FUTURE NEEDS AND PRIORITIES FOR DRINKING WATER AND HEALTH

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Contents

Summary

It is clear from recent literature reviews, from American Academy of Microbiology Reports and from WHO expert meetings, that we are a long way from guaranteeing safe drinking water even in the most developed nations. This chapter attempts to identify major knowledge gaps and summarize at least some of the needs and priorities for the future provision of safe drinking water. Obviously, the major benefits to human health are through basic hygiene and sanitation practices -- still much needed areas for public health intervention in many parts of the world. However, this chapter will emphasize more research-oriented needs and priorities. These include the need for a better understanding of biofilms and their control, improvements in risk assessment methodologies, the emergence of new disease, the balance between pathogens and disinfection-by-products, and the future promise of rapidly developing technologies.

1. Introduction

The concept of safe, cheap drinking water as an inalienable human right for everyone has emerged in the more developed nations in the latter part of the twentieth century. Although the quality of our source waters, and their protection, is recognized as the single most efficient factor in determining consistently high quality drinking water, the technology now exists to take wastewater and recycle it to potable water quality.

As cities have developed, both in the US and globally, both water distribution and waste collection systems have become more complex and far more difficult to maintain. Thirty percent leakage from water distribution systems appears to be a common estimate,

whether talking to utility personnel in Boston, USA, or Hyderabad, India. The fundamental difference between these two systems is pressure. According to the Hyderbad utility personnel, Hyderabad is able to provide a two-hour supply of water per day. The system therefore remains stagnant for twenty two hours per day and is highly susceptible to contamination through back-siphonage, cross connections, and biofilm regrowth. In contrast, Boston and other developed nation cities maintain pressure resulting in incredible wastage of treated, potable water, yet reduced risk to human health.

Now we have entered the twenty first century, what are the future options? While for many regions watershed protection is still problematic, filtration and disinfection technologies are constantly being improved. A typical multibarrier approach to provide safe drinking water is presented in Table 1.

S.No.	Description
1.	Watershed protection that minimizes anthropogenic and wildlife impacts on source water, including programs to reduce the impact of waterfowl, particularly near water intake sites.
2.	A treatment system with sufficient capacity to maintain adequate pressure throughout the distribution system for 24 hours/day, and that minimizes opportunities for microbial colonization in the distribution system. This could include, • Coagulation-flocculation and sedimentation to remove colloids, associated microorganisms, debris and macroorganisms. • Preozonation to effectively kill microorganisms in source waters, reduce odor, taste and color, precursors for DBPs (Disinfection byproducts are formed by ozonation of source waters, including aldehydes and brominated byproducts (discussed in Boorman et al, 1999). UV disinfection, used extensively in wastewater treatment, is rapidly gaining acceptance as an alternative to ozonation.), and reduce the amount of chlorine/ chloramine necessary to maintain a system residual. • Filtration to further remove particulates and microorganisms, including granular or biological activated carbon to remove AOC. • Cloramination to provide residual disinfection, minimize biofilm formation and reduce DBPs, with intermittent chlorination and system flushing.
3.	A rigorous program to upgrade distribution system networks and prevent interconnections through leakage, backflushing, improper hydrant use, etc.

Table 1. A multibarrier approach to maximize microbiological quality of water

A technology can always be developed to clean contaminated source waters, albeit at a high cost. It is harder, however, to find a technological solution to deteriorating

distribution systems. Replacing pipelines is an extremely slow and disruptive process, and lining existing pipes may only provide temporary solutions. Lining materials that are currently in use, e.g., cement and epoxy linings, may be susceptible to deterioration, particularly in microbiologically active environments.

There are many alternatives proposed for provision of safe drinking water, including separate potable and non-potable supplies, point-of-use treatment devices and bottled water. None of these alternatives are without risk to the consumer and are invariably many-fold more expensive than municipal supplies. Of course, there is a strong argument that centrally supplied drinking water is dramatically undervalued, and more appropriate costing of this invaluable resource would help to address some of the problems briefly listed above.

In the foreseeable future, drinking water is likely to continue to be supplied through distribution networks. What, therefore, do we see as future needs and priorities?

2. Risk assessment

To begin with, we are still unable to characterize and quantify health risks associated with drinking water meeting World Health Organization Standards. It is likely that those risks are minimal to individuals with no predisposing factors (e.g., compromised immunity). However, on a global scale it could be argued that the susceptible individuals are as common as the non-susceptible. In developed nations we think about the very young, the elderly, the pregnant and those with diseases that directly, or through treatment, compromise immunity. Even in developed nations, the burgeoning field of environmental health has shown us that exposure to pollutants in air, food and water can affect susceptibility to disease. Likewise malnutrition, stress and socioeconomic status (e.g., inner city communities) render individuals more susceptible. In developing nations, the burden of diseases may be vast and malnutrition levels high. Rapid industrialization also exposes populations to uncontrolled pollution, leaded petrol is still accepted as the norm, and smoking, drug, alcohol abuse and prostitution are rampant.

However, although exposures appear to be vast, diseases may not be apparent due to multiple prior exposures resulting in population immunity. This then is the paradox. By all the above criteria, these populations are highly susceptible, yet immunity results in lower than expected incidence of many waterborne diseases. This immunity must come at some cost to the individual - which provides some validation to the Disability Adjusted Life Years (DALY) approach to estimate burden of disease, which could take into account the reduced quality of life (and lifespan) from exposure to multiple infectious agents (and toxins).

A recent study by Arie Havelaar and colleagues in the Netherlands used the DALY approach to compare the risks of disinfection byproducts vs. infectious disease. They conducted a hypothetical case study involving a drinking water system typical of the Netherlands. Their goal was to compare the reduction in risk of infection with *Cryptosporidium parvum* from ozonation of the water source, with the potential risk of cancer from ingestion of bromate (formed by reaction of ozone and bromine compounds

in source water). Net health benefits (in DALYs) were calculated based on published clinical, epidemiologic, and toxicologic data on morbidity and mortality. Although bromate was produced in their model at concentrations exceeding US-EPA guidelines, they concluded that net benefits from ozonation outweighed risks by more than an order of magnitude, with a net benefit of approximately 1 DALY/million years. The DALY approach allowed the authors to consider life and health expectancy, including evaluation of the distribution of population susceptibilities. This approach provides a far more appropriate estimate of disease burden than can be obtained solely from annual mortality rates. Even so, considerable assumptions are made in 1). the exposure assessment; e.g., the median number of infectious *Cryptosporidium* oocysts, the median concentration of bromate, and the volume of water ingested; 2) in the hazard characterization; e.g., the shape of the dose response curves at low exposures, the applicability of rodent models to humans, and the distributions and models used to produce median parameter values and confidence intervals, 3) and in the risk characterization; e.g., assumptions made in calculating life years lost, years with disability and weightings for different population susceptibilities.

Paul Gale from the WRc-NSF Ltd., UK, has provided thoughtful analysis of the risk assessment process and has argued that distribution of pathogens, and in particular the protozoa, is extremely heterogeneous in drinking water. In other words, most consumers ingest zero *Cryptosporidium* oocysts and most water samples measure zero oocysts. However, a few individuals could consume a large number of oocysts. Gale argues that risk assessments based on median values obtained from spot sampling will underestimate risk as most samples are zero. Number of organisms present in a drinking water sample should be more accurately modeled as a distribution (in Gale's example for *Cryptosporidium*, a Poisson-log-normal distribution is used). Daily risks of infection are then calculated for this distribution using Monte Carlo simulation. However, Gale also reports that risks predicted by simple use of the arithmetic mean are very similar to those using Monte Carlo simulation. The arithmetic mean of pathogen density may be a better predictor of risk than the median value, as it provides a weighting to any positive samples based on the actual number of oocysts.

Gale also argues that spot sampling is inappropriate, as even during outbreak conditions most spot samples are zero, and that continuous monitoring, as is currently recommended in the UK for *Cryptosporidium*, is necessary. Similar arguments could be applied to pathogenic viruses and, in fact, to any pathogens with low infective doses and/or a tendency to adsorb to particles/biofilms contributing to a heterogeneous distribution. Gale has constructed a large number of risk assessments based on the arithmetic mean, rather than the median, including risk assessments for *Cryptosporidium parvum*, *Escherichia coli* O157, rotavirus and Bovine Spongiform Encephalitis (BSE; see later discussion).

Assumptions are also clearly present in estimating consumption of drinking water and it is argued that these too should be modeled on a distribution. The dose response relationship between number of pathogens ingested and infection is highly variable based on individual susceptibility (including immunity from prior exposures). Infectious doses measured in healthy volunteers may bear little relationship to the range of infectious doses in an average population.

Where else does uncertainty arise? For any pathogen, its presence in drinking water may not be enough to characterize risk. Organisms may lose their infectivity/virulence in the drinking water distribution system or after exposure to disinfection; or conversely, they may increase or change in virulence and in their ability to resist antibiotics.

Our risk assessment approach examines individual organisms. We are in fact exposed to complex mixtures of both microbes and chemicals. Questions that arise from this are:

1) What are the synergistic effects (both in terms of infectious dose and disease outcome) of exposure to mixtures of pathogens, opportunistic pathogens and non-pathogenic microbes?
2) What are the synergistic effects of exposure to mixtures of microbes and chemicals? For example, could simultaneous exposure to high concentrations of a contaminant chemical and an infectious agent effect the pathogen's infectious dose? Certainly, there is an argument that long-term exposure to chemical contaminants may increase susceptibility to infection.
3) How is a pathogen's infectivity and exposure route altered by association with biofilms?
4) How is a pathogen's infectivity and exposure route altered by intracellular survival within protozoa? (For example, it has been argued that the disease outcome from exposure to *Legionella pneumophila* could be related to mode of transmission; within biofilms, within protozoa or free-living).

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Bibliography

Albert M.J., Ansaruzzaman M., Talukder K.A., Chopra A..K., Kuhn I., Rahman M., Faruque A.S.G., Islam M.S., Sack R.B., Mollby R. (2000). Prevalence of enterotoxin genes in *Aeromonas* spp. isolated from children with diarrhea, healthy controls, and the environment. Journal of Clinical Microbiology. 38, 3785-3790. [Directly links the *Aeromonas* bacterium to diarrheal disease]

Alonso A., Sanchez P., Martinez J.L. (2001). Environmental selection of antibiotic resistance genes. Environmental Microbiology 3, 1-9. [Explores the environmental pressures that can result in selection of antibiotic resistance in pathogens]

Arvanitidou M., Kanellou K., Constantinides T.C., Katsouyannopoulos V. (1999). The occurrence of fungi in hospital and community potable waters. Letters in Applied Microbiology 29, 81-84. [Demonstrates that potable water can be an important source of fungal infections]

Bassler B. (1999). How bacteria talk to each other: regulation of gene expression by quorum sensing. Current Opinions in Microbiology 1, 582-587. [Describes the cell to cell signaling process that results in a bacterial "quorum," i.e., group behavior such as biofilm formation]

Bondi M., Messi P., Guerrieri E., Bitonte F. (2000). Virulence profiles and other biological characters in water isolated *Aeromonas hydrophila*. Microbiologica 23, 347-356. [Explores the wide range of virulence factors in the *Aeromonas* bacterium isolated from drinking water]

Boorman G.A., Dellarco V., Dunnick J.K., Chapin R.E., Hunter S., Hauchman F., Gardner H., Cox M., Sills R.C. (1999). Drinking water disinfection byproducts: review and approach to toxicity evaluation. Environmental Health Perspectives 1999; 107, 207-217. [A relatively comprehensive review of the toxicity of disinfection by-products formed in drinking water]

Cabanes P.A., Wallet F., Pringuez E., Pernin P. (2001). Assessing the risk of primary amoebic meningoencephalitis from swimming in the presence of environmental *Naegleria fowleri*.. Applied and Environmental Microbiology 67, 2927-2931. [An assessment of risk of primary amoebic meningoencephalitis from swimming. Given the ubiquity of the causative agent in surface waters, and seroprevalence studies suggesting there is considerable exposure, it is interesting that disease is so rare]

Chakraborty S., Mukhopadhyay A.K., Bhadra R.K., Ghosh A.N., Mitra R., Shimada T., Yamasaki S., Faruque S.M., Takeda Y., Colwell R.R., Nair G.B. (2000a). Virulence genes in environmental strains of *Vibrio cholerae*. Applied and Environmental Microbiology 66, 4022-4028. [Provides a sobering examination of just how prevalent virulence genes are in environmental isolates of *Vibrio cholerae*]

Garg P., Chakraborty S., Basu I., Datta S., Rajendran K., Bhattacharya T., Yamasaki S., Bhattacharya S.K., Takeda Y., Nair G.B., Ramamurthy T. (2000b). Expanding multiple antibiotic resistance among clinical strains of Vibrio cholerae isolated from 1992-7 in Calcutta, India. Epidemiology and Infections 124, 393-399. [Illustrates how antibiotic resistance has increased dramtically in clinical isolates of *Vibrio cholerae*, and how there is evidence of transfer between toxigenic and non-toxigenic serogroups]

Costerton J.W., Stewart P.S. (2001). Battling biofilms. Scientific American, July 2001, 75-81. [A highly readable review of modern and future research approaches to the control of bacterial biofilms]

Davies G.D., Parsek M.R., Pearson J.P., Iglewski B.H., Costerton J.W., Greenberg E.P. (1998). The involvement of cell-to-cell signals in the development of a bacterial biofilm. Science 280, 295-298. [Describes some of the first evidence of the phenomenon of cell-to-cell signaling in biofilm formation]

Egorov A.I., Paulauskis J., Lubov P., Tereschenko A., Drizhd N., Ford T. (2002). Contamination of water supplies with *Cryptosporidium* and *Giardia lamblia* and diarrheal illness in selected Russian Cities. International Journal of Hygiene and Environmental Health. 205, 281-289. [This paper, and other publications by the same group, describe epidemiological studies that link water quality with disease in selected Russian Cities]

Faruque S.M., Albert M.J., Mekalanos J.J. (1998). Epidemiology, genetics, and ecology of toxigenic *Vibrio cholerae.* Microbiology and Molecular Biology Review. 62, 1301-1314. [Reviews our current understanding of the epidemiology, genetics and ecology of the classic agent of waterborne disease, *Vibrio cholerae*]

Ford T.E. (1999). Microbiological safety of drinking water: united states and global perspectives. Environmental Health Perspectives. 107, 191-206. [Reviews the global state of the microbiological safety of drinking water. Although research has advanced, particularly in the field of molecular epidemiology, the information is still current]

Ford T.E. (1993). The microbial ecology of water distribution and outfall systems. Aquatic Microbiology - an Ecological Approach (ed. TE Ford), 455-482. Boston: Blackwell. [Describes a wide variety of microbially-mediated distribution system problems, including biofilm formation]

Ford T.E., Colwell R. (1996). A Global Decline in Microbiological Quality of Water: a Call for Action. 40pp. Washington, DC, USA: American Academy of Microbiology. [The first report produced by the American Academy of Microbiology on this topic, disseminated widely and still providing current information on research needs and priorities. Available on the Web in English and Spanish at http://www.asmusa.org/acasrc/pdfs/Colloquia/waterquality1995.pdf]

Ford T.E., Mitchell R. (1990). The ecology of microbial corrosion. Advances in Microbial Ecology 11, 231-261. [Describes the mechanisms behind microbially-induced corrosion, a major problem in drinking water pipelines]

Gale P. (2001). Developments in microbiological risk assessment for drinking water. Journal of Applied Microbiology 91, 191-205. [Reviews some of the more recent developments in Microbiological risk assessment, includes risk assessments for *Cryptosporidium parvum* and enteric viruses]

Gale P., Young C., Stanfield G., Oakes D. (1998). Development of a risk assessment for BSE in the aquatic environment. Journal of Applied Microbiology 84, 467-477. [A theoretical attempt to provide a risk assessment for BSE discharged to the surface waters from abattoirs, rendering wastes or landfills. Concludes that there is essentially no risk of exposure by the waterborne route. However, it needs to be emphasized that this is a theoretical modeling exercise with a number of assumptions]

Geldreich E.E. (1996). Microbial Quality of Water Supply in Distribution Systems, 504 pp. Boca Raton: CRC Press. [Classic edited book by a senior author in the field of drinking water. Together with the McFeters (1990) text, provides a very useful reference for understanding microbes in drinking water]

Havelaar A.H., De Hollander A.E.M., Teunis P.F.M., Evers E.G., Van Kranen H.J., Versteegh J.F.M., Van Koten J.E.M., Slob W. (2000). Balancing the risks and benefits of drinking water disinfection: disability adjusted life-years on the scale. Environmental Health Perspectives 108, 315-321. [Describes the use of the DALY approach to determine the relative risks between the toxicity of disinfection byproducts and infectious waterborne disease. Concludes that risks from infectious disease are an order of magnitude higher than cancer risks from DBP exposure (as estimated by the DALY methodology)]

Hazen T.C., Toranzos G.A. (1990). Tropical source water. In McFeters G.A. (ed). Drinking Water Microbiology, pp32-53. New York: Springer. [Looks specifically at drinking water issues that effect the developing world]

King C.H., Shotts E.B., Wooley R.E., Porter K.G. (1998). Survival of coliforms and bacterial pathogens within protozoa during chlorination. Applied and Environmental Microbiology 54, 3023-3033. [Describes the process of intracellular survival; how bacterial pathogens are able to resist chlorination and other stressors through survival inside protozoa]

Kingombe C.I.B., Huys G., Tonolla M., Albert M.J., Swings J., Peduzzi R., Jemmi T. (1999). PCR detection, characterization, and distribution of virulence genes in *Aeromonas* spp. Applied and Environmental Microbiology 65, 5293-5302. [Describes molecular approaches to characterize virulence genes in *Aeromonas* bacteria]

Kinsey G.C., Paterson R.R., Kelley J. (1999). Methods for the determination of filamentous fungi in treated and untreated waters. Journal of Applied Microbiology 85, 214S-224S. [Describes methodologies used to determine presence of fungi in treated and untreated water]

Komulainen H., Kosma V.M., Vaittinen S.L., Vartiainen T., Kaliste-Korhonen E., Lotjonen S., Tuominen R.K., Tuomisto J. (1997). Carcinogenicity of the drinking water mutagen 3-chloro-4-(dichloromethyl)-5-hydroxy-2(5H)-furanone in the rat. Journal of the National Cancer Institute 89, 848-856. [Documents the carcinogenicity of MX, considered to probably be the most mutagenic of DBPs]

Kramer M.H.J., Ford T.E. (1994). Legionellosis: Ecological factors of an environmentally 'new disease'. Zentralblatt fur Bacteriologie, Mikrobiologie und Hygiene 195, 470-482. [Explores the ecology of *Legionella* and provides a framework for understanding both exposure routes and disease outcomes]

Levins R., Awerbuch T., Brinkmann U., Eckardt I., Epstein P., Ford T., Makhoul N., Albuquerque de Possas C., Puccia C., Spielman A., Wilson M.E. (1995). The Emergence and spread of new diseases. The Ecologist 25, 21-26. [From the first academic group to attempt to seriously address the phenomenon of emerging disease – the Harvard Working Group on New and Resurgent Disease – this article explores issues of global change such as population increase and movement, development, pollution, and climate change in emergence of new diseases]

Levin R., Epstein P., Ford T.E., Harrington W., Olson E., Reichart E. (2002). US drinking water challenges in the 21st century. Environmental Health Perspectives, 110:43-52. [Reviews drinking water challenges specifically facing the US in this century]

Maximilien R., de Nys R., Holmstrom C., Gram L., Kjelleberg S., Steinberg P.D. (1998). Bacterial fouling is regulated by secondary metabolites from the red alga *Delisea pulchra.* Aquatic Microbial Ecology 15:233-246. [Describes how algal products may regulate bacterial fouling]

Marshall M., Naumovitz M., Ortega Y., Sterling C.R. (1997). Waterborne protozoan pathogens. Clinical Microbiology Review 10, 67-85. [Useful source of information on waterborne protozoan pathogens]

McFeters G. (ed). 1990. Drinking Water Microbiology, 502 pp. New York: Springer. [As mentioned for the Geldreich text, this classic edited book on drinking water microbiology by a highly respected author in the field, provides excellent reference material on microbes in drinking water]

Mohanty J.C., Ford T.E., Harrington J.J., Lakshmipathy V. (2002). Microbiological health risks of drinking water in Hyderabad City; a Preliminary Study. Journal of Water Supply: Research and technology-AQUA 51:239-251. [Relates water quality in the distribution system of a major Indian City with disease outcomes reported through questionnaire administration. Key elements contributing to burden of disease include lack of residual chlorine at point of use, poor distribution system condition and lack of wastewater collection]

Nilsson P., Olofsson A., Fagerlind M., Fagerstrom T., Rice S., Kjelleberg S., Steinberg P. (2001). Kinetics of the AHL regulatory system in a model biofilm system: how many bacteria constitute a "quorum"? Journal of Molecular Biology 309, 631-640. [Discusses the interactions between bacteria that lead to biofilm formation]

Rose J.B., Grimes D.J. (2001). Reevaluation of microbial water quality: powerful new tools for detection and risk assessment. Washgton, DC, USA: American Academy of Microbiology. [American Academy of Microbiology Report that focuses on new technologies to improve our ability to monitor pathogens in drinking water and conduct risk assessment]

Tamplin M., Gauzens A., Huq A., Sack D.A., Colwell R.R. (1990). Attachment of *Vibrio-cholerae* serogroup-O1 to zooplankton and phytoplankton of Bangladesh waters. Applied and Environmental Microbiology 56, 1977-1980. [Describes the now well-recognized association between *Vibrio cholerae* and planktonic organisms]

Lawrence J.R., Korber D.R., Hoyle B.D., Costerton J.W., Caldwell D.E. (1991). Optical sectioning of microbial biofilms. Journal of Bacteriology 173, 6558-6567. [Describes the use of confocal microscopy to provide 3D images of microbial biofilms]

Watnick P.I., Koulter R. (1999). Steps in the development of a *Vibrio cholerae* El Tor biofilm. Molecular Microbiology 34, 586-595. [Describes innovative molecular approaches used to understand biofilm formation by *Vibrio cholerae*]

WHO. 1993. Guidelines for Drinking-Water Quality, 2nd Ed, Vol 1, Recommendations. Geneva:WHO. [Generally globally-accepted international guidelines for water quality]

Biographical Sketch

Timothy Edgcumbe Ford has recently taken the position of department head of Microbiology at Montana State University (MSU), Bozeman, USA. He also retains an adjunct appointment at the Harvard School of Public Health, Boston, Massachusetts, USA where he was an Associate Professor of Environmental Microbiology and Director of the Program in Water and Health. He was a Faculty member in the Department of Environmental Health at the Harvard School of Public Health from 1992 until 2002. Prior to 1992, he was a Research Fellow and Lecturer in the Division of Applied Sciences at Harvard University.

His research interests (resulting in over 115 publications, to date) have included source and drinking water microbiology, microbial cycling and transformation of pollutants, surface microbiology (biofilms), microbiologically influenced deterioration of materials, and microbial populations as biomarkers of environmental stress. He has both directed and participated in water quality related projects in the US, Canada, the UK, Honduras, Mexico, India and Russia. Current research projects focus on the fate of opportunistic pathogens in drinking water biofilms, epidemiological studies on water and international health, and microbial interactions with pollutants.

Relevant activities have included:

- Co-Chair, American Academy of Microbiology Scientific Colloquium, "Global Issues in Microbiological Water Quality for the Next Century," Guayaquil, Ecuador, April 1995.

- Chair, Congressional briefing on "Increased Flooding Events and Risks to Human Health" Washington, DC (1998).
- Chair, Congressional briefing on "Water, Population and Human Health" Washington, DC. (1999).
- Chair, Congressional briefing on "Genetically Modified Crops" with Sea Change, Washington, DC.
- Invited participant: American Academy of Microbiology Scientific Colloquium, "Re-evaluation of Microbial Water Quality: Powerful New Tools for Detection and Risk Assessment," Amelia Island, Florida, March 2000
- Plenary speaker and moderator: Water Environment Federation (WEF)/ITT Industries forum, "Water and the Next Generation: a discussion on countermeasures to the water crisis," held at the UN on World Water Day, 2001
- Steering Committee member: American Academy of Microbiology Scientific Colloquium on "Infections through the Gastrointestinal Tract," Galway, Ireland, 2002
- Invited participant for WHO/US-EPA Expert group on environmental mycobacteria, Guildford, UK, 2002
- Waksman Foundation for Microbiology Speaker, 2003/2004
- Chair, International Colloquium on Protecting Public Health in Small Water Systems, Bozeman, Montana, 2004
- Member, editorial board of the Journal of Industrial Microbiology and Biotechnology
- Member, editorial board of the Journal of Environmental Science and Health
- Member, editorial board of Environmental Engineering Science