WATER QUALITY AND DISINFECTION

Takako Aizawa
Chief of Water Supply Engineering, National Institute of Public Health, Tokyo, Japan

Masanori Ando
Director of Environmental Chemistry, National Institute of Health Sciences, Tokyo, Japan

Mari Asami
Senior Researcher of Water Supply Engineering, National Institute of Public Health, Tokyo, Japan

Yasumoto Magara
Professor of Engineering, Hokkaido University, Sapporo, Japan

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Summary

The primary aim of the quality standards for potable drinking water is the protection of public health. The quality of water defined by potable drinking water standards is such that it is suitable for human consumption of health related chemicals and microbiological aspects and aesthetic and organoleptic characteristics, and for all usual domestic purposes, including personal hygiene.

Infectious microorganisms in water are scattered by water. Unlike chemical substances, they are safe as long as they are not taken into human bodies. In addition, many infectious microorganisms have different levels of infection according to their life cycle. Therefore, the risk that infectious microorganisms may have against human health is quite probabilistic. The influence of infectious microorganisms is generally curable—not incurable like cancer—because of the development of medical treatment. Group infection is defined as a situation where two or more people get infected with the same infectious microorganisms. Other waterborne infectious diseases occur in large cities, do not require their own standards in drinking water because of confusion with food-borne disease or their very low incidence.

It is important that tap water is not contaminated by pathogenic organisms, and that it is hygienically safe. Since it is not possible to completely remove microbes in water by sedimentation and filtration, tap water must be fully disinfected to secure hygienic safety in distribution systems. There are various kinds of disinfectants such as liquefied chlorine and other chlorination agents, i.e. chlorine dioxide, iodine, ozone or UV radiation process. Among them, liquefied chlorine is the most widely used because of its effectiveness, handling convenience and residual effects. On the other hand, it has the disadvantage that organic chlorine compounds, such as trihalomethane, are generated by reaction with certain substances, producing a strong odor. Furthermore, the disinfection effect is weakened by reaction with ammonium nitrogen.

Chlorination is known to generate chlorination by-products in reaction with natural organic matter (NOM) and with bromide—both present in the water. Chloroform was considered the by-product generated in the course of reaction between humic substances and chlorine. These chlorination by-products have induced a general concern about health risk. Hundreds of chlorinated organic compounds have been reported in chlorinated water. The most prominent group is the trihalomethanes, which are halogen-substituted single-carbon compounds. The cancer risks have been estimated, for example, on the basis of the fact that bromodichloromethane induces kidney tumors in male mice.

It is very difficult to control either disinfectant or disinfectant by-products (DBPs) while still ensuring pathogenic safety; especially if the water source is ubiquitously contaminated. In addition, analysis of DBPs requires skilled experts and expensive

analytical equipment., It is reasonable, therefore, to control disinfectant and DBPs with an appropriate protocol such as best available technology (BAT), as proposed by U.S. Environmental Protection Agency.

1. Introduction

Fresh water is supplied by precipitation and flows over the ground surface, and becomes available water resource. During the processes leading to water resources, water dissolves or suspends various kinds of impurities. There is an acceptable level of impurities for every purpose of water use. It is necessary to stipulate the level which does not cause any hazard, whether to human bodies or to use of water, according to the purpose of water usage. Many organic and inorganic chemicals and microorganisms exist in drinking water as well as ambient waters.

The primary aim of the quality standards for potable drinking water is the protection of public health. The quality of water defined by potable drinking water standards is such that it is suitable for human consumption of health-related chemicals and microorganisms, and aesthetic and organoleptic characteristics, and for all usual domestic purposes, including personal hygiene.

It is important that tap water is not contaminated by pathogenic organisms, and that it is hygienically safe. Since it is not possible to completely remove microbes in water by sedimentation and filtration, tap water must be fully disinfected to ensure hygienic safety in distribution systems. For this reason, purification facilities, both small and large, and irrespective of treatment methods, are recommended to provide disinfection systems.

2. Quality standards for potable water

2.1. Development of national standards

The World Health Organisation Drinking Water Quality Guidelines (WHODWQG) are able to provide for the establishment of national standard of drinking water. WHODWQG describe how guideline values for drinking-water contaminants are to be used, defines the criteria used to select the various chemical, physical, microbiological, and radiological contaminants included in the report, describes the approaches used in deriving guideline values, and presents brief summary statements either supporting the guideline values recommended or explaining why no health-based guideline value is required at the present time. The process for the development of water quality standard is given by the protocol for WHO drinking water quality guidelines. Since regulatory standards should be applicable and feasible to enforce in each country and area, in a range of natural, geological, cultural and economical situations, it is necessary to periodically reassess and re-evaluate the standards.

WHODWQG includes many drinking contaminants, but it is unlikely that all of these chemical contaminants will occur in all water supplies and even in all countries. Care should be taken in selecting substances and/or items for establishing national drinking water standards. However, a number of factors should be considered, including the types of human activities that take place in the region. For example, if a particular pesticide is not used in a region, it is unlikely to occur in the drinking water. In other cases, such as disinfection by-products (DBPs), it may not be necessary to set standards for all substances for which guideline values have been proposed. If chlorination is practiced, the trihalomethanes, of which chloroform is the major component, are likely to be main disinfection by-products, together with the chlorinated acetic acids in some instances. In many cases, control of trihalomethanes, halo-acetic acids and other disinfection by-products will also provide an adequate measure of control over other chlorination by-products.

In developing national standards, care should be taken to ensure that scarce resources are not unnecessarily diverted to the establishment of standards and monitoring of substances of relatively minor importance. Generally, microbiological indexes, inorganic and organic substances and aesthetic items comprise the national drinking water quality standards.

The potential consequences of microbial contamination are such that its control must always be of paramount importance and must not be compromised. The provision of a safe supply of drinking water depends upon the use of either a protected high quality groundwater or a properly selected and operated series of treatments capable of reducing pathogens to negligible levels not hazardous to health. Microbial water quality may change rapidly and over a wide range. Short-term peaks in pathogen occurrence may increase disease risks considerably and may also trigger outbreaks of waterborne disease that may affect large numbers of persons. For these reasons reliance cannot be placed on water quality measurements, even when frequent determination of the safety of drinking water is made—it is unable to provide timely indication of water quality deterioration.

The health risks due to toxic chemicals in drinking water differ form those caused by microbiological contaminants. The fact that chemical contaminants are not normally associated with acute effects places them in a lower priority category than microbiological contaminants, the effects of which are usually acute and widespread. Therefore, it can be argued that chemical standards for drinking water are of secondary consideration in a supply subject to severe bacterial contamination.

The problems associated with chemical substances in drinking water arise primarily from their ability to cause adverse health effects after prolonged periods of exposure; of particular concern are contaminants that have cumulative toxic properties, such as heavy metals, and substances with carcinogenicity.

It should be noted that the use of chemical disinfectants in water treatment usually results in the formation of chemical by-products, some of which are potentially hazardous. However, the risks for health from these by-products are extremely small in comparison with the risks associated with inadequate disinfection, and it is important that disinfection should not be compromised in attempting to control such by-products.

In assessing the quality of drinking water, the consumer relies principally upon their senses. Microbial, chemical, and physical water constituents may affect the appearance, odor, or taste of the water, and the consumer will evaluate the quality and acceptability of the water on the basis of these criteria. Water that is highly turbid, highly colored, or that has a detectable level of taste or odor may be regarded by consumers as unsafe and may be rejected for drinking purposes.

In extreme cases, consumers may avoid aesthetically unacceptable but otherwise safe supplies in favor of more pleasant but potentially unsafe sources of drinking water. It is, therefore, vital to maintain a quality of water that is acceptable to the consumer, and the absence of any adverse sensible effects does not guarantee the safety of the water.

Taste and odor problems in drinking-water supplies are often the largest single cause of consumer complaints.

Changes from the normal taste of a public water supply may signal changes in the quality of the raw water source or deficiencies in the treatment process. It is therefore wise to be aware of consumer perceptions and to take into account both health-related guidelines and aesthetic criteria when assessing drinking-water supplies.

2.2 Chemical and acceptability aspects

In the process for the execution of the drinking water quality standard, first, a priority list of contaminants is prepared by referring to reports and publications on environmental pollutants, and, second, a literature survey on their toxicity is implemented (see Figure 1). Then the primary acceptable concentrations of contaminants in drinking water are calculated.

The primary acceptable concentration in drinking water is basically calculated from the tolerable daily intake (TDI) (see below), which no-observed adverse effect or lowest observed adverse effect will occur.

$$TDI = (NOAEL \text{ or } LOAEL)/UF \qquad (1)$$

Where:

NOAEL = no-observed-adverse-effect-level
LOAEL = lowest-observed-adverse-effect-level
UF = uncertainty factor

The NOAEL is defined as the highest dose or concentration of a chemical in a single study, found by experiment or observation, that causes no detectable adverse health effect. Wherever possible, the NOAEL is based on long-term studies, preferably of ingestion in drinking water. However, NOAELs obtained from short-term studies and studies using other sources of exposure (e.g. food, air) may also be used.

If a NOAEL is not available, a LOAEL may be used, which is the lowest observed dose or concentration of a substance at which there is a detectable adverse health effect. When a LOAEL is used instead of a NOAEL, an additional uncertainty factors is normally applied.

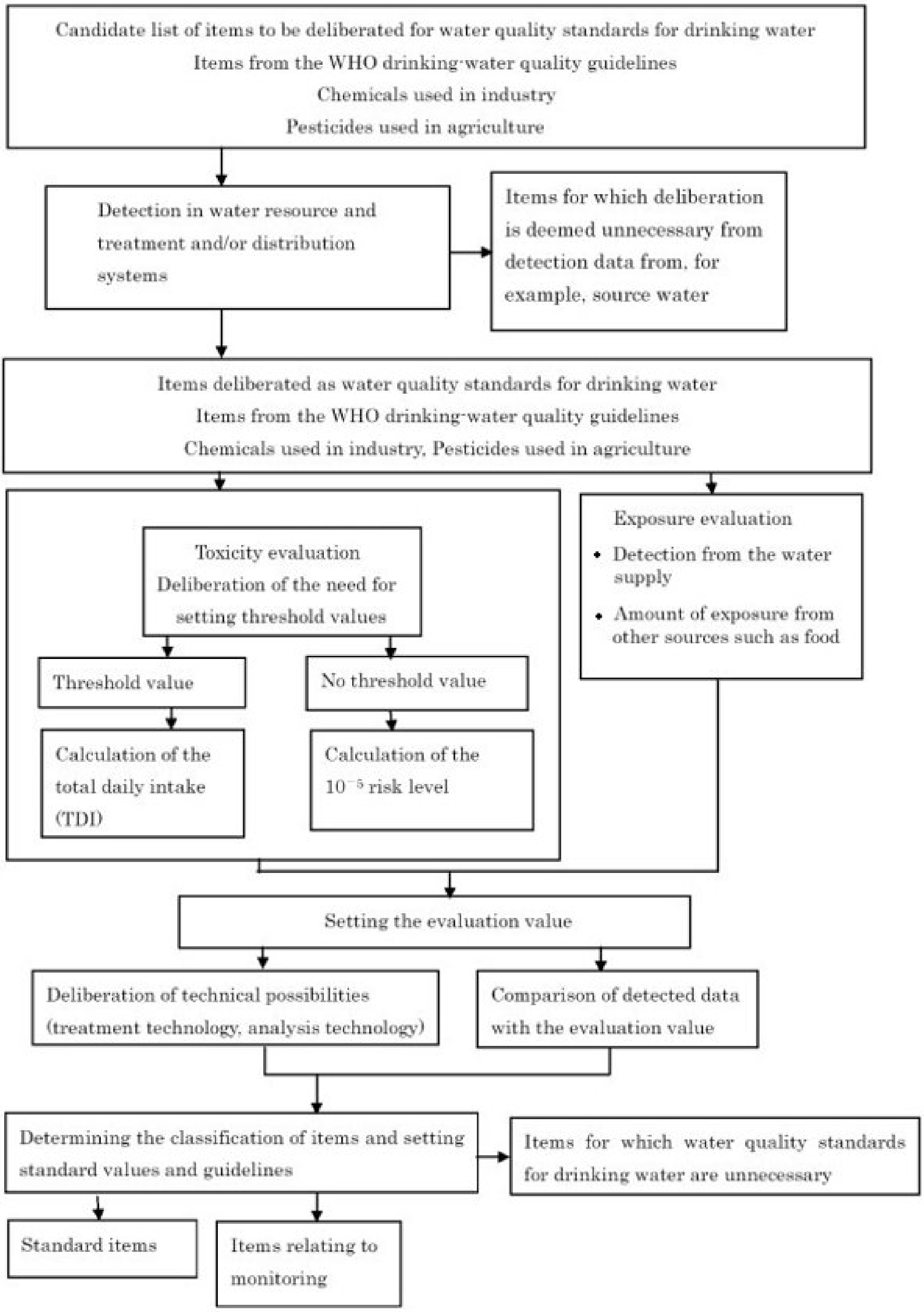

Figure 1. Example of a setting-chart of national water quality standards for drinking water

In the derivation of guideline values, uncertainty factors are applied to the NOAEL or LOAEL for the response considered to be the most biologically significant and are determined by the approach outlined in Table 1.

Source of uncertainty	**Factor**
Interspecies variation (animals to humans)	1 – 10
Intraspecies variation (individual variations)	1 – 10
Adequacy of studies or database	1 – 10
Nature and severity of effect	1 – 10

Table 1. Application of uncertainty factor for derivation of Guideline values

Inadequate studies or databases include those where a LOAEL was used instead of a NOAEL and studies considered to be shorter in duration than desirable. Situations in which the nature or severity of effect might warrant an additional uncertainty factor include studies in which the endpoint was mal-formation of a fetus or in which the end point determining the NOAEL was directly related to carcinogenicity. In the latter case, an additional uncertainty factor was applied for carcinogenic compounds for which a guideline value was derived using TDI approach.

Besides the TDI approach, each contaminant is evaluated for carcinogenicity according to a similar classification adopted by the IARC. In the case of compounds considered to be genotoxic carcinogens, evaluation values are determined using mathematical model, and evaluation values are presented as the concentration in drinking water associated with an estimated excess lifetime cancer risk of 10^{-5}. If a contaminant is classified as a known or probable human carcinogen, its primary acceptable concentration in drinking water is the value calculated using a low-dose extrapolation model. If a contaminant is classified to be a non-genotoxic carcinogen or a possible human carcinogen, its primary acceptable concentration in drinking water is the value after application of an additional uncertainty factor of ten to the value obtained using the TDI approach.

In many cases, the intake of the substances from drinking water is small in comparison with that from other sources such as food or air. Standard values derived using the TDI approach take the exposure from all sources into account by apportioning a percentage of the TDI to drinking water. Wherever possible, data concerning the proportion of total intake normally ingested in drinking water (based on mean levels in food, air and drinking-water) or intakes estimated on the basis of consideration of physical and chemical properties, are used in the derivation of the guideline values. Where such information is not available, an arbitrary (default) value of 10% for drinking water is used. However, in case of disinfectants and disinfection by products 20% of TDI is applied as an allocation factor because they are not commonly found in either food or air. Furthermore, in setting the national drinking water standard values for potentially hazardous chemicals, a daily consumption of two liters by person weighting 60 kg is generally assumed.

The provision of drinking water that is not only safe but also acceptable in appearance, taste, and odor is of high priority. The supply of water that is aesthetically unsatisfactory will undermine the confidence of consumers, leading to complaints and possibly the use of water from sources that are less safe. It can also result in the use of bottled water, which is expensive and sometimes of poor microbiological quality, and home treatment devices, which are costly and some of which can have adverse effects on water quality.

The acceptability of drinking-water to consumers can be influenced by many different constituents that are objectionable to consumers. This is dependent on individual and local factors, including the quality of the water to which the community is accustomed and a variety of social, economic, and cultural considerations. Therefore, the standard for acceptability should be set at the level at which consumers would normally reject water.

Practical implementation of water quality standard values or guideline values requires collection and analysis of samples. The sampling program should be designed to cover both random and systematic variations in water quality and to ensure that the collected samples are representative of water quality throughout the whole distribution system. The type and magnitude of spatial and temporal variations in the concentration of water constituents will depend on both their sources and their behavior in the distribution system.

Substances can be classified into two main types. Type One substances do not undergo any reaction in the distribution system. Type Two substances may participate in reactions and change concentration within the distribution system. The exact sites for sampling need to be chosen carefully to provide samples that are representative of the whole system or of the particular area. For Type One substances, it is generally sufficient to sample only where the water enters the supply. The concentrations of Type Two substances are affected by many process; and, therefore, tend to show complex and erratic variation with time. Sampling locations and times should be chosen jointly, as there are limitations on the amount of sampling and analysis that can be carried out. Two extreme strategies are: (1) to sample many taps, each on only one or a few occasions, and (2) to sample fewer taps, but each more frequently. The relative magnitudes of spatial and temporal variation will clearly be an important factor in selecting a strategy. Where spatial variations predominate, greater effort will generally be directed to strategy (1) than to strategy (2).

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Bibliography

AWWA. (1999). *Waterborne pathogens*, Manual of water supply practices, First edition. American Water Works Association, Denver, USA. 285 pp. [This manual includes chapters on waterborne disease outbreaks, water quality in treatment and distribution systems, water quality monitoring, sampling and testing, and sections for organisms classified as parasite, bacteria, or virus.]

Braghetta, A., Jacangelo, J., Trussell, R. R., and Meheus, J. (1997). *The practice of chlorination: application, efficacy, problems and alternatives*. IWSA. [The report on chlorination prepared by the scientific and technology committee of IWSA.]

DeZuane J. (1997). *Handbook of drinking water quality*, second edition. John Wiley & Sons, New York, USA. 575 pp. [This handbook is an essential volume for engineers, water supply and treatment personnel, environmental scientists, public health officials, or anyone responsible for assuring the safety of drinking water.]

Fewtrell L and Bartram J. (2001). *Water quality*: Guidelines, standards and health, Assessment of risk and risk management for water-related infectious disease. IWA Publishing, London, UK. 424 pp. [This book is useful to all those concerned with issues relating to microbial water quality and health, including environmental and public health scientists, water scientists, policy-makers and those responsible for developing standards and regulations.]

JWWA and JICA (1990). *Design criteria for waterworks facilities*. Japan Water Works Association and Japan International Cooperation Agency. [This book describes matters to be considered in promoting the new arrangement and improvement of waterworks facilities, the procedure for establishing a master plan, the contents of master plan, and criteria and items of note for designing.]

Ministry of Health and Welfare, Japan (1999). Outline of the review on water quality standards for drinking water.

Rook, J.J. (1977) Chlorination reactions of fluvic acids of natural waters, *J. Environ. Sci. Techlonol*, 11:478-482 [Traditional paper first pointed out generation of chlorination by-products.]

U.S. EPA (1998) Federal Register 40 CFR Parts, 141, and 142,Part IV, 1998.12.16. [New U. S. concept for disinfectant and DBPs are contained. A new standard for bromate is presented.]

WHO (1993). *Guidelines for drinking-water quality*, Second Edition, Volume 1, Recommendations, 188 pp. Geneva: World Health Organization. [This contains the guideline value together with an explanation of how they should be used, the criteria used in selecting the various contaminants considered, a description of the approaches used to derive the guideline values, and brief summary statements supporting the values recommended or explaining why no health-based guideline value is necessary at present.]

WHO (1996). *Guidelines for drinking-water quality*, Second Edition, Volume 2, Health criteria and other supporting information, 973 pp. Geneva: World Health Organization. [This explains how the guideline value for drinking-water contaminants are to be used, defines the criteria used to select the various chemical, physical, microbiological, and radiological contaminants included in the report, describes the approaches used in deriving guideline values, and presents brief summary statements either supporting the guideline values recommended or explaining why no health-based guideline value is required at the present time.]

WHO (2000) Disinfection and Disinfectant By-products, Environmental Health Criteria 216, International Programme on Chemical Safety, Geneva [Disinfectant and DBPs have been reviewed from various aspects. WHO guidelines should be reviewed with the results.]

Biographical Sketches

Takako Aizawa is Chief of Water Quality Management Division at National Institute of Public Health, where she has been in office since 1971. She has served as Chief of Division since 1988. She received her degree of Bachelor of Education at Yokohama National University in 1968. Since 1971, her research and professional activities have been on micro-pollutant in the water environment, and have included analysis and safety evaluation of micro-pollutants, evaluation of disinfectants and disinfection by-products for water supply, and development of new water treatment technology for micro-pollutant removal. In the meantime, she also obtained a PhD in Engineering from Hokkaido University. At present, she teaches occasional courses at post-graduate level on risk management of pesticides in water.

She has authored or co-authored more than 50 research articles and written books on the aquatic environment.

Masanori Ando is Director of Environmental Chemistry at National Institute of Health Sciences, where he has been in office since 1991. He was admitted to Meiji Pharmaceutical University in 1963 and received the degree of Bachelor of Pharmacology in 1967. He commenced his professional carrier at National Institute of Hygienic Sciences in 1968. He served as a researcher in Environmental Hygiene Chemistry Department. He was promoted to Senior Research Officer of the Department in 1983, then Section Chief in 1987. In the meantime, he also obtained a Ph.D. in Pharmacology from the University of Tokyo in 1977. Since 1995, the Institute has changed the name to National Institute of Health Sciences for which he is now serving. His research subject covers environmental chemistry, analytical science, chemical toxicology, health science, exposure assessment, etc.

Doctor Ando has written 'Analytical Methods for Drinking Water'. He has been the author or co-author of approximately 80 research articles.

Mari Asami is Senior Researcher of Water Quality Management Division in Department of Water Supply Engineering at National Institute of Public Health, where she has been in office since 1993. She obtained a Bachelor Degree of Engineering from the Department of Urban Engineering, University of Tokyo in 1991, and a Master Degree in 1993 from the Graduate School of the same department. At National Institute of Public Health, she mainly works on Risk Assessment and Management of Drinking Water and Analysis of Trace Chemicals in Drinking Water using GC/MS, IC and LC/MS.

She also works with Peking University, China on cooperative research entitled Risk Minimization of Hazardous Chemicals in Water.

Yasumoto Magara is Professor of Engineering at Hokkaido University, where he has been on faculty since 1997. He was admitted to Hokkaido University in 1960 and received the degree of Bachelor of Engineering in Sanitary Engineering in 1964 and Master of Engineering in 1966. After working for the same university for 4 years, he moved to National Institute of Public Health in 1970. He served as the Director of the Institute since 1984 for Department of Sanitary Engineering, then Department of Water Supply Engineering. In the meantime, he also obtained a Ph.D. in Engineering from Hokkaido University in 1979 and was conferred Honorary Doctoral Degree in Engineering from Chiangmai University in 1994. Since 1964, his research subjects have been in environmental engineering and have included advanced water purification for drinking water, control of hazardous chemicals in drinking water, planning and treatment of domestic waste including human excreta, management of ambient water quality, and mechanisms of biological wastewater treatment system performance. He has also been a member of governmental deliberation councils of several ministries and agencies including Ministry of Health and Welfare, Ministry of Education, Environmental Agency, and National Land Agency. He meanwhile performs international activities with JICA (Japan International Cooperation Agency) and World Health Organization. As for academic fields, he a plays pivotal role in many associations and societies, and has been Chairman of Japan Society on Water Environment.

Professor Magara has written and edited books on analysis and assessment of drinking water. He has been the author or co-author of more than 100 research articles.