rates far lower than they pay to vendors, with a quality far greater and more reliable in the long run. One obstacle to this solution is widespread distrust of the ability of government to provide the necessary service. It requires both education of the community to take a greater role in local government and a greater commitment of the national and external support agencies (Okun and Lauria 1991). Obviously, a significant condition for a safe urban supply of water is that service be maintained 24 hours per day. Few major cities in Asia, Africa, and Latin America now provide such service. Unfortunately, there are no regulatory pressures in those countries that would help remedy this situation, which is aggravated by its threat to health through the absence of adequate systems of sewerage. An approach to solving the problem through the United Nations and its agencies at the top-most levels of authority might be successful, perhaps providing global standards, as well.

SUMMARY

Global transmission of waterborne diseases cannot be prevented—travel and trade are too extensive. Risk of disease must, therefore, be controlled at the community level by provision of uncontaminated water and basic sanitation. To prevent transmission of waterborne disease, a holistic system approach of water management is recommended, including watershed protection, drinking water treatment and distribution, and wastewater collection and treatment.

Low technology options and education should be a priority for developing countries in meeting immediate needs, but, ideally, a multidisciplinary approach should be taken that includes sanitary engineers, microbiologists, epidemiologists, and public health officials, as well as politicians and the media. Health risks posed by microbial pathogens should be placed as the highest priority in water treatment to protect public health.

Pathogens responsible for the large percentage of waterborne diseases of unknown etiology must be identified, i.e., brought out of obscurity and made the focus of the search for new knowledge about microbiological safety of water. This information is essential for developing control strategies, such as appropriate treatment and monitoring systems, for the 21st century.

3. Water Quality Standards and Monitoring

3.1 INDICATOR ORGANISMS

The purpose of quantifying the presence of "indicator" microorganisms is to predict occurrence of a specific pathogen or group of pathogens. Currently, a useful indicator is considered to be one that is present when a pathogen is present; it should be present in sufficient concentrations to be easily detected before and after water treatment. The best indicators should clearly correlate with the public health risk of infection. Current water quality monitoring standards employ total coliform counts, thermotolerant coliform counts, and, in some cases, *Escherichia coli*. It must be recognized that these indicators were developed in the early 20th century as a measure of general water sanitary quality. They remain useful in this regard and as a measure of the efficiency of water treatment processes. However, in tropical climates, indicators such as *E. coli* can grow in the absence of fecal contamination and, therefore, their usefulness is limited. This is true as well for developed tropical countries (Rivera, Hazen, and Toranzos 1988).

At least in temperate climates, *E. coli* remains a useful indicator of recent fecal pollution, and its presence in drinking water has been considered a reasonable predictor of the likely presence of bacterial pathogens. However, the presence of *E. coli*, either before or after chlorination, does not correlate with the presence of protozoan parasites or viruses and, for that reason, should not be used as an indicator for these groups of organisms (Rose, Gerba, and Jakubowski 1991; Payment and Armon 1989). In addition, *E. coli* does not correlate with the presence of pathogenic bacteria from environmental sources, such as *Legionella*, *Vibrio cholerae*, and the mycobacteria, nor are survival times of *E. coli* in water necessarily longer than enteric pathogens. Furthermore, *E. coli* in the viable but non-culturable stage in the environment, e.g., river water in late fall or winter, would not be detectable by standard bacteriological culturing methods (Roszak and Colwell 1987). Factors that affect the survival of indicator organisms/pathogens in natural waters are given in Appendix 2.

3.2 SPECIFIC CONSIDERATIONS FOR DEVELOPING COUNTRIES

Developing countries tend to adopt water quality guidelines and standards of developed countries, even though risks and climatic conditions may be very different. Practically, at least initially, it is more important to emphasize disinfection and residual disinfectant monitoring over indicator testing. However, testing for indicator microorganisms can be useful for monitoring process efficiency, as is done in developed countries. Removal of fecal pollution from drinking water is a primary goal for developing countries. Given the limitations of indicator organisms, described in Section 3.1, achieving drinking water in which *E. coli* is not detectable by reliable methods is helpful as a presumptive step toward reducing risk. Reaching this goal is important, but efforts also should be taken to ensure that more persistent pathogens (protozoans, viruses) are also removed.

At the present time, chlorination is the principal disinfectant used in water treatment, with risks associated with chlorination byproducts being considered far less significant compared to consequences of waterborne disease. Monitoring residual disinfectant, therefore, should be a priority. Total coliforms can be monitored at sampling sites within a distribution system, as an indicator of loss of system integrity, regrowth or treatment deficiencies. Thermotolerant coliforms and/or *E. coli* may be monitored as potential indicators for fecal pollution; in the case of raw source water, regular monitoring for the presence of thermotolerant coliforms and/or *E. coli* is a minimum step in assessing risk of disease transmitted by water. Having stated these considerations, there are a number of further concerns that cannot be ignored. Specifically, appropriate sampling techniques and a sampling strategy are essential for adequate monitoring. Microbiological monitoring must be done by technical staff trained in microbiology. In addition, field and laboratory technicians should be well trained and a quality assurance system implemented. Monitoring programs should be evaluated to ensure data cover seasonal conditions and adjusted when necessary, e.g., when heavy rainfall occurs, more intensive monitoring may be needed. At the regional level, suitable laboratory facilities should be available for further testing when there is evidence that the population is being exposed to pathogenic bacteria, protozoa, and/or viruses. Inter-agency networks to coordinate and manage response to microbiological water quality threats and emergencies, both at the national level and internationally, must be established, preferably coordinated through an international body or organization.

3.3 SPECIFIC CONSIDERATIONS FOR DEVELOPED COUNTRIES

At present, thermotolerant coliforms and/or *E. coli* comprise the principal indicators of fecal contamination and predictors of the *potential* only for outbreaks of bacterial disease. New methods for pathogenic bacteria, viruses, and protozoa are badly needed and should be adopted as soon as available (Payment and Franco 1993). At the present time, there is considerable debate as to what the best indicators will be or whether direct detection of pathogens should be sought immediately or in the future. To be practical, new tests must be reliable, rapid, inexpensive, sensitive, and specific for indicating potential public health risks. It is possible that a hierarchical structure of standards could be employed initially, based on appropriate indicators, water treatment availability, monitoring capability, health status/risk, and cost/affordability.

Pragmatically, monitoring for thermotolerant coliforms, using first line methods, such as presence/absence tests, will continue to be employed until the newer, molecular genetic-based methods are available for routine application. Monitoring for the usual indicators, such as total coliforms, thermotolerant coliforms, and *E. coli*, using standard methods, will very likely accompany initial application of newly developed methods, the latter complementing routine monitoring and directed at detection of specific pathogens considered a risk in the setting under surveillance. Methods for direct detection of many potential pathogens or their surrogates must be developed. Furthermore, the choice of indicators for any pathogen or group of pathogens must take into account the climate and type of water, at least until direct detection of pathogens in these waters can be employed (Toranzos 1991).

The ability to detect specific pathogens is on the horizon. The use of tests for specific pathogens raises the question of whether indicators should simply be used to monitor treatment efficiency or whether they should also be applied to permit assessment of water quality assurance for public health. There is a difference of opinion as to whether direct testing for human pathogens will be useful. For example, some water utilities consider the number of *Cryptosporidium* in water sources is generally too small to recommend direct testing for this pathogen, especially since current tests are not fully reliable and are expensive. However, despite deficiencies in test methods, a national survey has already been conducted in the United Kingdom on incidence and distribution of *Cryptosporidium* (National *Cryptosporidium* Survey Group 1992), and the U.S. EPA has instigated an Information Collection Rule, which includes a requirement that each public water utility estimate concentrations of *Giardia* and *Cryptosporidium* in its source water (Environmental Protection Agency 1994). There is no doubt that these types of data are needed and will be valuable. Thus, the attitude of water utility managers is already changing as better methods of detection become available. Monitoring for specific pathogens will assist final water quality assurance, provided the test results can be obtained in a relatively simple, cost-efficient manner. If the capability for microbiological testing is not available, surrogate indicators for water quality allow a crude assessment of treatment effectiveness, e.g., monitoring particle concentration (turbidity or specific particle counting) or spore forming bacilli (as an indicator for protozoa) (LeChevallier and Norton 1992; Payment and Franco 1993).

Rapid environmental tests serve an important role. For example, cryptosporidiosis is a springtime disease in cattle and occurs mainly at calving time when the young animals are highly susceptible. However, the parasite is always present in some adult animals which act as reservoirs of constant recontamination. Spring run-off increases the risk of failure of treatment because high turbidity levels challenge treatment facilities. Furthermore, in temperate climates, this is a time when water is cold, disinfection efficiency is low, and recovery of *E. coli* less effective.

3.4 ALTERNATIVE INDICATOR/INDEX MICROORGANISMS

Development of new technologies for water microbiology analysis is generating its own controversies. With an array of tests for a variety of pathogens and indicator organisms, the question of which organism(s) to look for becomes problematical. The appropriate pathogens to monitor depend on features of the water catchment and local health situation.

Enterococci may substitute for thermotolerant coliforms as indicators of fecal contamination, particularly in tropical waters (McNeill 1992). Many of the disinfectant-resistant pathogens survive far longer in drinking water than the coliforms. In the case of water contaminated with human sewage, resistant pathogens may be monitored by the presence of the spore forming bacterium, *Clostridium perfringens* (Payment and Franco 1993).

In distribution waters, aeromonads appear to be the most sensitive group to indicate loss of disinfectant residual and/or biofilm regrowth potential (Havelaar, Versteegh, and During 1990; Ashbolt, Ball, Dorsch, et al. 1995). It is unclear at this stage whether routine monitoring of regrowth of other pathogens is appropriate, such as *Legionella pneumophila* or various *Mycobacterium* spp. Aeromonads may also give an indication of the degree of nutrification of receiving waters (Araujo, Arribas, and Pares 1991), and some members are opportunistic pathogens (Kueh, Kutarski, and Brunton 1992; Krovacek, Pasquale, Baloda, et al. 1994).

Human enteric viruses have regularly been reported in waters meeting current water quality criteria (Payment and Armon 1989; Gerba and Rose 1990). Furthermore, virus presence is severely underestimated, not only because of reliance on inefficient and/or ineffective culture methods, but also because of the target groups that are monitored. Coliphages are considered by some investigators to be useful in predicting the likelihood of pathogenic enteric viruses surviving treatment of drinking water or present in recreational water (Havelaar 1993). The human specific *Bacteroides fragilis* HSP40 bacteriophage has been proposed as a surrogate for human enteric viruses in seeding experiments or survival studies (Tartera, Lucena, and Jofre 1989). However, the presence of this bacteriophage does not necessarily mean human viruses are present and does not offer reliable correlation with presence of human viruses, although further research in warranted (Tartera, Jofre, and Lucena 1989). Relationships between bacteriophages and human enteric viruses need to be proven for a wide range of sites and types of treatment. There may be some potential value in the use of pathogen specific phages.

3.5 FLUORESCENT ANTIBODY/DNA PROBE TECHNOLOGIES FOR PATHOGENS

The past two decades have witnessed rapid development in areas of biological sciences, notably molecular and cell biology. A variety of new tools for detection and analysis of a wide range of biological molecules now exists. Over the same time period, there have also been major advances in electronics and laser physics, enabling the development of devices that can collect, process, store, and transmit large amounts of information. These advances are resulting in new technologies which have the potential to replace or supplement traditional techniques for monitoring indicator bacteria. At the research level, powerful new methodologies are emerging to detect both specific pathogens and indicator organisms. These new methodologies include antibody techniques, gene probes, electrorotation, PCR, flow cytometry, and biosensors (Vesey, Narai, Ashbolt, et al. 1994). Many of the techniques offer the prospect of almost instantaneous or "on-line" analysis and, thus, the potential for rapid response to most microbiological problems of public health significance. These technologies are already leading to a much better understanding of the ecology of environmental pathogens. More information on these technologies is given in Appendix 3.

3.6 INDICATORS FOR RECREATIONAL USES OF WATER

It has been established by a number of epidemiological studies that exposure to polluted bodies of water during recreational use (swimming, canoeing, surfing, windsurfing, etc.) is associated with disease (Dadswell 1993; Van Asperen, de Rover, Schijven, et al. 1995). As is the case for drinking water, total and thermotolerant coliform levels have also been used as indicators of fecal contamination in recreational waters. This may be acceptable for temperate waters; however, as discussed above, coliforms give no indication of health risks from protozoa or viruses, especially for marine waters, where coliform bacteria have been shown to lose culturability on routine bacteriological media more quickly than loss of recoverability of the viruses (Gerba, Goyal, LaBelle, et al. 1979; Dufour 1984). In addition, it has been shown that *E. coli* in seawater goes into the viable but non-culturable state, rather than dying off—leading to erroneous conclusions about public health safety (Pommepuy, Butin, Derrien, et al.; Xu, Roberts, Singleton, et al.1982). As part of a study by the EPA for reassessment of ambient water quality standards, Cabelli et al. (Cabelli, Dufour, Levin, et al. 1979), performed an epidemiological investigation of water quality and health effects at marine beaches. Water samples were analyzed for coliforms, enterococci, *Pseudomonas*, and *Clostridium* bacteria as possible indicators. A correlation was demonstrated between enterococci bacterial levels in water and excess gastrointestinal illness in swimmers using the water. Recommendations by the EPA in the 1986 Ambient Bacteriological Water Quality report (Environmental Protection Agency 1986) suggested that 35 enterococci/100mL related to a risk of 19 illnesses/1000 swimmer-days. Few states and very few countries outside the U.S. have chosen to use the enterococci as a monitoring tool for examining recreational waters.

3.7 BIOLOGICAL INDICATORS OF VULNERABILITY TO EMERGENCE OF PATHOGENS

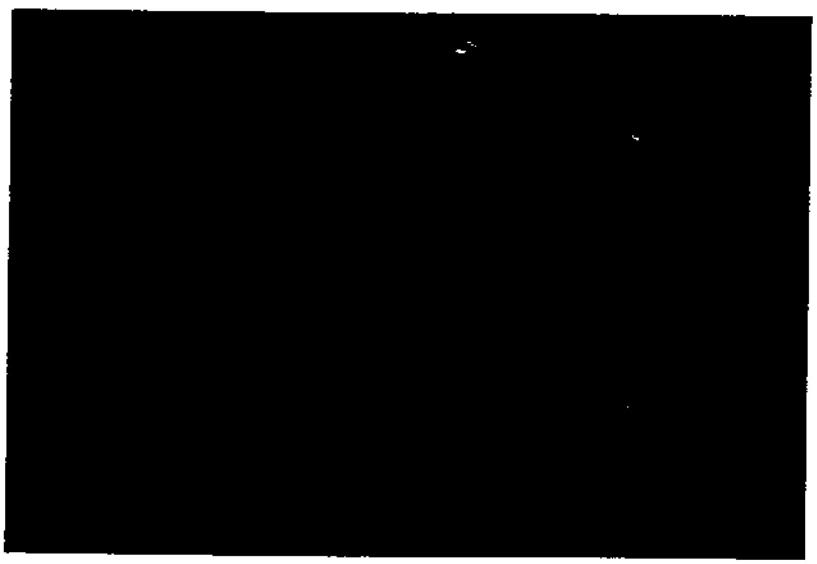
Multiple factors contribute to eutrophication and excessive algal blooms in fresh, estuarine, and marine waters. These include elevated temperature, excess discharge of nutrients from sewage, fertilizer application, airborne nitrous oxides, loss of wetlands, coral, mangroves, and loss of fish (Epstein, Ford, Puccia, et al. 1994).

Eutrophication and algae integrate multiple ecosystem functions and may harbor and help amplify multiple pathogens. For example, *Vibrios*, pseudomonads (and other gram negative rods) attach to sheaths of *Anabaena variabilis*, duckweed, water hyacinths, and to plankton (Epstein, Ford, and Colwell 1993). In addition, phytoplankton are food for zooplankton which have been shown to amplify and transmit *V. cholerae* (Huq, West, Small, et al. 1984). As indicators of ecosystem function and ecosystem stress, plankton may serve as key links between environmental monitoring and health surveillance. These key biological indicators may thus help simplify and integrate environmental and health programs and serve to meet the collaborative needs of such institutions as, for example, the United Nations environmental and biodiversity programs and those of WHO. Greater multidisciplinary, interagency-sponsored research is needed in integrative monitoring. Projects that integrate research and ecosystem management may begin to incorporate these biological indicators of vulnerability. Integrated programs of environmental monitoring and health impact assessment may serve the needs of global observing systems that are now in the planning stage for the next century.

SUMMARY

Water microbiology has depended on the use of bacteria that indicate recent fecal contamination, mainly the thermotolerant coliforms. It is now established that dependence on such traditional indicator bacteria can be misleading, especially since *Escherichia coli* has been found to grow in source waters in the absence of fecal contamination, leading to false positive results (Hazen and Toranzos 1990), and both pathogenic protozoa and viruses of fecal origin can be present in water when indicator bacteria are absent (Rose, Gerba, and Jakubowski 1991; Payment and Armon 1989). This problem is compounded by use of disinfectants that kill indicator bacteria, but spare pathogenic protozoa because of their resistance to chlorine. A further confounding fact is that indicators of microbial water quality, initially developed in and for temperate climates, were applied in tropical areas without, necessarily, the same value or significance. Other more appropriate indicators for the tropics are needed or, at the least, use of present indicators should be validated.

Coliform counts are, nevertheless, still useful in monitoring the success or failure of treatment processes, but clearly are not adequate to address potential waterborne risks. The indicator concept should include indicators that more directly reflect health risks, as well as surrogates for removal/inactivation of viruses and parasites. More appropriate, however, is testing for specific pathogens/indicators directly in source water, with the expectation that reduction in their number will occur with treatment. However, many pathogenic organisms will not be detected using currently employed techniques for testing finished water, but, rather, require more sophisticated methods, including molecular genetic approaches.



Cells of *Vibrio cholerae* 01, biotype ElTor, serotype Inaba, (strain ATCC 25870) stained with fluorescein isothiocyanate labeled monoclonal antibody. Courtesy of Bing Xu, Anwar Huq and Rita Colwell, University of Maryland Biotechnology Institute, Maryland.

4. Present and Future Risks

4.1 SUSCEPTIBILITY TO WATERBORNE DISEASE

Many factors contribute to the risk of waterborne disease. A change in any one of these factors or a combination of events can increase the potential risk. Urbanization is a good example. Urbanization necessarily means an increased density of people in a given area, which can result in increased competition for water resources, increased potential for person-to-person transmission, and, therefore, increased risk of disease. A consequence of urbanization is increasing population; this leads to increased demand for the finite resource, resulting in increased water reuse.

It also results in the need to increase food production, which leads to increased competition for water. Increasing population also means a greater potential for water contamination as a result of the increased quantity of waste produced. Associated with increased food production are changes in agricultural production methods. In many areas, animal operations are increasingly being carried out under high density conditions, oftentimes in close proximity to urban development. The proximity of animals and humans can lead to an increase in transmission of animal pathogens to humans.

Demographic changes also contribute to the risk of waterborne disease. As life expectancy increases in developed countries, there is an increase in the number of elderly people, who have an increased susceptibility to microbial infection with more severe consequences. In addition, there are worldwide increases in immunocompromised populations. Deteriorating economic conditions result in a reduction in resources available for water and wastewater treatment and a decrease in sanitation conditions, in general. A serious consequence is deterioration of delivery systems in developed countries and inadequate delivery systems in developing countries. Inadequate wastewater disposal and treatment capabilities cause an increase in microbial contamination of water and increased risk of microbial disease. Multiple infections decrease resistance.

Unstable political and environmental conditions, such as wars, famines, and floods, displace populations and are associated with epidemics, examples of which were cholera outbreaks among Rwandan refugees in 1994.

Prediction of disease rates and/or outbreaks is determined by human settlement conditions, poor housing conditions, the water supply situation, sanitation installations, stormwater systems, and solid waste handling. Waterborne disease occurrence must also be seen in a socio-economic context. For example, intra-urban health differentials lead to 5-10 times higher infectious disease rates in peri-urban areas than in the affluent inner cities (Bradley, et al. 1991). Lack of utility services, overcrowding (person-to-person transmission), and lack of personal hygiene are root causes for high endemic disease rates.

Problems are acute in estimating risks from new and emerging pathogens. For example, hepatitis E virus (HEV) causes devastating waterborne outbreaks in some parts of the world but not in others (e.g., 79,000 cases occurred in Kanpur in 1991 caused by sewage-polluted drinking water). Newly developed technology provides evidence that HEV is endemic in many parts of the world, where few, if any, clinical cases are seen. These seemingly anomalous findings suggest less virulent strains of the virus may exist. However, critical questions include: (1) what factors cause these strains to become more virulent and (2) what environmental conditions favor outbreaks on the scale of Kanpur? (Grabow, Favorov, Khudyakova, et al. 1994)

Other factors that may be increasing susceptibility to waterborne disease risks include global warming and ozone depletion. Global warming may increase evaporation rates, causing reductions in water supplies, particularly in drought susceptible areas. Increased heat elevates public demand for water, both as a coolant and for hydration. Warming changes weather patterns that can cause severe floods, droughts, and unusually heavy rains. These, in turn, exacerbate local water contamination and stress even advanced treatment technologies. Furthermore, there is evidence linking water warming to eutrophication, changes in microbial community structure (Cherry, Guthrie, and Harvey 1974), and toxic algal blooms (Epstein, Ford, and Colwell 1993).

Ultraviolet (UV) solar radiation appears to be increasing, due to ozone depletion. Certain components of the immune system are present in the skin, which makes the immune system accessible to UV radiation. Experiments in animals show that UV exposure decreases the immune response to skin cancers, infectious agents, and other antigens, and can lead to unresponsiveness upon repeated challenges. Suppressed immunity may occur either locally in sun-exposed skin or systematically, at nonexposed sites. Results of studies involving human subjects also indicate that exposure to UV-B radiation can suppress the induction of certain immune responses and may cause systemic alterations in immune function. The importance of these immune effects for infectious diseases in humans is unknown. However, in areas of the world where infectious diseases already pose a significant challenge to human health, and in persons with impaired immune function, the added insult of UV-B-induced immune suppression could be significant (Chapman, Cooper, Defabo, et al. 1995.).

4.2 MEASUREMENT OF WATERBORNE DISEASE RISK

How is waterborne disease measured? There is a spectrum of endpoints for measurement of disease, from natural immunization through gastroenteritis to death. In addition, economics must be considered, including time lost as a result of waterborne disease, expense of clinics, drugs, lost international trade, and the cost of behavior to avoid disease, such as boiling and carrying water (Okun 1991). To determine attributable risk, we need to specifically link recognized endpoint events to water as a vehicle and obtain numbers for morbidity and mortality.

Major obstacles are the limited public health infrastructure and trained work-force available for implementation of surveillance programs. However, just as national cancer registries have been developed, reporting and documenting infectious disease should go beyond those which are currently reportable. Hospital discharge data bases and other types of records are kept, with little effort to synthesize, compile, and interpret the data in regard to the role played by microbial contamination of water. The major difficulty is that morbidity is very problematic as a measure of system failure because most illness goes unreported, disease is often misdiagnosed, and illness may not appear significant even to the sufferer (Payment, Richardson, Siemiatycki, et al. 1991). Further, some of the most profound morbidity outcomes may be difficult to ascribe to a specific infection, such as malnutrition, immunodeficiency, and growth stunting, each of which may be the long-term result of childhood diarrhea (Taren and Crompton 1989). Even solid hospitalization records amassed during an outbreak will represent only a modicum of the total epidemic burden. The one reliable clinical indicator is mortality and then only if the etiologic cause can be determined. If mortality is significant, however, the system has utterly failed. In developing countries diarrheal disease is multifactorial and extremely common, making it inexpedient to bother ascribing specific etiologies to individual cases. In developed countries the index of suspicion among physicians for rare or newly emerging organisms is so low as to preclude requests for laboratory analysis, as occurred during the recent *Cryptosporidium* outbreaks in the U.S.

In developing countries routine clinical microbiology and pathology is limited to the most common endemic organisms and may take a considerable amount of time, which is in short supply during an outbreak. In developed countries, where a broader range of tests and technology may be available, there are still significant time lags in both recognition of the need to order such tests and in the speed of the laboratory diagnosis. Viruses and slow growing bacterial pathogens are not easily identified in water samples and the methods required are not readily available, especially for viable bacteria present but not culturable by the methods/media currently available (Roszak and Colwell 1987).

4.3 QUANTIFICATION OF RISK

To quantify and prioritize risk, better information on the status of water supply systems and infectious disease facts on a world-wide basis is needed. These data should be made available in published form and regularly updated. The demographics of who are affected should be recorded. Data on how individuals are affected, the types and severity of diseases, and productivity losses, in addition to medical costs, are needed to provide quantifiable end points of reference. These data can provide the basis for cost-benefit analysis, comparative risk analysis, and risk-based prioritization.

Severity of risk depends to some extent on the vulnerability of exposed populations and pathogenicity of the microorganism, i.e., infectious agent. The same level of microbial contamination of water may have different health consequences, depending on the age of the host, underlying disease, and previous exposure to pathogens. Entry may be via the respiratory tract, skin, conjunctivae, as well as via ingestion. Those at highest risk include infants in developing countries and the immunocompromised and elderly individuals in both developing and industrialized nations. In general, the indigent bear a disproportionate share of the disease burden related to water scarcity and water contamination. However, the middle and upper classes are also at risk during epidemics from, for example, infrastructure and disinfection failures, as well as through both direct and secondary spread. Large, unrecognized, uncounted populations that include squatters, "street people", i.e., the homeless of industrialized countries, refugees, and illegal migrants are excluded from calculations of water and sanitation coverage, resulting in falsely inflated coverage estimates and/or underestimated risk.

4.4 COST-BENEFIT ANALYSIS

Cost-benefit analyses are important in prioritizing risks. To estimate the benefits, data on the relation between water quality and health need to be generated by integrating the complementary approaches of risk assessment and ecological and human epidemiology. To achieve this, however, there is a clear need to improve risk assessment methodology, to design better sampling strategies for epidemiological studies, to recognize sentinel events as predictors for outbreaks, to improve typing methods for disease causative agents, and to clarify the relative roles of disinfection by-products and microbiological agents. A number of problems need to be addressed, including cost; data, which are seldom readily available; inability to assess virulence/infectivity of organisms; inadequacy of viable pathogen detection limits; existence of unknown agents; inadequate design of sampling programs for spatial and temporal variations; and limitations to models for fate and transport assessment.

The social cost of the so called "mild" gastrointestinal illness in industrialized countries is several orders of magnitude higher than the costs associated with acute hospitalized cases. For example, in the U.S., it was estimated in 1985 that the annual cost to society of gastrointestinal infectious illnesses was 19.5 billion dollars (US) for cases with no consultation by a physician, 2.75 billion dollars for those with consultations, and only 760 million dollars for those requiring hospitalization (Garthright, Archer, and Kvenberg 1988; Roberts and Foegeding 1991). These estimates do not address deaths associated with these illnesses, particularly in children, immunocompromised populations, and the elderly. The costs of gastrointestinal illnesses, alone, and the number of hospitalization and deaths were only recently analyzed by Gangarosa, Glass, Lew, et al. (1991).

Using a database that contains about one-sixth of the total number of hospitalizations in the U.S., these authors calculated that 87,181 hospitalizations and 514 deaths were due to gastrointestinal illnesses from all sources, of these 62% were in adults. Assuming that these account for only one-sixth of the cases: in 1985, about 500,000 hospitalizations and 3,000 deaths were due to gastrointestinal illnesses in the U.S.. the majority of unknown etiology. These numbers are likely to be a gross underestimate due to unreported or unanalyzed illnesses. Over 13% were due to viral illnesses while 4.9% were bacterial and 1.1% parasitic. Canadian researchers (Payment, Richardson, Siemiatycki, et al. 1991) have observed that 35% of gastrointestinal illnesses were waterborne. Other diseases, such as gastritis due to *Helicobacter pylori* infections, could also be transmissible by the water route. Although the risk of this route has not been well documented. the evidence is becoming stronger (Klein 1991).

A decrease in morbidity and mortality is not the only benefit which should be considered in a cost benefit analysis. In general, the benefits of microbiologically safe water should be carefully considered, especially since such benefits go beyond the absence of disease, and affect the productivity of industry, as well as the prices of goods and services.

4.5 DECISION THEORY

Current understanding of the health consequences of consumption of pathogens in drinking water is imperfect, at best. Dose-response relationships have only recently been developed and are available for only a limited number of organisms (Rose and Gerba 1991). In addition, measures of population exposure to pathogens in community water supplies are imprecise, due to limitations in the methodologies discussed in Section 3. To decision makers and public officials responsible for providing safe water and protecting public health, these uncertainties pose obstacles that may make it more difficult to choose appropriate strategies for water supply, water treatment, and waste disposal. These may be overcome only by gathering the scientific data needed to improve our understanding of waterborne exposure, infection, and disease.

Despite efforts to gather good scientific data, uncertainties will exist. Decision theory provides a framework for decision making under uncertainty and, therefore, offers a way to address this dilemma. According to the tenets of decision theory, options which lead to the highest expected utility or lowest total social cost are preferred. The underlying concept is that these choices maximize social welfare when averaged over a large number of decisions.

Decision analysis and risk assessment provide insights, not only about the choice of control strategy, but also about the value of alternative research strategies. Recently, these approaches have been applied to a number of problems in environmental risk management. They can provide insight about control and research strategies for dealing with waterborne pathogens. There are numerous publications that describe the applications and limitations of risk management and decision theory (Finkel and Evans 1987; Lindley 1988).

4.6 COMPETING HEALTH RISKS

Other areas of health risk associated with water quality that are currently receiving public attention are toxicity of disinfection byproducts and the potential for transfer of antibiotic resistant factors via drinking water. Existing water treatment processes do produce some undesirable side effects, including some inadequately characterized risks of chronic disease and, in some cases, materials that support bacterial growth. However, chlorine and other reactive chemicals had been used successfully for more than 60 years to control waterborne infectious diseases before it was recognized that they produce a variety of byproducts. Some of these by-products have been found to be associated with a variety of toxicological effects, including cancer and birth defects, when administered at high doses to experimental animals. While the collective epidemiological and toxicological data suggest that there may be some risk to human health associated with disinfection by-products, the magnitude of these risks is very uncertain (Morris, Audet, Angellillo, et al. 1992; Murphy 1993). It is important to point out that there is no direct and conclusive evidence that disinfection by-products (DBPs) affect human health at concentrations found in drinking water (Bull 1993). Therefore, it is too early to suspend the use of simple, well established, and valuable public health measures without a much more thorough evaluation of these risks based on direct human data (Craun 1994). Concerns over the toxicology of DBPs should not be allowed to compromise successful disinfection of drinking water, at least without data to support such decisions.

The risk of waterborne transmission of antibiotic resistant bacteria will be decreased by adequate treatment of drinking water supplies, as well as sewage. Such measures reduce pathogen circulation within the community, as well as the ecosystem, and opportunities for emergence of bacterial resistance, either by mutation or transfer of genetic information from normal flora to pathogens. Antibiotic resistant waterborne pathogens may well be a problem if treatment is not adequate to eliminate them, but that problem is potentially so large in scope that it will be addressed in greater detail in a future report. Antibiotics in agriculture, animal husbandry, and aquaculture may present problems for drinking water by promoting resistance in environmentally transmitted pathogens or as residues. It is also possible that antibiotic activity may directly contaminate water sources due to the very large amounts of antibiotics that are used in these activities, e.g., to combat diseases of fish in intensive aquaculture.

National and international policy formulated to control water-related disease requires a base of protection against the risk of infectious disease, minimizing both microbially- and chemically-induced disease. However, solutions to problems of DBPs and antibiotic resistance require strong, coordinated, and on-going research programs to provide, not rigid, uniform standards, but rather guidelines allowing adaptation to the varying conditions of water supplies of individual communities, states, and nations. It is very important to recognize that the priorities will vary, and must do so, depending upon local rather than national and international conditions. Requirements for well-water based drinking sources are different from those where riverine or brackish water sources receiving sewage wastes, either treated or untreated, serve as the drinking water source.

SUMMARY

Current and future challenges in developed countries involve decisions of how to assure that drinking and source water are safe in a time of increasing demands on public funds and resources. This raises the issue of how to quantify the economic importance of good quality water. The recent outbreaks of cryptosporidiosis in the U.K., U.S., and Canada offer good examples of the potential enormous negative economic consequences of providing contaminated water in a developed country.

The recent massive cholera epidemics in Latin America and Southeast Asia constitute a significant increase in waterborne disease outbreaks and fatalities (Tauxe, Seminario, Tapia, et al. 1994). The perception of increased waterborne disease outbreaks is supported by increases in urban, underserved, and susceptible populations. Sanitation and water supply have been outstripped by population growth. It may be possible that the increasing number of immunocompromised individuals create an amplifier effect for certain enteric pathogens (Garrett 1994). Political upheaval is a significant contributing factor; refugees are a special high risk population overwhelming available water and sanitation infrastructure. Other factors include natural disasters, such as the floods that occurred in the Mississippi basin, which resulted in sewage contamination of private wells and increased incidence of gastroenteritis.

Comparative risk evaluation and public education and awareness raising via the media and schools are needed on a massive scale, with the prime objective of human health improvement. Professional organizations involved in these issues should be the source of press kits, fact sheets, and appropriate scientific documents highlighting the decline in microbiological safety of drinking water and its sources and the need for active surveillance of agents of waterborne disease, as well as incidence and occurrence.

5. Policy and Education-related Issues

5.1 RESPONSIBILITIES OF ORGANIZATIONS AND SOCIETIES

Responsibility for safe clean drinking water is shared by multidisciplinary segments of society. The role of health organizations, water utilities, government, and industry are all intertwined and all of these groups must interface and build coalitions, based on mutual concern for safe drinking water. Common goals must be recognized and processes for information and data sharing need to be developed if appropriate prioritization is to be given to microbial contaminants and safe water issues. Scientists and scientific societies are the key to providing education and the necessary data and should interface with various disciplines and groups involved. Clearly, communication is important; the media, whether print, radio or television, are the conduit to the public.

Much of waterborne disease prevalence is linked to poverty. Thus, targeted programs to improve environmental health (water supply, sanitation, overcrowding, etc.) must be interlinked with poverty alleviation programs. Two target groups most affected by waterborne diseases should be addressed: rural areas and peri-urban populations.

Almost all water systems worldwide are dependent on a limited range of funding sources: local and federal government; the World Bank; regional development banks; and United Nations agencies. These funders represent a powerful, perhaps primary source of pressure for change. Many international agencies invest in capital development, but do not invest in "in-country" institutions. The focus needs to be placed on investing resources in developing local opportunities for risk reduction.

Funding for water project development should be linked to demands for the following:

- Accountability: Is funding directed in a cost-effective manner?
- Public access to information regarding water quality.
- Standardization of treatment and monitoring technologies.
- Notification: A clear requirement that all outbreaks and deteriorating water quality that might cause a risk to health be publicly reported, particularly to public health authorities and to the public at large.
- Sustainability: A requirement that institutional capacity be adequate to manage facilities and particularly to assure cost recovery, at least for operation and maintenance.
- Public education.

Some governments have done much to improve their water quality situations; for example, Chile stopped fertilizing vegetables with raw sewage and saw a decrease in typhoid fever and hepatitis A. Costa Rica spent relatively more on water, sanitation, education, and health, and less on defense, than its neighbors. It has been relatively free from cholera, despite epidemic activity in surrounding countries (Levine 1991; Mata 1994).

5.2 ECONOMIC FACTORS

Consistent economic underrating of the true value and costs of water has been recognized as one of the root causes of the deplorable state of many water supplies (Dublin Water Conference; 1992; Rio conference 1992). The economic factor, the value of clean water, needs to be recognized and emphasized as an important force to drive local governments and global associations into action. Accurate valuation of clean water is necessary if costs and benefits are to be correctly estimated. The cost of not providing clean water is dependent on the value of this commodity to individuals, business, and governments. Factors which influence the value of clean water include (1) the availability of water (scarcity increases value), (2) income (increased income expands consumption choices), and (3) information (the accuracy and completeness of information available to the individual concerning the benefits of clean water). Therefore, a certain level of basic education is necessary for assimilation of such information.

Clean water also has value to commercial industry as a production resource. Absenteeism by the workforce caused by waterborne illness adversely affects industrial output. Additionally, clean water is required as a resource in, for example, food and beverage, restaurant and hotel, pharmaceutical and fine chemical, and health care industries. Failure to provide this commodity incurs costs to business and can result in loss of opportunities for economic development and growth. Governments should value clean water directly because it has an impact on government workers and tourism revenues and indirectly as it affects tax revenues. Productivity losses for business and individuals decrease tax revenues while productivity gains increase such revenue.

The economic impact of infectious disease was clearly illustrated by the cost to India of the 1994 plague outbreak in Surat. In terms of lost tourism, trade and other forms of income, losses were estimated (by the Indian Government) to be two billion dollars (India Today magazine 1994).

5.3 EDUCATION ISSUES

There are several targets for educational efforts related to waterborne diseases in both developed and developing countries. These include government authorities, legislators, administrators, industrialists, community leaders, teachers, journalists, and the general population. Education efforts depend on the existing educational infrastructure of a particular country, but can, and should, include formal education at the school or college level, adult and continuing education programs, workshops, and community-based efforts through distribution of pamphlets or other media. Television can be used effectively and surprisingly may reach remote areas of the world when other means of communication may fail. Cultural misconceptions about water quality should be targeted. For example, resistance to the "taste" of boiled water in many developing countries is a social custom that needs to be overcome through education. The population must be empowered with information in order to effect change at the government level and demand action on water quality issues.

A two-pronged effort is needed: (1) families and communities must be educated where central water treatment and distribution are not available and (2) where there is central treatment and distribution, emphasis must be on maintaining, managing, and improving treatment and distribution. Good hygiene, appropriate maintenance and safety of water delivery systems, and storage of water in the household are critical. Hygiene education is the key, preferably of school children, who carry the messages into their families. In addition, early education will help generate behavioral change over time. A high literacy rate of women is the long-term basic goal to improve the health situation within families and communities. Numerous studies have shown that the overall educational status of a mother is a significant marker for diseases of all infectious kinds in her children (U.N. Chronicle 1990). In any education program, it should be emphasized that good nutrition reduces susceptibility to waterborne disease, and improvements in habitation and general sanitation are important preventive measures.

In developed countries, there has been a decline in higher education for water-related issues. For example, the number of programs in the U.S that train microbiologists at the graduate level has decreased significantly in the past two decades. Within industrialized countries, more support is needed for education and training in public health microbiology. In addition, there is a clear need for graduate level training in other disciplines related to water quality and supply, including chemists and engineers. There is also a need to train microbiologists, chemists, engineers, and managers at the level of water utilities and health departments. If properly developed, this system would provide for the effective translation of current microbiological concepts and analytical tools to individuals who either supervise or carry out water quality tests on a routine basis. International organizations, such as WHO, should initiate training programs in developing countries to train public health professionals in sanitation and water quality issues and in specific implementation strategies, such as the use of safe water storage vessels and point-of use disinfection, currently promoted by the U.S. Centers for Disease Control and Prevention and the Pan American Health Organization (Mintz, Reiff and Tauxe 1995).

5.4 COMMUNICATION AND THE ROLE OF THE MEDIA

A major issue is one of communicating water quality and health risk to the general public in a way that makes the issue holistic—in other words, how use and disposal of water affects the water cycle and eventually returns to affect the safety of drinking water supplies. It is important to convey to the public that water quality issues are germane and important to their quality of life. The media (print, radio, and television) are the main avenues for communication with the public, community leaders, and politicians. However, it is recognized that the media may be either generally ill-informed or even misinformed. For example, hiding or denying disease occurrence or outbreaks to protect the economy can occur. Authorities must be completely open and candid about potential public health hazards and involve the press on a regular basis, rather than only as incidents occur. The media provide opportunities for reporting hard scientific facts in a manner that is accessible to the general public and for organizing responses during crises. The media can also alert the public to unknown dangers, sway public opinion, and affect education in general. In order to achieve this, the interface of scientists involved in water with professional journalists is imperative for communicating the issues. The problem of water-related disease must be emphasized frequently, with careful presentations by scientists. Risk communication requires integrated health measures (Quality Adjusted Life Years, Disability Adjusted Life Years) and cost/benefit analysis. The media should be encouraged to utilize outbreak reports to emphasize the critical importance of safe water.

It is beneficial to capitalize on media attention with respect to outbreaks/epidemics, particularly when it can lead to changes that will have an impact far beyond the epidemic. However, media attention to endemic water-related health problems is less likely to occur and is probably more important. The media were extremely helpful in stimulating government responses to cholera in Peru, Chile and the rest of Latin America. As a result of the epidemic, improvements in sanitation helped reduce the incidence of many diseases and improve the quality of life in those countries.

5.5 SYSTEMS ACCOUNTABILITY

Ideally, the global community should strive for standardized surveillance of waterborne disease outbreaks, allowing for comparative analyses of trends. Problems recorded to date are grossly under-reported, and there are large deficiencies in our epidemiological database. These knowledge gaps prompt disagreement about key areas of necessary research. For example, the occurrence of an enteric disease outbreak does not imply that water was the major source of transmission (compared to food, daycare center contact or family hygiene). In many countries there is a dearth of information that would allow researchers to prioritize sources of infection. Certain baseline parameters of testing and reporting should be followed by developing countries, and augmented by developed countries. It is important to avoid the creation of vast information collection bureaucracies, as occurred with the failed global fight against malaria. It is essential that data collection reflect local concerns, be as simple as possible, and be immediately useful. One striking advantage to global or regional standardization is negotiating power for purchase of reagents and advanced technology. For example, WHO has successfully organized regional purchases of essential drugs.

Disease surveillance programs cost money. However, the data gathered from effective surveillance provide incentives for establishment of programs, prioritizing issues, and realizing savings in health care costs, as well as improvements in the quality of life. Surveillance of food-borne disease has just recently been implemented by the Pan American Health Organization for South America (PAHO 1993). Guidelines have been established for investigating and reporting foodborne disease; the first report for 1994 has been released, a monumental accomplishment and to be commended. A total of 99 outbreaks with 13,865 cases and 16 deaths were reported from seven countries in 1994 (PAHO 1995). Four outbreaks implicated water in the transmissions of *Salmonella*, *Shigella*, hepatitis A virus, and gastroenteritis of unknown etiology. With this public health infrastructure in place, the opportunity for building a better data base on waterborne disease in South America should not be missed.

Data collection must be linked to system accountability. Publication of water quality assessments will provide consumers and their politicians with the tools to question current water quality provisions. Given the expansion of computer on-line services worldwide, efforts should be made to connect water researchers, providers, regulators, and funding agencies, achievable through a UN agency initiative coupled to the CDC in the U.S, for example. A help line should be established, allowing observers all over the world to issue global inquiries on a real time basis.

SUMMARY

Water is a requirement for life. Therefore, access to water must be viewed as a fundamental human right, fraught with implications for national and international policy. The political and social patterns that contribute to waterborne diseases can only be attacked through the activities of individuals and organizations who thoroughly understand local economic conditions, attitudes, and other social factors. Successful solutions will only be possible if all factors, including those that may interfere with and those that can enhance practical solutions, have been identified.

Strong incentives to change social and political patterns so that waterborne diseases are reduced are likely to be economic in nature. For example, the contribution of tourism to economic growth may be very important. However, waterborne disease outbreaks will discourage tourists and are, therefore, a disincentive. If a country or region is otherwise attractive as a site for business or industrial development, poor water quality and associated waterborne diseases may drive prospective industry/business elsewhere. Lack of waterborne illness in the local population means a healthier workforce for a prospective industry/ business.

Basic education is critical to improvement of human health worldwide. Programs designed to reduce the incidence of waterborne disease must focus on nutritional status, sanitation, and housing, as well as water quality. Research and training at the graduate level is also critical for improvements in technologies, increased understanding of waterborne pathogens and their control, and improvements in risk assessment methodologies.

Water resources, distribution, allocation and safety will rise to the top of the agenda of priorities for all nations as we approach the 21st century. If the issues are left to metastasize to the crisis stage, the social problems created by epidemics, droughts, and battles between nations for water resources will destabilize governments—the issues are global and, so too, must be the solutions. It is a time for action, for response to the warning signals that are occurring throughout the world. Microbiologically safe drinking water can no longer be assumed, even in the United States and other developed countries. The situation will worsen unless measures are taken in the immediate future. The crisis looming is global, and the solutions are international in scale, even though local in application. Indeed, the need for safe drinking water is a need that binds all of humanity into a single, global community.

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Appendix 1

- Infection by *E. coli* 0157:H7 can lead to kidney failure and brain damage.[1]
- Enteric pathogens, such as *Salmonella*, *Campylobacter*, and *Yersinia*, can cause reactive arthritis.[2,3] *Campylobacter* infections are also associated with Guillain-Barr and Miller-Fisher Syndromes.[4,5]
- Recent data indicate that ingestion of enteric viruses may be related to miscarriages, diabetes and heart disease.[6,7,8]
- Ingestion of the bacterium *Helicobacter pylori* and subsequent chronic infection may be a major cause of stomach cancer.[9]
- Multiple episodes of diarrheal disease in childhood can have serious nutritional consequences that cause stunted growth and impair intellectual development.[10]

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Appendix 2

CHARACTERISTICS IMPORTANT FOR BACTERIAL SURVIVAL

Many bacteria, including viable but non-culturable human pathogens, e.g., enterotoxic *Escherichia coli, Vibrio cholerae, Salmonella spp., Shigella spp.*, and *Campylobacter jejuni* enter a survival or dormant stage in the natural environment.[1,2,3] These bacteria retain their pathogenic capabilities, requiring that public health methods be revised to estimate public health risk from waterborne disease more accurately.[4] Furthermore, injured and non-injured sewage bacteria discharged into freshwater and seawater are exposed to environmental stress.[5,6] Sublethal exposure of enteric bacteria to stressors, including disinfectants, metals and UV, results either in a form of injury or viable but non-culturable state, that renders them unable to form colonies on selective media that are commonly used to determine water potability.[7] Such stressed indicator bacteria can pass undetected from the treatment system into the distribution network and result in the underestimation of indicator and pathogenic bacterial populations in water.[8,4]

- Different species react differently to temperature changes; *Salmonella spp.* exhibited less mortality and stress than *E. coli* at low temperatures.[9] Lower temperatures have also been studied as sewage is released into coastal marine water with the same result.[10,1]

- Water with relatively high concentrations of organic material does not necessarily represent a rich nutritional environment for microorganisms. A large part of the organic material may be refractory, and only bacteria with minimal activity or those capable of rapid organic matter uptake during short periods of nutrient abundance can survive, i.e., reproduce rapidly.[11] Survival mechanisms of *Vibrio cholerae, E. coli* and *Shigella spp.* related to organic matter concentration may require important physiological and structural transformations.[12,3] Their metabolism changes and surviving bacteria are no longer culturable but viable, i.e. they are alive and able to use exogenous material, but they no longer multiply.[13,14]

- Enteric bacteria are subject to osmotic shock when effluents are discharged in seawater, but cellular uptake of special molecules acting as osmoprotectors can prevent dehydration.[15] The negative effect of visible light on enteric bacteria in aquatic ecosystems is a well known fact.[16,17] It is assumed that light induces a state of dormancy in cells that are no longer culturable although cells stay morphologically intact.[2,18] This negative effect is attributed to damage to different cell components, but there is still a lack of knowledge about the mechanisms of light's action. An indirect effect mediated by the formation of photoproducts has been suggested.[19] So far, little is known about the possibility that plasmids of plasmid carrier *E. coli* strains codify resistance to environmental factors such as light and disinfectants. High concentrations of particles in water will prevent light penetration and therefore reduce bacterial mortality. In any case, depending upon bacteriological culturing methods will not provide accurate data on incidence and distribution of pathogens in water and water distribution systems.

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Appendix 3

MOLECULAR APPROACHES

While many of the molecular technologies work well in the research laboratory using clean water, problems have been experienced with their application for environmental samples. For example, PCR is a reliable method for the detection of microorganisms in pure water; however, there are many 'natural' sources of interference from chemical constituents (e.g. humic acids). Further, questions arise as to quantification of viable organisms using PCR. Considerable debate is emerging regarding the cost of these new technologies. While the equipment to develop and establish such tests may be expensive, the reagents used for many tests could be relatively cheap, for example oligonucleotide probes could be produced on a mass scale for only a few cents (US). Additionally, molecular methods should eventually reduce costs because they are not as labor intensive as current assays and they are more generic.

The greatest potential for fluorescent antibody/DNA labeling technologies lies in their exquisite sensitivity. The new technologies are not only very sensitive, they are also relatively fast in performance. They are particularly exciting in their application for virus detection because, for the first time, they offer the possibility of detecting noncultivable viral pathogens at the low levels present in environmental samples. However, use of these methods will require additional testing to document utility in environmental samples and their correlation with health risk. Currently these methods do not distinguish between viable and nonviable microorganisms. Thus, a positive test result can be meaningful as an indicator of human fecal contamination but real health risk assessment is not currently possible. It is anticipated that the problem of organism viability will be solved with additional research. For example, methods have been developed using fluorescent antibodies and a physiological fluorochrome to detect specific bacteria that are physiologically active in environmental samples including water. Such a method has been described for *E. coli* 0157:H7[1] and *V. cholerae*.[2,3]

The successful use of the new technologies by water utilities will require that these assays are simple, and cost effective. Alternatively, samples may be sent to centralized, relatively high technology, laboratories. It is anticipated that, at least initially, these new technologies would be established in developed countries, possibly in large water utility areas where consumers are more able to bear the cost of testing and/or where consumers are particularly concerned about quality control and assurance of drinking water safety. For example, many of the large water providers in the UK currently use immunofluorescence techniques to identify *Cryptosporidium* contamination. Use of molecular techniques in developing countries has been shown to be successful, e.g., use of reverse transcriptase PCR to monitor the eradication of poliovirus.[4] The prospect exists for the establishment of regional testing centers in developing countries.

Detection of *Cryptosporidium* using flow cytometry provides an instructive case history of development of new methods since *Cryptosporidium* emerged as a significant cause of waterborne illness in several developed countries. This organism is of considerable concern because it has caused disease in situations where the water meets all the criteria for water quality (turbidity, coliform, fecal coliforms, etc). Thus, traditional measures of water quality do not appear to be reliable for this organism. Further, this organism cannot be cultured using traditional methods. A method was developed in the US which involved filtering large quantities of water, eluting the debris from the filter, density gradient centrifugation, sample fixation to a side, staining with a fluorescently labeled monoclonal antibody, and examination with fluorescence microscopy.[5] This method has enabled the study of *Cryptosporidium* in the environment but is tedious and very labor intensive. A new method using flow cytometry has significantly increased the speed and reliability at which samples can be analyzed.[6] However, this new method suffers from the high cost of the instrument required ($250,000 US) and the need for a highly skilled operator. Currently new methods are being developed that will run on very simple flow cytometers (~$50,000 US) that can be operated by a non-specialist technician. These analyses will be very rapid and should only cost a few dollars (US) for reagents.

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PROTECTING PUBLIC HEALTH

US outbreaks of cryptosporidiosis

An overview of US cryptosporidiosis outbreaks suggests that conventional treatment processes operated at minimum regulatory compliance levels are ineffective at preventing transmission of the disease.

Helena Solo-Gabriele
and Shondra Neumeister

Drinking water has been implicated as the mode of transmission in several outbreaks of cryptosporidiosis throughout the United States. This review of US outbreaks describes characteristics of the raw water supply, suspected sources of contamination, water treatment methods, and corrective actions. Of the total number of outbreaks, roughly half were associated with groundwater sources; the majority of affected individuals, however, were served by drinking water drawn from surface water. Wastewater was implicated as the source of contamination of raw or treated water for roughly half of the outbreaks. Nonpoint sources, such as agricultural runoff, were suspected sources of contamination in the remaining outbreaks. The majority of affected individuals were served by treatment plants using coagulant addition, filtration, and chlorine disinfection processes. Although treatment deficiencies and suboptimal operational practices were noted during some of the outbreaks, all treatment plants were complying with federal and local regulations. Existing regulations and water supply systems, especially those utilizing surface water sources, should be reevaluated.

Cryptosporidiosis is an acute diarrheal [illegible] humans that is caused by the pro[illegible] *m parvum. Cryptosporidium* species [illegible] rred to as *Cyptosporidium*) are trans[illegible] the environment as an oocyst that is resistant to environmental stresses. Especially notable characteristics of the oocyst are its resistance to chlorination and its very small size (3–7 μm), which make it difficult to remove via filtration. Currently there is no effective medical treatment for cryptosporidiosis.[1] In immunocompetent individuals, the illness is self-limiting, with symptoms lasting an average of five days. In immunocompromised populations (including HIV-infected individuals and AIDS patients), the illness can be prolonged and life-threatening.[2,3]

Outbreak studies show that the majority of people who have contracted cryptosporidiosis are served by surface water sources.

Cryptosporidium is transmitted by ingestion of oocysts excreted in the feces of infected humans or animals (especially cattle and newborn mammals). The disease can be transmitted through contact with animals, person-to-person contact (especially at day care centers), ingestion of fecally contaminated water or food, or contact with fecally contaminated environmental surfaces.[4]

The first human case of cryptosporidiosis was diagnosed in 1976.[5] From 1976 to 1982, reported cases were primarily associated with immunocompromised people, and in 1982, the number of reported cases began to increase dramatically in conjunction with the AIDS epidemic. With recent developments in laboratory diagnostic techniques, outbreaks among immunocompetent individuals began to be recognized.[4] In 1993, *Cryptosporidium* was the etiologic agent in the largest US waterborne outbreak ever[6] and is quickly becoming recognized as a public health threat.[5]

In response to these outbreaks, regulations and current treatment processes are being reevaluated to assure that public health is protected.

Introduction

Water supply systems are designed to protect public health by supplying consumers with drinking water that is sufficiently free of microbial pathogens to prevent outbreaks of disease. This level of public health protection can be achieved through (1) protection of the raw water source against contamination and (2) treatment to assure that pathogens found in the raw water supply are removed or inactivated. Several waterborne outbreaks of cryptosporidiosis have occurred in which both means of protection were breached: the raw water supply was contaminated with *Cryptosporidium* and the treatment system failed to remove sufficient quantities of the microbe. Tables 1–4 summarize available information on US outbreaks of cryptosporidiosis, including characteristics of the raw water supply, suspected sources of contamination, water treatment methods, and corrective actions. The following sections provide a comprehensive overview of the episodes and the environmental situations and treatment processes in effect prior to the outbreaks. The facts of each case emphasize the importance of raw water protection and maintenance of optimal water treatment at all times.

US outbreaks

Bexar County, Texas. In 1984, two distinct outbreaks of diarrheal illness occurred in Braun Station, Texas, a San Antonio suburb with a population of 5,900. One outbreak occurred in May, the other in July.[3] An epidemiologic study strongly implicated the community's water supply as the source of illness. Analysis showed that protection against the disease was afforded to local residents on vacation during the first week of the July outbreak and that attack rates of diarrhea correlated with greater consumptions of tap water. Approximately 2,000 people became ill during the outbreaks.

It is uncertain how much of the illness can be attributed to *Cryptosporidium*.[8] *Cryptosporidium* oocysts were found in stool specimens of 47 of 79 residents who became ill in July, and the parasite was identified as the major cause of illness during the July outbreak.[3] Investigation of the May outbreak, however, was conducted retrospectively. Analysis of serum samples collected in May indicate that the Norwalk virus could also have contributed to the diarrheal illness.

It is speculated that the outbreaks were caused by intermittent contamination of the community's water supply. The raw water source is well water, and treatment is limited to chlorination. Raw water tested positive for fecal coliform; however, no *Cryptosporidium* oocysts were recovered from the raw water source.[8] Dye tracer studies indicated that the well water was affected by the community's sewage system. The exact site of contamination was not identified. Since the outbreak, the Braun Station well has been decommissioned, and water is now supplied from the San Antonio treatment system. The raw water source for the San Antonio system is groundwater, and its treatment is limited to chlorination.[8] [illegible]

TABLE 1 Affected populations and characteristics of the raw water supply

County, State (City)	Date	Estimated Number of People Affected (Confirmed Cases)*	Raw Water Source	Suspected Sources of Contamination
Bexar County, Texas (Braun Station)	May–July 1984	2,000 (47)	[illegible]	Raw sewage [illegible]
Bernalillo County, N.M. (Albuquerque)	July–October 1986	[illegible]	[illegible]	[illegible]
Carroll County, Ga. (Carrollton)	January–February 1987	[illegible]	[illegible]	[illegible]
Berks County, Pa.	August 1991	[illegible]	[illegible]	[illegible]
Jackson County, Ore. (Talent and Medford)	January–June 1992	[illegible]	[illegible]	[illegible]
Milwaukee County, Wis. (Milwaukee)	January–April 1993	[illegible]	[illegible]	[illegible]
Yakima County, Wash.	April 1993	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

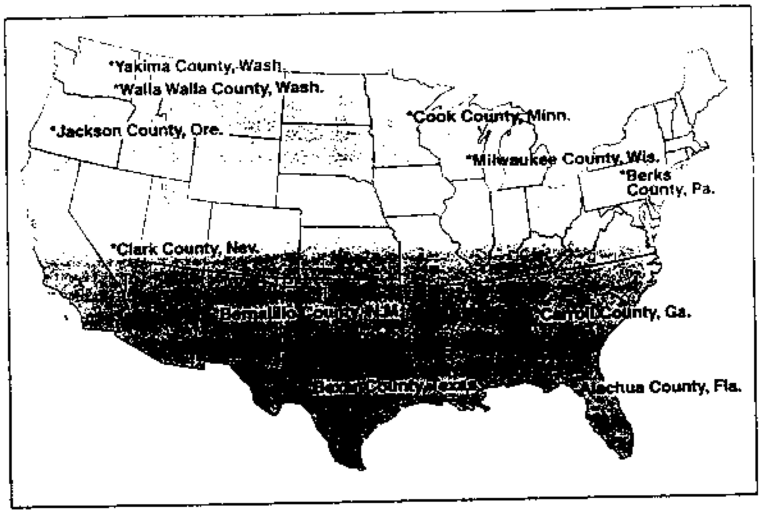
TABLE 2 Characteristics of spring and groundwater treatment systems

County, State (City)	Type of System (Population Served)	[illegible]	[illegible]	[illegible]	[illegible]
Bexar, Texas	Community (5,900)	[illegible]	[illegible]	[illegible]	[illegible]
Berks, Pa.	Noncommunity (Picnic area, capacity of 5,000 people per day)	0.004 (0.09)	[illegible]	[illegible]	[illegible]
Jackson, Ore. (Medford)	Community (70,000)	[illegible]	[illegible]	[illegible]	[illegible]
Yakima, Wash.	Noncommunity (10 exposed; 1 household)	[illegible]	[illegible]	[illegible]	[illegible]
Walla Walla, Wash.	Community (227)	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]—positive for fecal coliforms; C—positive for coliforms; Cr—positive for Cryptosporidium [illegible]
†Capacity of two wells that were in operation.
‡Capacity of new well that replaced the well in operation during the outbreak.

Bernalillo County, N.M. In 1986, an epidemiologic investigation found a strong statistical association between consumption of untreated surface water and illness among 78 confirmed cases of cryptosporidiosis.[8,10,11] Swimming in surface waters and attendance at a day care center where other children were ill were also identified as risk factors. Exposure to surface water (either through drinking or swimming) had occurred in New Mexico, Colorado, and Mexico. If the patients exposed to surface water in Mexico are eliminated from the epidemiologic analysis, drinking surface water was still found to be significantly associated with the illness.[11] Surface runoff from livestock grazing areas was identified as a potential source of contamination.[10]

Carroll County, Ga. This 1987 outbreak[12,13] affected an estimated 13,000 people within Carroll County (population 64,900). Epidemiologic evidence strongly implicated the public water supply as the source of the outbreak.



US outbreaks of cryptosporidiosis have occurred in rural communities as well as urban areas.

The county's raw water source is river water. *Cryptosporidium* oocysts were found in the tributary waters to the river, treated water at the plant, and water within the distribution system. Suspected sources of contamination included runoff from cattle grazing areas and a sewage overflow. Dye studies indicated that the sewage affected river water quality upstream of the plant.[12] Treatment included rapid mix (alum and lime addition), flocculation, sedimentation, dual-media filtration, and chlorination using chlorine dioxide. Treatment deficiencies at the time of the outbreak included suboptimal filtration primarily attributable to nonoperational flocculators and restarting of filters without backwashing.[12,14,15]

Despite operational deficiencies, the treatment plant was complying with federal regulations at the time of the outbreak. Following the outbreak, treatment was upgraded by installation of baffled flocculators, increased monitoring of filter performance, polymer addition as a coagulant aid, improved chemical dosing, and better operational practices.[14,15]

Berks County, Pa. In August 1991, 551 individuals of an exposed population of 1,987 became ill at a picnic facility in Berks County.[16,17] An epidemiologic investigation implicated drinking water supplied by an on-site well as the source of illness. Treatment of the well water was limited to chlorination.

Raw water samples tested positive for fecal coliform and various surface water indicators including rotifers, insects, diatoms, algae, *Cryptosporidium*, and *Giardia sp*. The treated water indicated a bacteriologically safe water. Although water analyses identified more than one pathogen, *Cryptosporidium* was the only parasite consistently identified in stool samples from ill individuals. Potential sources of contamination included septic tank effluent and infiltration from a nearby creek. Since the outbreak, a new well has been drilled in a location farther away from these suspected sources of contamination.[17]

Jackson County, Ore. Epidemiologic evidence suggests that outbreaks in Jackson County during 1992 were associated with two distinct water supplies, one in the city of Medford and the other in Talent.[16] There is some controversy, however, whether the Medford water supply was truly a contributor to the spread of the disease.[18]

Because these cities are geographically adjacent to each other and the outbreaks overlapped in time, case counts were combined during the epidemiologic investigation. The number of people affected by the outbreaks was estimated at 15,000.[7,19] A lower value of 3,000[16] affected people, which was reported in the early literature, is believed to have underestimated the number of individuals affected because it was based on a very strict case definition.[20]

During the outbreak, the water source for Medford came exclusively from Big Butte Springs and was treated only by chlorination. Low numbers of *Cryptosporidium* oocysts were found in the first few samples of the raw spring water,[16,19] and sporadic low levels of coliform, algae, and diatoms suggest that the spring may have been influenced by surface water.[16] For 10 weeks after the outbreak, the spring water tested negative for *Cryptosporidium*, and the boil-water order was lifted with no major changes in treatment of the spring water. For a short period after the outbreak, filtered river water, which was originally designed to augment the spring water supply on a seasonal basis, was used to flush the distribution system prior to bringing the spring water back on line.[19]

Although the majority of laboratory-confirmed cases occurred among the HIV-infected population, evidence suggests that the outbreak may have extended into the general community.