MONITORING DRINKING WATER SUPPLIES

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Contents

Summary

The defining characteristic of drinking water is its use for consumption and other domestic purposes. This allows limits to be set based on a risk to health with the measures of safety defined based on microbial and chemical hazards. The importance of drinking water supply on public health demands that the monitoring of sources of drinking water is an integral and essential part of water resource monitoring and requires systematic routine monitoring and assessment. The impact of microbiological quality tends to be acute and is related to infectious disease outbreaks. Given the wide range of pathogens and an overwhelmingly fecal source, microbial hazards are usually assessed using indicators, although increasing evidence of limitations with current indicators emphasizes the need for other approaches to define risk. Microbiological quality shows significant spatial and temporal variability and this must be borne in mind when developing monitoring networks. Chemical hazards are in general linked to chronic effects based on long-term exposure to raised concentrations. There are multiple

exposure routes, and guidelines and limit values for water take into account the degree to which exposure occurs through drinking water. Chemical quality is generally less variable than microbiological quality, leading to lower frequency of assessment. Interpretation of the findings of monitoring must take into account a number of other factors such as seasonal and source influences. In addition to water quality analysis, other forms of data collection such as sanitary inspection and community interview are important. Sampling will usually involve the source and in the case of microbiological quality, subsequent distribution, collection and storage. Monitoring data should lead to improvements in the management of water supplies through technical, environmental, educational and regulatory processes. Small or community-managed supplies represent particular problems both in terms of data collection and use of the data.

1. Introduction

The definition of quality as 'suitable for a given purpose' is generally difficult to apply to water, which is subject to diverse uses and where different uses may have diverse quality requirements. Furthermore, there exists a general public and professional awareness that a water may be degraded (ie of lower quality) without this being measurable with respect to defined indices and limit values.

The defining characteristic of drinking water is its use for consumption and other domestic purposes including hygiene. One result of this clear definition is that fixed points of reference or measures of quality may be derived. These measures of quality are almost exclusively based upon public health considerations. Because of its paramount importance, this work will emphasize public health aspects of drinking water quality.

Other aspects of the quality of drinking water quality include aesthetic parameters such as colour and turbidity (although the principal importance of the latter relates to its significance for microbiological quality and therefore to human health); quality in relation to the cost of treatment (in turn oriented principally to the protection of public health); and the influence of water quality on the longevity and maintenance requirements of distribution systems (eg 'aggressivity'; which again has direct health significance through dissolution of potentially toxic materials).

Notwithstanding the orientation of this work towards water quality, health-related monitoring of drinking water sources also concerns quantitative aspects of drinking water sources and source reliability. Restricted access to drinking water for domestic use and for consumption may have profound impacts upon human health. Resource availability often has a quality dimension, as over-abstraction of water resources often leads to an associated decline in water quality. Furthermore, any estimate of water resource quantity should take into account quality as this will determine the degree to which additional costs will be incurred to make the water suitable for drinking purposes. Thus quality and quantity aspects of drinking water sources are intimately interconnected.

As drinking water is a fundamental requirement for human existence and because the provision of water supplies for consumption must take into account health impacts of

poor quality water, the monitoring of water resources should include the monitoring and protection of drinking water sources. Thus monitoring of water resources, which will typically assess trends in availability (quantity) and quality, must also take into account the need to ensure that sources of water available for drinking water supplies are not unduly degraded in quality or restricted in availability.

2. Scientific Basis

Understanding the scientific basis of drinking water source monitoring has three fundamental components: defining 'safety' or 'quality'; understanding the relationship between the findings of monitoring activities and measures of safety/quality; and understanding the relationship between source water quality and the quality of water received by a consumer. All three components interact with one another.

2.1. Drinking water quality: defining safety

The definition of 'safety' adopted by the World Health Organization (WHO) for drinking water is that water: 'should not result in any significant risk to the health of the consumer over a lifetime of consumption'**.** It is illustrative of the approach adopted by most regulatory agencies. The hazards concerned may be either microbiological, chemical or radiological in nature.

2.1.1. Microbial Hazards

Typically, microbiological hazards are of greatest concern and constitute the causative agents of disease (pathogens) that may be transmitted through consumption of contaminated water. They may be protozoa, viruses or bacteria. There are a wide variety of microbiological agents that may be transmitted through drinking water (Table 1) (see *Classification of water-related disease*, *New and emerging waterborne infectious diseases*). Analytical methods are available for some of these, but unavailable for many others. Where analytical methods exist they may not be quantitative, may have insufficient sensitivity and problems may be encountered in their application to water as an analytical medium.

Pathogen	Health significance[b]	Persistence in water supplies[c]	Resistance to chlorine[d]	Relative infectivity[e]	Important animal source
Bacteria					
Burkholderia pseudomallei	High	May multiply	Low	Low	No
Campylobacter jejuni, *C. coli*	High	Moderate	Low	Moderate	Yes
Escherichia coli – Pathogenic[f]	High	Moderate	Low	Low	Yes
E. coli – Enterohaemorrhagic	High	Moderate	Low	High	Yes
Legionella spp.	High	May multiply	Low	Moderate	No

Non-tuberculous mycobacteria	Low	May multiply	High	Low	No
Pseudomonas aeruginosa[g]	Moderate	May multiply	Moderate	Low	No
Salmonella typhi	High	Moderate	Low	Low	No
Other salmonellae	High	May multiply	Low	Low	Yes
Shigella spp.	High	Short	Low	High	No
Vibrio cholerae	High	Short to long[h]	Low	Low	No
Yersinia enterocolitica	Moderate	Long	Low	Low	Yes
Viruses					
Adenoviruses	Moderate	Long	Moderate	High	No
Enteroviruses	High	Long	Moderate	High	No
Astroviruses	Moderate	Long	Moderate	High	No
Hepatitis A virus	High	Long	Moderate	High	No
Hepatitis E virus	High	Long	Moderate	High	Potentially
Noroviruses	High	Long	Moderate	High	Potentially
Sapoviruses	High	Long	Moderate	High	Potentially
Rotavirus	High	Long	Moderate	High	No
Protozoa					
Acanthamoeba spp.	High	May multiply	Low	High	No
Cryptosporidium parvum	High	Long	High	High	Yes
Cyclospora cayetanensis	High	Long	High	High	No
Entamoeba histolytica	High	Moderate	High	High	No
Giardia intestinalis	High	Moderate	High	High	Yes
Naegleria fowleri	High	May multiply[i]	Low	Moderate	No
Toxoplasma gondii	High	Long	High	High	Yes
Helminths					
Dracunculus medinensis	High	Moderate	Moderate	High	No
Schistosoma spp.	High	Short	Moderate	High	Yes

Table 1. Examples of pathogens found in drinking water

For all of the agents listed in Table 1 a single exposure may be significant for public health and, for example, sufficient microbes to cause disease may be consumed in a single glass of apparently innocuous water. Furthermore, this 'infectious dose' may be extremely small - potentially as little as a single viable cyst or virion for some protozoa and viruses. The principle that no pathogens should be present in drinking water has therefore become widely accepted.

This principle, alongside the lack of analytical methods and the fact that almost all of the pathogens of interest are primarily derived from human excreta (feces) led to the development of the concept of 'fecal indicators'. The value of quantitative estimates of fecal indicator bacteria in water was recognised early in the history of sanitary microbiology. The definition of microbiological quality now used in most regulatory and non-regulatory monitoring world-wide is therefore based on the premise that fecal contamination of drinking water is unsafe and that assessing the presence of indicators of fecal contamination provides an indication of the safety of drinking water. The characteristics of the ideal indicator have been defined and are summarized below in box 1.

The use of fecal indicators has made a significant contribution to the protection of human health over a sustained period and it continues to be valuable and popular. It is nevertheless imperfect both in conception and in application. Its principal limitations relate to well-recognized shortcomings of the principal available indicators and their ability to meet the basic criteria presented in Box 1. The majority of currently used indicators are bacteria and this has important implications regarding their use and the information they provide in relation to non-bacterial pathogens.

There has been increasing evidence of presence of pathogens in water meeting current Guidelines and standards for the principal fecal indicator bacteria, *E. coli.* In some cases this has been associated with outbreaks of infectious disease related to the consumption of contaminated water. As a result, greater attention has been placed on defining alternative methods of defining microbiological quality, including testing for pathogens, identification of alternative indicators especially for non-bacterial pathogens (for instance phage as an indicator of potential viral contamination) and risk assessment approaches. For instance, in the case of *Cryptosporidium* spp., monitoring is perhaps better focused on ensuring adequate sanitary completion of groundwater sources and control of turbidity during treatment.

The use of the indicator approach is based upon a target of 'zero risk'. It is increasingly recognized that zero risk is unachievable and its pursuit inhibits the application of risk-benefit approaches. It is unlikely that any approach will provide the degree of certainty required to define a 'safe' water supply in all circumstances and current indicators can be taken as indicative of recent and gross fecal pollution. This then leads to change in the way we view microbiological contamination, which is that no water is 'safe', but rather may be low, intermediate or high risk.

The indicator approach also fails to address the idea of a 'tolerable disease burden'. Any attempt to address the concept of tolerable disease burden would change the role of fecal indicator organisms as indicators of quality, without necessarily changing their role as operational tools in drinking water quality management. The idea of tolerable disease burden (TDB) is especially important in drinking water microbiological safety because of the variable health outcomes from different exposures. Most studies have addressed diarrhoeal diseases which, although they account for a significant global burden of disease, are often self-limiting and may be contrasted with more severe health outcomes. Different pathogens may produce diseases of varying public health importance, e.g. enteric hepatitis viruses (hepatitis); *Vibrio cholerae* (cholera);

Cryptosporidium spp (cryptosporidiosis); or *Salmonella typhi* (typhoid). The World Health Organization in its Guidelines for Drinking-water Quality therefore uses a TDB approach based on disability-adjusted life years or DALYs.

Translating TDB into practical descriptions of quality is complex. The distribution of microbes in water (individual or clustered on particulates) may have a profound effect on the probability of infection or of developing disease. The relationship between exposure, infection and disease, especially at low dose exposures remains poorly understood for most pathogens and inter-relates with external factors such as immunity and the form of exposure (e.g. from food, aerosols etc). In this respect, approaches to defining a TDI for pathogens would have to follow a similar conceptual framework as that used for 'non-threshold' chemicals, discussed below. Increasing attention is being paid to the characteristics of individual pathogens and the concept of TDB and the corresponding WHO Guidelines. Substantial ongoing work will see this theme develop rapidly in future years (see *Burden of disease: current situation and trends*).

2.1.2 Chemical hazards

In order to establish safe levels of chemical contaminants in drinking water or food it is necessary to first determine the total dose that is considered to be without adverse health effects when consumed daily over a lifetime of exposure from all possible routes. This rate of consumption is referred to as a 'tolerable daily intake'. Most standards that are derived for chemical substances are based on the WHO Guidelines for Drinking-Water Quality and within the WHO Guidelines approach, a lifetime consumption is taken as 70 years.

The preferred source of information for establishing a tolerable daily intake is from studies on human populations - such as from naturally-exposed populations. However such epidemiological studies are often inadequate or have not been undertaken. Most frequently therefore information is derived from studies on animals that are artificially exposed to a substance of interest in a controlled manner.

One of the major shortcomings with animal studies is that animals and humans differ in their sensitivity so that uncertainty factors need to be incorporated to take account of this. A further major shortcoming of these studies concerns the route of exposure. The contaminants of interest will be more or less toxic depending on whether they are administered by the intravenous or intraperitoneal routes or ingested. For some contaminants of interest obtaining sufficiently pure material in a form still relevant to exposure through ingestion may prove problematic.

Whether human or animal studies are being used, the highest dose which is not associated with any adverse health effects is referred to as the No Observed Adverse Effect level or NOAEL. If available studies fail to identify a NOAEL, then sometimes the Lowest Observed Adverse Effect level or LOAEL is employed. If animal data is being employed then typically uncertainty factors of 1 - 10 (often the latter) will be applied to account for each of differences in inter-species and intra-species sensitivity. Additional uncertainty factors may also be applied to take account of inadequacies in the information base and/or severity of the health outcomes. When human data is being

used, exposures have often been poorly characterized and this may cause problems in data interpretation and in addition some of the uncertainty factors employed in interpreting animal data may also be relevant.

Once a reasonable estimate of the TDI has been made, it is necessary to relate this to the concentrations that may be accepted as safe in drinking water. In the WHO Guidelines approach, a guideline value for lifetime consumption of a chemical contaminant of drinking water is usually calculated by applying the derived TDI to a typical daily water intake in litres by an individual of a given body weight. The proportion of intake that is ingested through drinking water is considered because intake through air or by inhalation may be significant or dominant for some contaminants.

It is generally considered that the initiating event in the process of chemical carcinogenesis is the induction of a mutation in the genetic material (DNA) of somatic cells (i.e., cells other than ova or sperm). As the genotoxic mechanism theoretically does not have a threshold, there is a probability of harm at any level of exposure. Therefore, the development of a TDI is considered inappropriate and mathematical low-dose extrapolation is applied. On the other hand, there are carcinogens that are capable of producing tumors in animals or humans without exerting genotoxic activity, but acting through an indirect mechanism. It is generally believed that a threshold dose exists for these non-genotoxic carcinogens. Each compound that is known to be a carcinogen is evaluated with respect to the underlying mechanism of carcinogenicity. This takes into account the evidence of genotoxicity, the range of species affected and the relevance to humans of the tumors observed in experimental animals.

For carcinogens for which there is convincing evidence to suggest a non-genotoxic mechanism, WHO Guideline Values are calculated using a TDI approach. In the case of genotoxic carcinogens, the Guideline Values are determined using a mathematical model, in most cases this is the linearized multistage model. The value presented in the Guidelines for Drinking-water Quality, are the concentrations in drinking water associated with an estimated upper bound excess lifetime cancer risk of 10^{-5} (one additional cancer case per 100, 000 of the population ingesting drinking water containing the substance at the guideline value for 70 years). Concentrations associated with estimated excess lifetime cancer risk of 10^{-4} and 10^{-6} can be calculated by multiplying and dividing, respectively, the guideline value by 10. These values are also presented in the Guidelines for Drinking-water Quality to emphasize the fact that each country should select its own appropriate risk level.

Guideline Values for carcinogenic compounds computed using mathematical models must be considered at best as a rough estimate of the cancer risk. These models do not usually take into account a number of biologically important considerations, such as pharmaco-kinetics, DNA repair, or immunological protections mechanisms. The models used are conservative and probably err on the side of caution. Furthermore ‘upper bound’ values are used.

To account for differences in metabolic rates between experimental animals and humans – the former are more closely correlated with the ratio of body surface areas than with body weights – a surface area to body weight correction is sometimes applied to

quantitative estimates of cancer risk derived on the basis of models for low-dose extrapolation. Incorporation of this factor increases the risk by approximately an order of magnitude (depending on the species upon which the estimate is based) and increases the risk estimated on the basis of studies in mice relative to that in rats. The incorporation of this factor is considered to be overly conservative, particularly in view of the fact that linear extrapolation is likely to overestimate risk at low doses; indeed, it has been suggested that 'all measures of dose except dose rate per unit of body weight tend to result in overestimation of human risk'.

It is important that guideline values are both achievable and protective of public health. For instance, WHO does not establish guideline values lower than the detection limits achievable under normal laboratory operating conditions. Moreover Guideline Values are recommended only when control techniques are available to achieve the concentration of the contaminant to the desired level. In these circumstances the guideline values are referred to as provisional. In some instances provisional guideline values may be established for constituents for which there is some evidence of a potential hazard but where the available information on health effects is limited. WHO also establishes provisional Guideline Values where the NOAEL/LOEAL is likely to be exceeded as a result of disinfection to ensure microbiological safety, given the evidence of the effectiveness of disinfection to inactivate most pathogens. Illustrative guideline values for different groups of chemicals are shown in Table 2.

Type of substance	**Parameter**	**Guideline value**
Inorganic	Arsenic	0.01 mg/l (Provisional)
	Fluoride	1.5 mg/l
	Nitrate	50mg/l
Organic	1,1 di-chloroethene	30µg/l
	Dichloromethane	20µg/l
	Tributyltin oxide	2µg/l
Pesticides	Atrazine	2µg/l
	Lindane	2µg/l
	Methoxyclor	20µg/l
Disinfectant by-product	Dichloroacetic acid	50 µg/l (Provisional)
	Formaldehyde	900µg/l
	Bromoform	100µg/l

Table 2. Illustrative guideline values for groups of chemicals

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Biographical Sketches

Dr James K. Bartram has been based at the World Health Organization's Headquarters in Geneva since 1998, where he is the Coordinator of the Water, Sanitation, Hygiene and Health Programme. The Programme has received international recognition for leadership in evidence based policy and good practice and also leads WHO's work on cholera and epidemic diarrhoeal diseases.

In WHO HQ, Dr Bartram has also served as Coordinator for the Programme on Assessing and Managing Environmental Risks to Health, charged to ensure an adequate evidence base for policy making and decision-taking in public health and environment.

From 2004 to 2006 Dr Bartram also served as the first chair of UN-Water – the mechanism responsible to ensure coherence and coordination in UN system actions related to water - overseeing establishment of Terms of Reference, inter-agency workplan development, increased financial support and establishment of two new offices.

Dr Bartram's previous posts have included: Manager, Water and Wastes at the WHO European Centre for Environment and Health in Rome – working especially on management of international waters; Head of the Environmental Health Division of the Robens Institute of the University of Surrey in the UK; and Public Health Scientist in Peru.

He has worked in diverse areas of public health and disease prevention, especially in relation to environment and health and water supply and sanitation; and in more than 30 developing and developed countries worldwide.

Dr Bartram was awarded the IWA (International Water Association) 'Grand Award' in 2004 and holds Honorary Professorships at the University of Wales at Aberystwyth, and at the University of Bristol, UK. He received his first degree and PhD from the University of Surrey, UK and is author of more than 60 academic papers and more than 40 book chapters, and editor of around 25 books.

Guy Howard is a water and sanitation expert with over 20 years experience in low and middle income countries and a PhD in surveillance of water supply in urban areas of developing countries. He works for the UK Department for International Development (DFID) providing policy guidance on water resources, water supply and sanitation. Within this work he takes a lead on water resources for DFID and the

development of international programmes of support to water resources development and management. He led the Government of Bangladesh Arsenic Policy Support Unit for 3 years 2003-2006, supporting the implementation of the National Policy for Arsenic Mitigation and commissioning key research and capacity-building programmes. He was responsible for the introduction of water safety plans into Bangladesh and for undertaking quantitative health risk assessments of arsenic mitigation technologies. Previous to joining DFID, Dr Howard worked at WEDC, Loughborough University and Surrey University undertaking research, consultancy and training. This included a 3-year secondment into the Ministry of Health, Uganda. He has been a member of the WHO Drinking Water Committee since 1996.