UNICEF HANDBOOK
ON
WATER QUALITY

United Nations Children's Fund
(UNICEF)

UNICEF Handbook on Water Quality

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Preface

Water quality is a growing concern throughout the developing world. Drinking water sources are under increasing threat from contamination, with far-reaching consequences for the health of children and for the economic and social development of communities and nations.

Deteriorating water quality threatens the global gains made in improving access to drinking water. From 1990 to 2004 more than 1.2 billion people gained access to improved water sources, but not all of these new sources are necessarily safe. Unsafe handling and storage of water compounds the problem. Water drawn from protected sources may be contaminated by the time it is ultimately consumed in households.

Deteriorating water quality also threatens the MDG water target of halving the proportion of people without sustainable access to **safe** water. While the world is currently on track to meet the target in terms of numbers of sources constructed, it may not be on track if the quality of water in new sources is fully taken into account.

The chemical contamination of water supplies – both naturally occurring and from pollution – is a very serious problem. Arsenic and fluoride alone threaten the health of hundreds of millions of people. But more serious still is the microbiological contamination of drinking water supplies, especially from human faeces. Faecal contamination of drinking water is a major contributor to diarrhoeal disease, which kills millions of children every year. As populations, pollution and environmental degradation increase, so will the chemical and microbiological contamination of water supplies.

An increasing body of evidence shows that water quality interventions have a greater impact on diarrhoea mortality and morbidity than previously thought, especially when interventions are applied at the household level and combined with improved water handling and storage. Water quality is thus becoming a major component of sectoral programmes.

UNICEF is a major stakeholder in the water, sanitation and hygiene (WASH) sector and has a responsibility to work with its partners to improve the quality of water through its programmes around the world. This responsibility was highlighted in the 2006 UNICEF WASH Strategy Paper that emphasized the need both to protect water resources and to contribute to global efforts to mitigate water quality problems.

This handbook is a comprehensive a new tool to help UNICEF and its partners meet this responsibility. It is primarily aimed at UNICEF WASH field professionals, but it will also be useful to other UNICEF staff and for partners in government, other external support agencies, NGOs and civil society. The handbook provides an introduction to all aspects of water quality, with a particular focus on the areas most relevant to professionals working in developing countries. It covers the effects of poor water quality,

quality monitoring, the protection of water supplies, methods for improving water quality, and building awareness and capacity related to water quality. Finally, the handbook provides an extensive set of links to key water quality references and resources.

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Acronyms and Abbreviations

AAS	atomic absorption spectrometry
AAS-HG	atomic absorption spectroscopy with hydride generation
ACADA	assessment, communication, analysis, design, action
AD	Alzheimer's disease
ARGOSS	assessing the risk to groundwater from on-site sanitation
ARI	acute respiratory infections
BUET	Bangladesh University of Engineering and Technology
CCCs	core commitments for children
CDC	US Centers for Disease Control
CLTS	community-led total sanitation
DALYs	disability-adjusted life years
DBP	disinfectant by-product
DDT	dichloro-diphenyl-trichloroethane
DFID	Department for International Development (UK)
DU	depleted uranium
EC	electrical conductivity
ETEC	Enterotoxigenic E. coli
EPEC	enteropathogenic E. coli
EAEC	enteroaggregative E. coli
EIEC	enteroinvasive E. coli
EHEC	enterohemorrhagic E. coli
EAWAG	Swiss Federal Institute of Aquatic Science and Technology
FN	false negative
FP	false positive
GC	gas chromatography
GDWQ	Guidelines for Drinking-Water Quality
GEMS	Global Environment Monitoring System (UNEP)
GV	guideline value
H_2S	hydrogen sulphide
HACCP	hazard analysis and critical control points
HPC	heterotrophic plate count
HPLC	high performance liquid chromatography
IC	ion chromatography
ICP	inductively coupled plasma
ID	infectious dose
IPCS	International Programme on Chemical Safety
IRC	IRC International Water and Sanitation Centre
ISO	International Organization for Standardization
JMP	WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation
KAP	knowledge, attitudes and practices
MAC	maximum allowable concentrations
MCL	maximum contaminant levels
MF	membrane filtration
MICS	multiple indicator cluster surveys
MPN	most probable number
MSD	minimum safe distance
MSF	multi-stage filtration
MTF	multiple tube fermentation

NRC	National Research Council (US)
NTU	nephelometric turbidity unit
ORT	oral rehydration therapy
P	provisional
P/A	presence/absence
PPCP	pharmaceutical and personal care products
PSI	Population Services International
QA	quality assurance
QC	quality control
RWSN	Rural Water Supply Network
SABS	South African Bureau of Standards
SODIS	solar disinfection
TCLP	toxicity characteristic leaching procedure
TCU	true colour units
TDS	total dissolved solids
TN	true negative
TP	true positive
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICEF	United Nations Children's Fund
USAID	United States Agency for International Development
USEPA	US Environmental Protection Agency
UV	ultraviolet
WASH	water, sanitation and hygiene
WEDC	Water Engineering Development Centre
WES	water, environment and sanitation
WHO	World Health Organization
WSP	World Bank Water and Sanitation Program
WSP	Water Safety Plan
WSSCC	Water Supply and Sanitation Collaborative Council

Chapter 1
Introduction

1.1 The importance of water quality

Safe water is a precondition for health and development and a basic human right, yet it is still denied to hundreds of millions of people throughout the developing world. Water-related diseases caused by insufficient safe water supplies coupled with poor sanitation and hygiene cause 3.4 million deaths a year, mostly among children. Despite continuing efforts by governments, civil society and the international community, over a billion people still do not have access to improved water sources.

The scale of the problem of water quality is even larger. It is increasingly clear that many of the existing improved sources in developing countries do not provide water of adequate quality for domestic purposes. A well-known example of this is the extensive contamination of tubewells with naturally occurring arsenic in Asia. As serious as this and other cases of chemical contamination are, the principal cause of concern is microbiological contamination, especially from faeces. While groundwater is generally of much higher microbiological quality than surface water, an increasing number of sources and systems used by people for drinking and cooking water are not adequately protected from faecal contamination. This is due to a variety of factors, including population pressure, urbanization and the inadequate construction, operation and maintenance of water systems.

Even fully protected sources and well-managed systems do not guarantee that safe water is delivered to households. The majority of the world's people do not have reliable household water connections and many of these must still physically carry water and store it in their homes. Studies show that even water collected from safe sources is likely to become faecally contaminated during transportation and storage. Safe sources are important, but it is only with improved hygiene, better water storage and handling, improved sanitation and in some cases, household water treatment, that the quality of water consumed by people can be assured.

An increasing body of evidence is showing that water quality interventions have a greater impact on diarrhoea incidence than previously thought, especially when interventions are applied at the household level (or point-of-use) and combined with improved water handling and storage (Fewtrell et al, 2005; Clasen et al, 2007).

In recognition of the growing importance of ensuring safe water in programming for children, the 2006 global UNICEF strategy paper (UNICEF water, sanitation and hygiene strategies for 2006-2015) stresses the importance of water quality in its sectoral programmes. The strategy paper outlines specific water quality strategies in the areas of strengthening national monitoring systems, community-based surveillance and the protection of freshwater resources. The strategy paper also highlights the need for

UNICEF country programmes to promote improved water safety at the household level including the development of point-of-use water treatment systems.

The task of governments, UNICEF and all other stakeholders in the area of water quality, is to create conditions to ensure that water remains safe throughout the supply cycle: from catchment basins, through water systems and into the home.

1.2 Purpose, scope and use of this handbook

This handbook is designed as a resource for field staff members from UNICEF and its partners involved in the water, environment and sanitation (WES) sector. Water quality is an increasingly important component of WES programmes, and new skills are required to effectively plan, implement and management water quality activities. Relatively few sector professionals have a detailed knowledge of the water quality sub-sector and this handbook aims to address this.

This handbook does not attempt to cover all aspects of water quality programming. The subject area is very broad, encompassing everything from the promotion of improved water resources management to the design of household water filters. What it does provide is an introduction to all aspects of water quality, with a particular focus on the areas most relevant to professional staff members working in developing countries. The handbook focuses on real-world problems faced by poor people, and on community- and household-based, low-cost solutions.

The handbook provides extensive pointers to key texts and resource materials for reference when users require more detailed information. Preference is given to texts and resources freely available on the Internet. Two key references that should be used by WES professionals along with this handbook are the UNICEF WES programme guidelines series on water and sanitation (including manuals on water, sanitation, communication and hygiene promotion) and the WHO guidelines for drinking-water quality.

The handbook is made up of six chapters, including this introduction.

Chapter 2 focuses on the effects of poor water quality, covering microbiological contamination and the main chemical contaminants that pose a threat to human health. It also provides information on WHO water quality guideline values and the processes for national standards development.

Chapter 3, on water quality monitoring and surveillance, discusses both the techniques for measuring water quality and the management of national monitoring and surveillance programmes, including community surveillance.

Protecting water supplies from contamination is generally more effective than treating contaminated water. Chapter 4 describes contamination sources and pathways and techniques for water system protection. It includes sections on hygiene, sanitation and the safe handling and household storage of water.

Chapter 5 outlines the principal technologies for water treatment, both for microbiological contamination and the main chemical contaminants. Included in the chapter is specific information on water quality treatment at the municipal, community and household levels, and on treating water in emergencies.

The handbook concludes with Chapter 6, a discussion on advocacy for increased national resource allocation for water quality, communication with communities on the importance of water quality, and capacity building at national and community levels.

Chapter 2
The Effects of Poor Water Quality

In spite of concerted efforts to improve access to safe drinking water (notably the International Drinking Water and Sanitation Decade, from 1981 to 1990), an estimated 1.1 billion people lack access to an improved water source. Over three million people, mostly children, die annually from water-related diseases. Almost two million of these deaths are the result of diarrhoeal diseases, which are caused by the ingestion of water contaminated by faecal matter, as well as by inadequate sanitation and hygiene. Contaminated water resources can also contribute to the spread of diseases caused by skin contact or by vectors.

In addition to causing direct health impacts, unsafe drinking water has a number of subtle or indirect adverse health effects:

- Children weakened by frequent diarrhoea episodes are more likely to be seriously affected by malnutrition and opportunistic infections (such as pneumonia), and they can be left physically stunted for the rest of their lives.
- Chronic consumption of unsafe drinking water can lead to permanent cognitive damage (see box).
- People with compromised immune systems (e.g., people living with HIV and AIDS) are less able to resist or recover from water-borne diseases. Pathogens which might cause minor symptoms in healthy people (e.g., *Cryptosporidium*, *Pseudomonas*, rotaviruses, Heterotrophic Plate Count microorganisms) can be fatal for the immunocompromised.

The consequences of poor water quality go beyond health. Chronic bouts of water-related diseases impose significant social and economic burdens both on victims themselves and society as a whole. Poverty alleviation and the other Millennium Development Goals will be difficult to achieve without improvements in water quality.

Safe water and cognitive impairment

Lack of safe drinking water contributes to intestinal helminth infections, which cause malnutrition and anaemia in children (Stephenson et al., 2000). Chronic diarrhoeal disease can also exacerbate malnutrition. Both early childhood malnutrition and anaemia can cause permanent effects in brain development: malnourished and anaemic children grow up to be less intelligent and do less well in school (Pollitt, 1995).

Recent research indicates that diarrhoeal disease may also directly impact cognitive development (Dillingham and Guerrant, 2004). Brazilian children aged six to ten who had suffered serious and ongoing episodes of diarrhoea during the first two years of life performed less well than other children on standard intelligence tests, even after controlling for socio-economic status and early childhood malnutrition or helminth infections (Niehaus et al., 2002). Similarly, Berkman et al. (2002) showed that Peruvian children who experienced multiple infections with *Giardia* scored lower on intelligence tests.

Chronic exposure to chemicals in drinking water may also affect cognitive development. It is well known that ingestion of lead leads to significant behavioural change and cognitive impairment in children. Other chemicals can also have effects: for example, children exposed to high levels of arsenic during early childhood score significantly lower on neurobehavioural tests than children not exposed to arsenic (e.g. Tsai et al., 2003; Wasserman et al., 2004). High levels of manganese in water can also have neurological effects (Wasserman et al, 2006).

Cognitive impairment can last a lifetime and contributes to a vicious cycle of malnutrition and poverty.

While microbiological contamination is the largest public health threat, chemical contamination can be a major health concern in some cases. Water can be chemically contaminated through natural causes (arsenic, fluoride) or through human activity (nitrate, heavy metals, pesticides). The physical quality of water (e.g., colour, taste) must also be considered. Water of poor physical quality does not directly cause disease, but it may be aesthetically unacceptable to consumers, and may force them to use less safe sources. Finally, drinking water can be contaminated with radioactivity, either from natural sources or human-made nuclear materials.

2.1 Regulatory limits for water quality

Because of the negative public health impacts of unsafe water, national government agencies have established drinking-water quality standards that public sources must meet or exceed. In most cases, private water supplies are not subject to national drinking-water standards. A distinction is often made between standards based on health impacts and those based primarily on the acceptability of drinking water, with health-based standards more strictly enforced.

When setting national drinking-water standards, most countries consider the standards set in other countries and the *Guidelines for Drinking-Water Quality* (GDWQ) (WHO, 2006). The most recent versions of GDWQ is the third edition (available as a hardcopy) published in 2004 and the same edition incorporating the first addendum published in 2006 and available electronically on the WHO water quality web pages: (www.who.int/water_sanitation_health/dwq/guidelines/en)

The GDWQ provides guidance in setting health-based targets for three classes of contaminants: microbiological, chemical and radiological. For some contaminants, WHO recommends guideline values (GVs) for safe levels in drinking water. A guideline value represents the concentration of a constituent that does not exceed tolerable risk to the health of the consumer over a lifetime of consumption. A fourth category is the aesthetic quality of drinking water, but WHO makes no specific recommendations for these parameters, since they do not directly impact health and acceptability is dependent on local conditions. Instead, the GDWQ refers to typical levels that may lead to complaints from consumers.

WHO guideline values should not be interpreted as mandatory universal drinking-water standards. Rather, they should be used to develop risk management strategies in the context of local or national environmental, social, economic and cultural conditions. This approach should lead to standards that are realistic and enforceable in a given setting, to ensure the greatest overall benefit to public health. This may lead to national targets that differ appreciably from the guideline values. It would be inappropriate, for example, to set such stringent drinking-water standards that regulatory agencies lack the funding or infrastructure to enforce them. This would result either in too many water sources being closed and insufficient access to water, or widespread flouting of the regulation. An important concept in the allocation of resources to improving drinking-water safety is that of incremental improvements towards long-term quality targets. Priorities set to remedy the most urgent problems (e.g., protection from pathogens) may be linked to long-term targets of further water quality improvements (e.g., improvements in the acceptability of drinking-water). See Chapter 6 for further discussion of advocacy for national drinking-water standards.

"*The judgment of safety – or what is a tolerable risk in particular circumstances – is a matter in which society as a whole has a role to play. The final judgment as to whether the benefit resulting from the adoption of any of the health-based targets justifies the cost is for each country to decide*" (WHO, 2006 Chapter 3).

Guidelines for potable water in South Africa

South African regulations define three guidelines for chemical quality of drinking water: Class 0 represents ideal drinking water. Class I is a level considered to be acceptable for lifetime consumption, and Class II is the maximum level allowable for short-term consumption. Most Class 0 standards are very similar to WHO guideline values, but some are more stringent.

Table 2.1 Comparison of selected WHO GVs and South African guidelines for potable water

All values in mg/L

Constituent	WHO GV	Class 0	Class I	Class II
Aluminium	0.1-0.2*	0.15	0.3	0.5
Arsenic	0.01	0.01	0.05	0.2
Chromium	0.05	0.05	0.1	0.5

Copper	2.0	0.5	1.0	2.0
Fluoride	1.5	0.7	1.0	1.5
Iron	0.3*	0.01	0.2	2.0
Manganese	0.4	0.05	0.1	1.0
Nitrate and nitrite as N	11.3**	6	10	20

* WHO has not fixed a health-based GV for aluminium or iron, but notes that drinking water containing higher levels than those listed above may be unacceptable to consumers for aesthetic reasons.
** WHO GV is 50 mg/L as NO_3, which is equivalent to 11.3 mg/L as N.

As for microbiological quality, WHO guidelines values are only given for *E. coli* or faecal bacteria, and indicate that these should not be detected in any 100 mL sample. South African microbiological standards, like chemical standards, have three levels of strictness. At least 95% of samples should have no detected faecal coliforms, somatic coliphages, enteric viruses or protozoan parasites. However, up to 4% of samples could have up to 1 count per 100 mL of these pathogens, and up to 1% of samples could contain up to 10 counts per 100 mL. A similar rule exists for total coliforms, except that 10 and 100 counts per 100 mL are permissible at the 4% and 1% levels. In spite of this, the goal of disinfection should be to attain 100% compliance with no detected incidence of contamination.
Source: SABS, 2001

National drinking water standards online

A number of countries make their national drinking-water standards freely available online. These can serve as points of reference, along with the WHO GDWQ, when developing national drinking-water standards.

Australia	www.nhmrc.gov.au/publications/synopses/eh19syn.htm
Canada	www.hc-sc.gc.ca/ewh-semt/water-eau/drink-potab/guide/index_e.html
European Union	www.emwis.org/IFP/Eur-lex/l_33019981205en00320054.pdf
Japan	www.env.go.jp/en/standards/
New Zealand	www.moh.govt.nz/water
United Kingdom	www.dwi.gov.uk
United States	www.epa.gov/safewater/mcl.html
WHO	www.who.int/water_sanitation_health/dwq/guidelines

2.2 Microbiological contamination

Pathogens are micro-organisms that can cause disease in humans. They fall into three major classes:

- **Bacteria** are single-celled organisms, typically 1 to 5 µm in size (1000 µm = 1mm).

- **Viruses** are protein-coated genetic material that lack many cell structures, and are much smaller than bacteria – in most cases 10 to 300 nm (1000 nm = 1µm).
- **Parasites** are single-celled organisms that invade the intestinal lining of their hosts. The two main types of parasites are protozoa and helminths (intestinal worms). Parasites have a complex life cycle, and most at some stage form large protective cysts or eggs (4-100 µm), which can survive outside of the host bodies.

Diseases are usually classified by pathogen class in medical texts. However, for public health purposes it is more useful to follow the Bradley classification (White et al., 1972), based on transmission routes in the environment (Table 2.2). The advantage of this classification system is that it is easy to see what interventions are likely to reduce the incidence of different water-related diseases.

Table 2.2 Bradley classification system for water-related diseases*

Category	Example	Intervention
Water-borne	Diarrhoeal disease, cholera, dysentery, typhoid, infectious hepatitis	Improve drinking-water quality, prevent casual use of unprotected sources
Water-washed	Diarrhoeal disease, cholera, dysentery, trachoma, scabies, skin and eye infections, ARI (acute respiratory infections)	Increase water quantity used Improve hygiene
Water-based	Schistosomiasis, guinea worm	Reduce need for contact with contaminated water, reduce surface water contamination
Water-related (insect vector)	Malaria, onchocerciasis, dengue fever, Gambian sleeping sickness	Improve surface water management, destroy insect breeding sites, use mosquito netting

* including microbiological-related diseases only, see section 2.3 for diseases caused by chemical contamination

Sources: Adapted from Cairncross and Feachem (1993); ARI included based on more recent research including Luby et al (2003), Cairncross (2003) and Rabie and Curtis (2006)

Communicable diseases and methods for preventing them are discussed in detail in (WHO, 2006, Chapter 7) and (Rottier and Ince, 2003). The US Centers for Disease Control also maintains an excellent website with information about communicable diseases (www.cdc.gov).

Since most pathogens in drinking water derive from faecal contamination, the WHO GDWQ gives guideline values for microbiological indicator species (see 3.2.1 for more discussion).

Table 2.3 Guideline values for verification of microbial quality

Water class	Indicator species	Guideline value
All water directly intended for drinking	***E. coli* or thermotolerant coliform bacteria**	Must not be detectable in any 100-ml sample
Treated water entering the distribution system	*E. coli* or thermotolerant coliform bacteria	Must not be detectable in any 100-ml sample
Treated water in the distribution system	*E. coli* or thermotolerant coliform bacteria	Must not be detectable in any 100-ml sample

Source: WHO (2006), Table 7.7

WHO recognizes that these targets would be difficult to achieve in some cases, especially in rural communities with untreated water supplies, and recommends that in these settings, the guidelines values should be seen as goals for the future, rather than an immediate requirement. More realistic health-based targets for microbiological quality should be set, using quantitative risk assessment and taking into account local conditions and hazards. These health-based targets form the basis for Water Safety Plans, and may include specific water quality targets, performance targets for water treatment, directly specified water treatment practices, or a measurable reduction in disease incidence.

2.2.1 Water-borne diseases

Definition: water-borne diseases are diseases caused by the ingestion of water contaminated by human or animal faeces or urine containing pathogens.

Many bacteria, viruses, protozoa and parasites can cause disease when ingested. The majority of these pathogens derive from human or animal faeces, and are transmitted through the faecal-oral route. Although both animal and human faeces are threats to human health, human faeces are generally the most dangerous. Faecal pathogens can be classified as causing both water-borne and water-washed diseases, so they are discussed in this section. Section 2.2.2 focuses on those pathogens that are likely to be exclusively water-washed.

Table 2.4 lists some of the main pathogens of concern in drinking water. Most of these pathogens can be found in faecal matter from infected humans and many may also be present in animal faeces.

Table 2.4 Orally transmitted waterborne pathogens and their significance in water supplies

Pathogen	Health significance	Persistence in water supplies[a]	Resistance to chlorine[b]	Relative infectivity[c]	Important animal source
Bacteria					
Campylobacter jejuni/coli	High	Moderate	Low	Moderate	Yes
E. coli – pathogenic[d]	High	Moderate	Low	Low	Yes
E. coli – enterohaemorrhagic	High	Moderate	Low	High	Yes
Legionella spp.	High	Multiply	Low	Moderate	No
Salmonella typhi	High	Moderate	Low	Low	No
Other salmonellae	High	May multiply	Low	Low	Yes
Shigella spp.	High	Short	Low	Moderate	No
Vibrio cholerae	High	Short	Low	High	No
Yersinia enterocolitica	High	Long	Low	Low	Yes
Pseudomonas aeruginosa[e]	Moderate	May multiply	Moderate	Low	No
Viruses					
Adenoviruses	High	Long	Moderate	High	No
Enteroviruses	High	Long	Moderate	High	No
Hepatitis A	High	Long	Moderate	High	No
Hepatitis E	High	Long	Moderate	High	Potentially
Noroviruses and Sapoviruses	High	Long	Moderate	High	Potentially
Rotavirus	High	Long	Moderate	High	No
Protozoa					
Acanthamoeba spp.	High	Long	High	High	No
Cryptosporidium parvum	High	Long	High	High	Yes
Cyclospora cayetanensis	High	Long	High	High	No
Entamoeba histolytica/dispar	High	Moderate	High	High	No
Giardia lamblia/intestinalis	High	Moderate	High	High	Yes
Naegleria fowleri	High	May multiply[f]	High	High	No
Toxoplasma gondii	High	Long	High	High	Yes
Helminths					
Dracunculus medinensis	High	Moderate	Moderate	High	No
Schistosoma spp.	High	Short	Moderate	High	

[a] Detection period for infective stage in water at 20°C: short, up to 1 week; moderate, 1 week to 1month; long, over 1 month.

[b] When the infective stage is freely suspended in water treated at conventional doses and contact times. Resistance moderate, agent may not be completely destroyed.

[c] From experiments with human volunteers or from epidemiological evidence.

[d] Includes enteropathogenic, enterotoxigenic and enteroinvasive.

[e] Main route of infections is by skin contact, but can infect immunosuppressed or cancer patients orally

[f] In warm water

Source: WHO (2006), Table 7.1

The dose makes the infection

Pathogen infectious doses (ID$_{50}$, or the dose required to cause infection in 50% of healthy adults) may vary widely, from around 10^3 for *Shigella* to 10^8-10^{11} for *V. Cholera*. ID$_{50}$s are typically lower ($< 10^2$) for viruses and parasites, and may be as low as one for some viruses. The doses needed to affect children, especially when malnourished or suffering from chronic diarrhoea, may be significantly lower. The severity of diarrhoeal episodes is also related to infectious dose: for many pathogens a low ingested dose can result in mild, self-limiting diarrhoea while a high ingested dose is more likely to cause severe, life-threatening illness (Esrey et al., 1985). Also, populations build up a certain level of tolerance to local pathogens – visitors from other areas may be much more susceptible to water-borne illnesses than locals.

Proper treatment of drinking water, including disinfection, should produce pathogen-free water. However, the great majority of people in developing countries, especially in rural areas, rely on untreated (though possibly improved and protected) water sources. These water sources almost certainly contain measurable levels of coliforms, most of which are harmless, and may well contain low to moderate levels of faecal coliforms. While the goal should always be to ensure access to a pathogen-free drinking-water source, it would be a mistake to strictly enforce a zero-pathogen standard for untreated water sources. For example, the closure of a lightly contaminated source could force users to collect drinking water from grossly contaminated sources such as irrigation canals (Cairncross and Feachem, 1993).

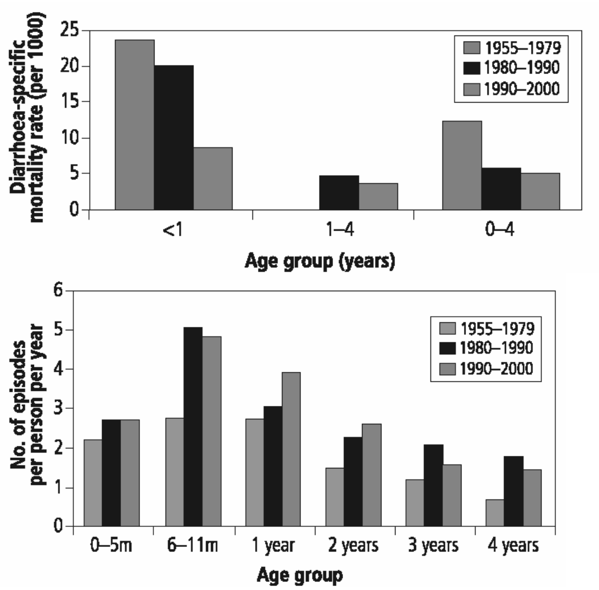
Impact of diarrhoeal disease

Approximately 4 billion cases of diarrhoea each year cause at least 1.8 million deaths, 90% are children under the age of five, mostly in developing countries. This is equivalent to one child dying every 15 seconds, or 20 jumbo jets crashing every day. These deaths represent approximately 4% of all deaths, and 18% of under-five child deaths in developing countries. Only acute respiratory infections (ARI) have a higher impact, causing 19% of under-five deaths.

88% of these deaths are attributable to unsafe water supply, inadequate sanitation, and poor hygiene. Water, sanitation, and hygiene interventions reduce diarrhoeal disease on average by between one-quarter and one-half.
Source: WHO/UNICEF (2000), WHO (2005a)

The number of diarrhoeal deaths has decreased significantly over the past 50 years. A review of epidemiologic studies (Kosek et al., 2003) found an estimated 4.2 million deaths per year (mostly in children under 5) from diarrhoeal disease from 1955-1979, dropping to 3.3 million per year from 1980-1989, and 2.5 million per year from 1992-2000. The improvement was most evident for children under 1: diarrhoeal mortality rates dropped from 23.3 deaths per thousand children to 8.2 over the same period (see Figure 2.1a).

Figure 2.1 Diarrhoeal mortality (a) and morbidity (b) trends, 1955-2000



Source: Kosek et al. (2003)

However, the rate of reported diarrhoeal cases (morbidity) has not shown a similar improvement (see Figure 2.1b). Children under 5 had a median of 3.2 episodes of diarrhoea per year between 1992 and 2000, little changed from previous reviews. Since population continues to grow, especially in poorer areas where diarrhoea is more prevalent, the number of cases of diarrhoeal disease is actually increasing (Guerrant et al., 2002).

The improvement in mortality but not morbidity can partially be explained by improved case management of diarrhoeal disease: use of oral rehydration therapy (ORT) in diarrhoeal disease treatment is estimated to have increased from 15% to 40% between 1984 and 1993. A second explanation is that water, sanitation and hygiene interventions have decreased the number of pathogens being ingested, which would be expected to result in improvements in mortality but not morbidity (Esrey et al., 1985; Esrey, 1996). Finally, improvements in nutrition over the past two decades might also have contributed to shorter and less severe bouts of diarrhoea.

Most water-borne pathogens infect the gastrointestinal tract and cause diarrhoeal disease. In most cases, the specific pathogen responsible for infection is not identified, and case identification and treatment is fairly generic. Two very serious forms of diarrhoeal disease, cholera and shigellosis, should be considered separately because of their severity and tendency to create epidemics.

Indeterminate diarrhoeal disease

The most common causes of severe diarrhoeal disease (see also “Pathogens that cause diarrhoeal disease in children under 5”) are:

- Rotaviruses. Rotavirus is the leading cause of severe diarrhoea among children, resulting in the death of over 600,000 children annually worldwide. By age 5, nearly every child will have an episode of rotavirus gastroenteritis, 1 in 5 will visit a clinic, 1 in 65 will be hospitalized, and approximately 1 in 293 will die (Parashar et al., 2003).

- Pathogenic E. coli. Most strains of E. coli are harmless, but some can cause serious diarrhoea. Pathogenic, or diarrhoeagenic, E. coli is primarily ingested through food, but can also contaminate drinking-water supplies. Pathogenic E. coli are further broken down into several groups based on the way in which they cause disease. Enterotoxigenic E. coli (ETEC) and enteropathogenic E. coli (EPEC) are the main causes of childhood diarrhoea. Other groups include enteroaggregative E. coli (EAEC), enteroinvasive E. coli (EIEC), and enterohemorrhagic E. coli (EHEC). ETEC is the most frequently isolated pathogen in studies of children with diarrhoeal disease, accounting for some 210 million diarrhoeal episodes and 380,000 deaths annually. Taken together, pathogenic strains of E. coli represent one of the most common causes of infant diarrhoea worldwide (Nataro and Kaper, 1998).

- Campylobacter jejuni. Approximately 5%-14% of all diarrhoea worldwide is thought to be caused by ingestion of C. jejuni in contaminated food or water. Infection may cause bloody diarrhoea, fever, nausea and vomiting, though many of those infected show no symptoms. Campylobacteriosis is rarely fatal, except among very young, very old, or immunocompromised people.

- Protozoan parasites. Entamoeba hystolica, the cause of amoebic dysentery, is prevalent worldwide – it is estimated that more than 10% of the world’s population is infected with E. histolytica, but on average, only 1 in 10 infected people show symptoms, which include stomach pain, bloody stools and fever. Giardia intestinalis (also known as G. lamblia) and Cryptosporidium parvum are also globally prevalent parasites. Both have animal as well as human hosts, can persist in surface water, are resistant to chlorination, and have very low infectious doses (as low as one cyst). Some stool surveys of patients with gastroenteritis have found 20% contained Cryptosporidium, and 3-20% contained Giardia. One survey of children in a Brazilian shantytown found Cryptosporidium infection in 90% of children under one year old. Up to 20% of AIDS deaths in industrialized countries are attributed to cryptosporidiosis (WHO, 2002b).

- Calciviruses. Tests have only recently been developed to identify this family of viruses, which includes the Norwalk-like viruses. However, calciviruses have been identified as the most common cause of diarrhoeal outbreaks in the United States. Some evidence suggests that these viruses may also play an important role in diarrhoeal diseases among children in developing countries.

Pathogens that cause diarrhoeal disease in children under 5

A number of epidemiologic studies have attempted to identify the pathogen responsible for diarrhoea in infected children. Three recent studies conducted in Bogota, Colombia; Dhaka, Bangladesh; and Montevideo, Uruguay illustrate that pathogenic *E. coli* (especially ETEC and EPEC) and rotavirus are the two most frequently found pathogens. Other pathogens tend to be more variable with location. The Bogota and Dhaka studies also examined non-diarrhoeal control populations, and found a significant number were infected with one or more diarrhoeal pathogens. This illustrates that only a fraction of people infected with diarrhoeal pathogens develop symptoms.

Table 2.5 Major pathogens isolated from stools of children with diarrhoea

Pathogen	Proportion of positive samples from diarrhoeal children		
	Bogota	Dhaka	Montevideo
Pathogenic *E. coli*	30.7	28.3*	39.3
Rotavirus	19.7*	20.3	18.8
Campylobacter	1.4	17.4*	8.5
Shigella	0.0	9.2	7.1
Cholera	--	8.7	0.4
Salmonella	6.2	1.8*	3.1
Cryptosporidium	--	1.4	8.5
Giardia	0.2	0.9	3.6
Entamoeba	12.1	0.6	--

*Prevalence was at least half as high in the non-diarrhoeal control population
Sources: Albert et al. (1999), Mattar et al. (1999), Torres et al. (2001)

Epidemic diarrhoeal disease

Two diarrhoeal pathogens, *Shigella* and *Vibrio cholera*, are particularly infectious and can cause severe epidemics.

Shigella dysenteriae type 1 is the pathogen responsible for bacillary dysentery, or bloody diarrhoea. *Shigella* has a very low infectious dose and has caused epidemics in Central America, south and southeast Asia, and sub-Saharan Africa since the late 1960s. There are an estimated 165 million cases of *Shigella* infection each year, resulting in some 1.1 million deaths, mostly of children under 5 (Kotloff et al., 1999). *Shigella* causes diarrhoea with blood and/or pus, high fever, abdominal or rectal pain, but not vomiting. Treatment is problematic: oral rehydration therapy is not as effective for dysentery as for watery diarrhoea, and *Shigella* is increasingly resistant to antimicrobial drugs. Severe shigellosis is common among immunocompromised patients.

Epidemics of cholera have devastated Europe and North America since the early 1800s. Cholera originated in the Ganges delta, where it remains endemic, apparently surviving in rivers and estuaries associated with blue-green algae. Occurrence is often seasonal, with peaks in spring and fall associated with algal blooms. The current global epidemic, or pandemic (the seventh) is caused by the classical El Tor O1 biotype, though since 1992 a new biotype, designated O139 or Bengal, has caused epidemics in South Asia. This strain has since been identified in several other Asian countries, but has not yet extended to other continents. Cholera continues to be a very serious health threat. In 2006, over 230,000 cases of cholera were reported, including over 6,300 deaths, but WHO estimates that this represents only 5-10% of the actual number of cases.

Cholera results in severe water ("rice-water like") diarrhoea and vomiting, but no fever. More than 90% of cases are mild, and most cases respond well to treatment with oral rehydration therapy. However, if untreated, severe dehydration and death can occur within days.

Epidemic diarrhoea (both shigellosis and cholera) can be triggered by natural disasters or political upheavals that disrupt the normal water supply. For example, following the Rwanda crisis in 1994 over 500,000 refugees fled into camps in Goma, Democratic Republic of the Congo. During the first month after the influx, epidemics of cholera and antimicrobial-resistant shigellosis caused at least 48,000 cases and 23,800 deaths.

Non-diarrhoeal water-borne diseases

While most water-borne pathogens cause diarrhoeal disease, a few important water-borne diseases affect other parts of the body.

Typhoid fever (not to be confused with typhus fever, caused by body lice) is caused by ingestion of *Salmonella typhi* bacteria in food or water, and affects about 17 million people each year, causing some 600,000 deaths. Infection causes a sudden high fever, nausea, severe headache, and loss of appetite. It is sometimes accompanied by constipation or diarrhoea.

Hepatitis, or liver inflammation, is caused by viral infection. Symptoms include yellowing of the skin and eyes (jaundice), dark urine, fatigue, nausea and vomiting. Two forms of the disease, hepatitis A and E, are primarily caused by ingestion of faecally contaminated drinking water. Hepatitis A causes about 1.5 million infections each year (mostly in children), and can occur in epidemics. Hepatitis E is less common than hepatitis A, and occurs mainly in epidemics caused by monsoon rains, heavy flooding, contamination of well water, or massive uptake of untreated sewage into city water treatment plants. No specific treatment exists for hepatitis A or E, but most (>98%) patients recover completely. Hepatitis can have more serious effects on older or immunocompromised people, and pregnant women are particularly vulnerable to hepatitis E, with approximately 20% mortality rates. Hepatitis B, C and D are not considered water-borne diseases, as they are transmitted by contact with body fluids.

Polio is a highly infectious viral disease that mainly affects children under 5. Most infected people show no symptoms, but severe cases cause irreversible paralysis. As a result of a concerted initiative – the Global Polio Eradication Project – reported cases have declined by over 99% since 1988, from an estimated more than 350,000 cases to 1,919 reported cases in 2002. Still, polio can easily spread among unimmunised populations, and in 2003 polio was still endemic in Afghanistan, parts of India, and Pakistan in Asia; and Egypt, Niger, northern Nigeria and Somalia in Africa. Since poliovirus is primarily transmitted through the faecal-oral route, safe water and sanitation interventions can help reduce risk, but the top priority is to ensure high immunization coverage of infants and children.

Legionellosis may also be considered a water-borne disease, but infection occurs through inhalation of water droplets containing *Legionella* bacteria. Severe infection leads to Legionnaire's disease, characterized by pneumonia and 5-15% mortality rates. More mild infections cause Pontiac fever, which usually requires no treatment. *Legionella* prefer warm environments (>36°C) and can survive in the environment in association with bacteria or protozoan hosts. *Legionella* can grow in water storage tanks, boilers, or pipes in distribution systems. Outbreaks of Legionnaire's disease are fairly rare.

Leptospirosis is a bacterial disease caused by ingestion or bodily contact with water contaminated with the urine of infected animals, especially rats. Symptoms include a high fever, headache, vomiting, chills and aches. If not treated, the disease can cause serious damage to internal organs. The disease is difficult to diagnose and is often overlooked, but may be important, especially following flooding.

2.2.2 Water-washed diseases

Definition: water-washed diseases are diseases caused by inadequate use of water for domestic and personal hygiene.

Control of water-washed diseases depends more on the quantity of water than the quality (see box, "Water quality and diarrhoea", Chapter 5). Most of the diarrhoeal diseases should be considered to be water-washed as well as water-borne, and are not discussed further here. Four types of water-washed diseases are considered here: soil-transmitted helminths; acute respiratory infections (ARI); skin and eye diseases; and diseases caused by fleas, lice, mites or ticks. For all of these, washing and improved personal hygiene play an important role in preventing disease transmission.

Soil-transmitted helminths

Helminths are intestinal worms (nematodes) that are transmitted primarily through contact with contaminated soil. The most prevalent helminths are ascaris (*Ascaris* *lumbricoides*), hookworm (*Ancylostoma duodenale* and *Necator americanus*) and whipworm (*Trichuris trichiura*). Together, these 'geohelminths' currently infect about one-quarter to one-third of the world's population. Worms suck blood and deprive their hosts of essential nutrients (particularly iron and Vitamin A). Children with heavy worm burdens are more likely to have iron deficiency anaemia, malnutrition, and to suffer impaired growth and cognitive development. Over 130 million children suffer from high-intensity geohelminth infections; helminths cause about 12,000 deaths each year (WHO, 2002a). These diseases can be considered water-washed, and improved hygiene and sanitation can reduce disease incidence. Mass deworming of children is also recognized as an effective control measure.

Acute Respiratory Infections

Acute respiratory infections (ARI) including pneumonia are responsible for approximately 19% of total child deaths every year. There is an increasing body of evidence demonstrating that good hygiene practices, especially hand-washing with soap, can significantly reduce the transmission of ARI. For example, a 2005 study in Karachi, Pakistan found that children younger than five years in households that received soap and hand-washing promotion had a 50 percent lower incidence of pneumonia than children in control areas. Because of this link between ARI and hygiene, it can now be considered a water-washed disease (Luby et al, 2003; Cairncross, 2003; Rabie and Curtis, 2006).

Skin and eye diseases

Trachoma is the world's leading cause of preventable blindness: about 6 million people are blind due to trachoma, and more than 10% of the world's population is at risk. Globally, the disease results in an estimated US $2.9 billion in lost productivity each year (International Trachoma Initiative, 2003). Trachoma is caused by the *Chlamydia trachomatis* bacteria, which inflame the eye. After years of repeated infections, the inside of the eyelids may be scarred so severely that the eyelid turns inwards with eyelashes rubbing on the eyeball. Flies are implicated in the transmission of trachoma, and are often seen feeding on the discharge from infected eyes. The best control method for trachoma (and for **conjunctivitis**, a less serious eye disease) is improved access to water for face-washing.

Ringworm (tinea) is an infectious disease of the skin, scalp or nails. In spite of the name, the disease is caused by a fungus.

Flea, lice, mite and tick-borne diseases

Scabies is a pimple-like skin disease caused by the microscopic mite *Sarcoptes scabei* and characterized by intense itching. Scabies spreads rapidly, and causes an estimated 300 million cases each year. Epidemic or lice-born **typhus** is an acute and often fatal fever caused by *Rickettsia prowazekii*. African tick-borne **relapsing fever** is caused by infection with *Borrelia recurrentis.* Infection can be prevented by controlling body lice through improved hygiene.

2.2.3 Water-based diseases

Definition: water-based diseases are infections caused by parasitic pathogens found in aquatic host organisms.

Schistosomiasis (bilharziasis) is a major parasitic disease in tropical and sub-tropical regions, second only to malaria in terms of socio-economic and public health importance. An estimated 160 million people in 74 countries are infected and about 10% of these suffer severe consequences from the disease, including tens of thousands of deaths every year. Infection is caused by flatworms, or blood flukes, called schistosomes, which spend part of their life cycle inside snail hosts. People become infected through skin contact with infected water, mainly during fishing and agricultural activities. Integrated water, sanitation and health interventions can reduce disease prevalence by up to 77%, mainly through improved hygiene and less contact with contaminated surface water (Esrey et al., 1991). However some Asian snail varieties (including S. japonicum and perhaps S. mekongi) have important animal reservoirs, and improved hygiene and sanitation are not effective control measures. Therefore control of the snail population is an important part of shistosomiasis control programmes.

Dracunculiasis (guinea-worm disease) is a debilitating disease caused by the roundworm *Dracunculus medinensis*. Guinea-worm larvae in water bodies are ingested by the *Cyclops* water flea. People become infected by drinking water contaminated with *Cyclops*: the larvae are released in the stomach, migrate through the intestinal wall, and grow to adult worms, which can reach 600 to 800 mm in length. The worms eventually emerge (usually from the feet), creating intensely painful sores. When infected people try to relieve the pain by soaking their feet in ponds, the female worms expel hundreds of thousands of larvae into the water, completing the cycle. Improving drinking-water quality, by either switching from surface to groundwater sources or filtering surface water to remove *Cyclops*, can reduce transmission by over 75% (Esrey et al., 1991). As a result of intensive eradication efforts, guinea-worm disease prevalence has dropped from about 50 million in the 1950s to about 50,000 cases in 2002, the majority of which were in Sudan.

2.2.4 Water-related diseases

Definition: water-related diseases are caused by insect vectors which either breed in water or bite near water.

These diseases are not directly related to drinking-water quality. However, consideration of vector control during the design, construction and operation of surface water reservoirs and canals (for drinking water or irrigation purposes) can reduce the potential for water-related disease transmission. The most common vector insects are mosquitoes and flies.

Mosquito-borne diseases
- malaria
- yellow fever
- dengue fever
- filariasis

Fly-borne diseases
- onchocerciasis (river-blindness)
- trypanosomiasis (West African sleeping sickness)
- leishmaniasis (Kala-azar)
- loiasis

2.3 Chemical contamination

Water quality planners have traditionally focused on ensuring that drinking water is microbiologically safe for consumption. This emphasis was, and still is, justified by the serious health threat posed by microbiological contamination of drinking water and the fact that many people have access only to water that is clearly unsanitary. However, the chemical quality of drinking water cannot be taken for granted. Yet in many water supply projects, the only chemical parameters tested are pH, and perhaps iron and chloride, because of the aesthetic problems these can cause (see 2.4). It is increasingly recognized that chemical contamination of drinking-water resources can seriously damage health.

Unlike microbiological contamination, chemical contamination leads to health problems primarily through chronic exposure. (Nitrate is one exception to this rule, as short-term exposure can cause methaemoglobinaemia – see section 2.3.3). Contamination may persist for years before detection, and when people have developed chronic health problems from unsafe drinking water, it may be too late to restore health simply by switching to a safe water source.

There are literally thousands of chemicals that could in theory cause health problems in drinking water. WHO lists guideline values (GVs) for nearly 200 chemicals, ranging from naturally occurring arsenic and fluoride to synthetic chemicals found only in industrial settings. Fortunately only a relatively small number are likely to pose real threats in drinking water. WHO has developed a useful classification system based on classes of contaminant sources, rather than chemical characteristics, which we will follow here:

1. Naturally occurring
2. Industrial sources and human dwellings
3. Agricultural activities
4. Water treatment or materials in contact with drinking water

5. Pesticides used in water for public health purposes
6. Cyanobacterial toxins

Priority chemical contaminants

It is not possible to test water for all of the chemicals that could cause health problems, nor is it necessary: most chemicals occur rarely and many result from human contamination of a small area, only affecting a few water sources. However, three chemicals have the potential to cause serious health problems and to occur over widespread areas. These are **arsenic** and **fluoride**, which can occur naturally, and **nitrate**, which is applied to large areas of agricultural land as fertilizer. These three contaminants are more often found in groundwater, though surface water can also be impacted. When planning new water supply projects, especially using groundwater resources, these three contaminants should be given priority. A second priority should be inorganic compounds that commonly cause water to be rejected for aesthetic purposes: metals (principally **iron** and **manganese**), and **salinity**.

These priority contaminants are discussed in detail below in section 2.3.1, and in Chapter 5. See also the box on removal of priority inorganics in section 5.2.

Table 2.6 summarizes guideline values for inorganic contaminants, along with Maximum Allowable Concentrations (MACs) fixed by the European Union and Maximum Contaminant Levels (MCLs) set by the US Environmental Protection Agency.

Table 2.6 Inorganic chemical contaminants in drinking water and various guideline values, in mg/L

Chemical	WHO GV	EU MAC	USEPA MCL	Discussed in Section
Aluminium	0.1-0.2 (A)	0.2 (A)	0.05-0.2 (A)	2.4
Antimony	0.020	0.005	0.006	2.3.4
Arsenic	0.01 (P)	0.01	0.01	2.3.1
Asbestos	-- (X)	--	7 MFL	2.3.4
Barium	0.7	--	2	2.3.1
Beryllium	-- (X)	--	0.004	2.3.2
Boron	0.5 (T)	1	--	2.3.1
Bromate	0.01 (Q, T)	0.01	0.01	2.3.4
Cadmium	0.003	0.005	0.005	2.3.2
Chlorine (as Cl_2)	5 (C)	--	4	2.3.4
Chloramines (as Cl_2)	3 (1)	--	4	2.3.4
Chlorine dioxide (as Cl_2)	-- (X)	--	0.8	2.3.4
Chromium	0.05 (P)	0.05	0.1	2.3.1
Copper	2	2	1.3 (TT)	2.3.4
Cyanide	0.07	0.05	0.2	2.3.2
Fluoride	1.5	1.5	4	2.3.1
Iron	0.3 (A)	0.2 (A)	0.3 (A)	2.4
Lead	0.01	0.01	0.015 (TT)	2.3.4
Manganese	0.4 (C)	0.05 (A)	0.05 (A)	2.3.1
Mercury	0.006 (M)	0.001	0.002	2.3.2

Chemical	WHO GV	EU MAC	USEPA MCL	Discussed in Section
Molybdenum	0.07	--	--	2.3.1
Nickel	0.07	0.02	--	2.3.4
Nitrate (as NO_3^-)	50	50	44.3	2.3.3
Nitrite (as NO_2^-)	3 (S) 0.2 (L, P)	0.5	3.3	2.3.3
Selenium	0.01	0.01	0.05	2.3.1
Silver	-- (X)	--	0.1 (A)	2.3.4
Sulfate	250 (A)	250 (A)	250 (A)	2.4
Thallium	--	--	0.002	2.3.2
Uranium	0.015 (P, T)	--	0.03	2.3.1
Zinc	3 (A)	--	5 (A)	2.4

Notes

A: Based on aesthetic concerns, not health impacts. WHO does not set GVs based on aesthetic concerns, but does note concentrations which may cause complaints.

1: For monochloramine alone. Data are insufficient to set GVs for dichloramine or trichloramine.

C: Concentrations of the substance at or below the health-based guideline value may affect the appearance, taste or odour of the water, causing consumer complaints.

L: for long-term exposure

M: for inorganic mercury

P: Provisional guideline: evidence of a potential hazard, but the available information on health effects is limited.

Q: Because calculated guideline value is below the practical quantification level

S: For short-term exposure

T: Guideline value is set at the practical treatment limit, rather than a lower value based solely on health effects.

X: Excluded from guideline value because of a lack of evidence that ingestion causes adverse health effects, or unlikely to occur in drinking water.

TT: Lead and copper are regulated by a Treatment Technique that requires systems to control the corrosiveness of their water. If more than 10% of tap water samples exceed the action level, water systems must take additional steps.

2.3.1 Naturally occurring chemicals

WHO has established guideline values for 9 compounds that can occur naturally in water (WHO, 2006, Table 8.18). These chemicals are of particular concern since the area of contamination can be quite extensive, and because contamination can go unnoticed in the absence of a testing program.

Arsenic *As* *GV 0.01 mg/L (P)*

Arsenic in drinking water is a global threat to health, potentially affecting about 140 million people in at least 70 countries worldwide (Ravenscroft, 2008). It is considered by some researchers to have more serious health repercussions than any other environmental contaminant (Smith, 2007).

Arsenic occurs naturally in soils and rocks, with typical concentrations of about 2-10 mg/kg. Igneous rocks tend to have low arsenic content, while shales, coals and volcanic rocks have higher levels. Arsenic is often found near deposits of sulfide minerals and ore deposits of metals such as tin and gold. In unconsolidated sediments, arsenic is primarily found in fine fractions, associated with metal oxides (especially iron) and to a lesser degree, clay minerals.

Arsenic can occur in drinking water at levels up to several mg/L, either as the reduced species As^{III} (arsenite) or the oxidized form, As^{V} (arsenate). As^{III} is uncharged (H_3AsO_3) under natural conditions, and as such is more mobile than As^{V} ($H_2AsO_4^-$ or $HAsO_4^{2-}$). Contamination can occur in surface water, but is more common in groundwater. Rainwater contains negligible amounts of arsenic. Household burning of coal can also represent an important source of arsenic exposure, especially in parts of China (Finkelman et al., 1999; Guangqian et al, 2007). There is an increasing body of evidence showing that rice from paddy fields irrigated with arsenic-contaminated water is also a significant source of arsenic. In some cases, the WHO recommended maximum tolerable daily levels of inorganic arsenic can be exceed through rice intake alone (Williams et al, 2006).

Under most geochemical conditions, arsenic in aquifers remains tightly bound to sediments, and dissolved levels remain low. However, two geochemical environments have been recognized which can lead to high levels of dissolved arsenic even when concentrations in sediments are unremarkable: reducing conditions in alluvial aquifers, and arid oxidizing conditions (Smedley and Kinniburgh, 2002).

Reducing and oxidizing environments

Molecules are composed of atoms, which in turn are made up of protons, neutrons and electrons. An element always has the name number of protons and neutrons, but can have several different stable forms (called valences) with different numbers of electrons. A chemical reaction that involves the transfer of electrons from one atom to another is called a *redox* or *reduction-oxidation* reaction. Electrons have a negative charge, so when an atom accepts more electrons, its electrical charge is lowered and the atom is *reduced*. Atoms that can easily donate electrons to other atoms are strong *reductants*. Atoms that are good electron acceptors are called *oxidants* (so called because oxygen is a very good electron acceptor), and atoms that lose electrons are called *oxidized*. Whenever one species is reduced another must be oxidized.

When alluvial aquifers are formed by river systems, a lot of organic matter is deposited along with sand, silt and clay. Bacteria in the aquifer can consume this organic matter, getting energy by oxidizing organic carbon to carbon dioxide. However, this requires a chemical oxidant to indirectly accept electrons from the carbon atoms. Bacteria in the aquifer will first use the strongest available electron acceptors, which in natural systems is oxygen. When all of the oxygen is used up, bacteria can use weaker oxidants such as nitrate or sulfate. As this happens, the aquifer becomes an increasingly reducing environment. Strongly reducing groundwaters are characterized by a lack of oxidants (oxygen, nitrate, sulfate) and the presence of reductants (ammonia, hydrogen sulfide, methane). In contrast, oxidizing conditions occur where there is a plentiful supply of oxygen, such as surface water or unsaturated sediments.

Many metals are more soluble under reducing conditions. For example, ferrous iron (Fe^{II}) is a strong reductant often present in groundwater. When pumped to the surface, it reacts with atmospheric oxygen and gives up one electron. Ferrous iron is oxidized to the much less soluble ferric iron (Fe^{III}), and forms a reddish-brown precipitate. In the process, oxygen is reduced, forming water.

In some areas, such as Bangladesh, a surface layer of fine clay or silt restricts transport of oxygen to young shallow aquifers, leading to the establishment of strongly reducing conditions. After bacteria have used up oxygen and nitrate, they can use weaker electron acceptors such as manganese oxide or iron oxide coatings on sediments. The solid oxides dissolve as they are reduced, releasing any bound arsenic to the groundwater. Iron oxides are a major reservoir of arsenic in sediments, so if they dissolve large amounts of arsenic may be liberated. In these waters, arsenic may be associated with high levels of iron, manganese, phosphate, ammonia, and alkalinity; and with low sulfate; and nitrate. pH is generally near neutral. As^{III} dominates in these waters, though As^{V} may also occur at significant levels. Bangladesh, West Bengal, Cambodia, Taiwan, China, Vietnam, Hungary and Romania provide examples of this type of environment.

A completely different environment exists in internal geologic basins, where conditions can be oxidizing, with pH moderate to high. It is thought that elevated arsenic in these aquifers is caused by the high pH levels (>8), which favour desorption of negatively charged arsenic species from oxide surfaces. This type of mobilization has been seen in Mexico, Chile, Argentina, and the USA.

Arsenic causes a wide range of adverse health effects. As^{III} is somewhat more toxic in acute exposures, but because the low levels of As^{V} ingested in drinking water are reduced to As^{III} internally, the two species can be considered equally toxic in drinking water. The first symptoms noticed are often skin lesions (keratosis, melanosis), but other effects can include weakness, diarrhoea, bronchitis, vascular disease and diabetes mellitus. The main health concerns, however, are cancers of the skin or internal organs (bladder, lung or kidney). The effects of low levels of arsenic exposure remain unclear, but many researchers believe that even trace levels could lead to unacceptable cancer rates. Because of the ongoing uncertainty about low-level effects, and the difficulties involved in measuring arsenic below 0.01 mg/L (or removing As to this level), WHO has set 0.01 mg/L as a provisional guideline value.

There is no effective medical treatment for chronic arsenicosis, except for switching to an arsenic-free drinking-water source. However, palliative care such as application of ointments for cracked skin lesions can ease suffering. Chelation therapy is effective for short-term, acute poisoning, but not for long-term exposures.

Additional resources on arsenic occurrence, monitoring and mitigation

Due to the seriousness of the arsenic problem in Asia and elsewhere, there are an increasing number of resources for policy makers and field practioners involved in arsenic mitigation. Below is a selection of resources:

Ravenscroft, P., H. Brammer and K.S. Richards. (2008) (in press). Arsenic pollution: a global synthesis. Blackwell-Wiley.

IRC Thematic Overview Paper: Arsenic in Drinking Water
www.irc.nl/page/33113

UNICEF Fact Sheets on Arsenic, 2008
(under development – contact the UNICEF Bangladesh and India country offices; will also be available on the UNICEF intranet)

United Nations Synthesis Report on Arsenic in Drinking Water
www.who.int/water_sanitation_health/dwq/arsenic3/en
(from 2002, an updated version is pending – see WHO site for details)

West Bengal and Bangladesh Arsenic Crisis Information Centre website
bicn.com/acic

WHO web pages on Arsenic in Drinking Water
www.who.int/water_sanitation_health/dwq/arsenic/en/

World Bank/WSP study report - Arsenic Contamination of Groundwater in South and East Asia: Towards a More Operational Response.
- Volume 1: Policy Report: siteresources.worldbank.org/INTSAREGTOPWATRES/Resources/ArsenicVolII_PaperI.pdf
- Volume 2: Technical Report: siteresources.worldbank.org/INTSAREGTOPWATRES/Resources/ArsenicVolII_WholeReport.pdf

See also section 3.2.2 on arsenic testing and section 5.2 on arsenic mitigation in this handbook.

Barium *Ba* *GV 0.7 mg/L*

Barium occurs naturally in rock, with an average of 250 mg/kg in continental crust. It is positively charged in water (Ba^{2+}) and typically occurs at less than 0.1 mg/L, though natural concentrations in groundwater can exceed 1 mg/L.

There is no evidence that barium is carcinogenic, but chronic exposure can cause hypertension in humans, leading to the GV of 0.7 mg/L. Short-term exposure to high levels of barium can also cause gastrointestinal disturbances and muscular weakness.

Boron	*B*	*GV 0.5 mg/L (T)*

Boron concentration in rocks averages 10 mg/kg, with up to 100 mg/kg found in sedimentary rocks, shales and coal deposits. Like arsenite ($As^{III)}$, boron is predominantly neutral (H_3BO_3) in water but can bear a negative charge ($H_2BO_3^-$) at high pH (>9).

Boron levels in natural waters range widely, and are dependent on local geology and geochemical conditions, though local industrial inputs may be important. Ocean water contains relatively high levels of boron (4-5 mg/L), and boron in surface water is highly variable, though concentrations above 1 mg/L are rare. Groundwater levels range more widely, from < 0.3 to over 100 mg/L. Aquifers in internal basins may have elevated levels of boron due to evaporative concentration, and in coastal areas salt-water intrusion can lead to contamination of freshwater aquifers. Globally, the average concentration of boron in drinking water has been estimated to be between 0.1 and 0.3 mg/L. In most cases the main human exposure source is dietary, with a mean daily intake of about 1.2 mg.

Boron is not a known carcinogen, and some evidence indicates that it may be an essential trace nutrient for humans. There are few studies involving human exposure, but animal studies have shown that ingestion can cause lower foetal weight and testicular damage, leading to the GV of 0.5 mg/L. This guideline value is provisional, due to the difficulty of removing boron from drinking water.

Chromium	*Cr*	*GV 0.05 mg/L (P)*

Chromium is a trace metal that occurs in several forms in the environment. The most important are the trivalent (Cr^{III}) and hexavalent (Cr^{VI}) species. These two forms have very different physical properties and health impacts, but drinking-water standards are typically made for total chromium.

Cr^{III} is relatively non-toxic, and is in fact an essential trace element for humans. In water, the main dissolved species are the neutral $Cr(OH)_3$ and $Cr(OH)_2^+$, though levels are quite low due to the low solubility of solid $Cr(OH)_3$. Naturally occurring chromium is almost always present as Cr^{III}, though relatively few data are available describing speciation of Cr in natural waters. In contrast, Cr^{VI} has severe health impacts and occurs almost exclusively from industrial sources such as ferrochrome production, electroplating, pigment production, and tanning. Coal plants and waste incinerators can also release Cr^{VI} to the environment. In water, Cr^{VI} forms negatively charged species ($HCrO_4^-$ or CrO_4^{2-}), which are relatively mobile.

There is no evidence that Cr^{III} is carcinogenic, but numerous occupational studies have shown that inhalation of Cr^{VI} can cause lung cancer in humans. The health impacts of Cr^{VI} ingested through drinking water are controversial. Some people advocate strict controls on Cr^{VI} levels in water, since it is a known human carcinogen when inhaled. Others argue that Cr^{VI} is completely converted to the harmless Cr^{III} internally, and cite a number of epidemiological and animal studies that found no adverse effects of even relatively high exposures to Cr^{VI} in drinking water (Flegal et al., 2001). Because of the ongoing controversy, WHO has kept the provisional GV at 0.05 mg/L for total chromium ($Cr^{III} + Cr^{VI}$).

Fluoride *F* *GV 1.5 mg/L*

Fluoride, along with arsenic, is one of the most serious chemical contaminants that occurs naturally in drinking water. Fluoride is a fairly common element, with an average concentration of 300 mg/kg in the earth's crust. Granite, granite gneisses and pegmatite can contain significant amounts of fluorite (CaF_2). Fluoride can also be concentrated in coal or evaporite deposits such as gypsum and fluorite.

In natural waters, fluoride is present as the anion F^-. Surface water generally contains less than 0.3 mg/L, while groundwater can contain up to 10 mg/L, with much higher levels occasionally reported. High fluoride levels in groundwater are primarily caused by interactions with rock and sediments, and can occur in a wide range of geological environments, including the foothills of large mountains, areas of ancient marine deposits, and areas impacted by geothermal waters. In many cases, affected areas are characterized by a semi-arid climate, crystalline igneous rocks (e.g., granite), and alkaline soils. Fluoride concentrations have been observed to increase along groundwater flow lengths, due to rock-water interactions. Alkaline waters (pH >7.5) and the presence of other anions (e.g., bicarbonate) increase fluoride mobility by displacing fluoride from clay and other mineral surfaces.

Groundwater with high fluoride concentrations can be found in many areas of the world, including large parts of Africa, China, Mexico, the Middle East and southern Asia (India, Sri Lanka). One of the best-known high fluoride belts on land extends along the East African Rift from Eritrea to Malawi. Another belt extends from Turkey through Iraq, Iran, Afghanistan, India, northern Thailand and China. While the most common source of fluoride in drinking water is geological, considerable amounts may also be contributed from industrial sources or impurities in phosphorus fertilizers. Also, coal burning can release large amounts of fluoride to the environment, and is a significant source of domestic exposure in China.

Unlike arsenic, fluoride is beneficial at low doses. Higher rates of dental caries are observed below approximately 0.5 mg/L, and in many countries fluoride is routinely added to drinking water (typically from 0.7-1.2 mg/L) to improve dental health. This protective effect increases up until about 2 mg/L.

However, ingestion of water containing more than approximately 1 mg/L F can lead to dental fluorosis, characterized by staining or pitting of dental enamel, in children under 6 years of age. At higher concentrations skeletal fluorosis may occur, involving stiffness and pain in joints. In severe cases, ligaments can calcify and bone structure may change, causing pain and impaired mobility or crippling. Some studies have shown a link between elevated fluoride levels and hip fractures, while others have found no link or even a protective effect. Ingestion of 14 mg/day poses a clear risk of skeletal fluorosis, and there is evidence suggestive of increased risk at 6 mg/day. It is thought that fluorosis affects tens of millions of people across the world, with dental fluorosis being much more prevalent than the more serious skeletal form.

The WHO GV for fluoride is set at 1.5 mg/L, because of the increased risk of dental fluorosis above this level, and of skeletal fluorosis at higher levels. It should be emphasized that in assessing exposure to fluoride, it is particularly important to consider climatic conditions, volume of water intake and intake of fluoride from other sources than drinking water.

As part of its series addressing contaminants with significant adverse impact on public health, in 2006 WHO published a comprehensive monograph on fluoride addressing occurrence, health effects, testing and mitigation (see additional resources section below).

Additional resources on fluoride

Janssen, P.J.C.M., A.G.A.C. Knaap, et al. (1989). Integrated Criteria Document Fluorides: Effects. Appendix to report 75847010. Bilthoven, The Netherlands: National Institute of Public Health and Environmental Protection (RIVM).

NRC (1999). Health Effects of Ingested Fluoride. Washington, D.C.: Subcommittee on Health Effects of Ingested Fluoride, National Research Council.

Fawell J. et al (2006). Fluoride in Drinking-water. WHO Drinking-water Quality Series. Geneva: WHO.
www.who.int/water_sanitation_health/publications/fluoride_drinking_water/en/

Manganese *Mn* *GV 0.4 mg/L*

Manganese is one of the most abundant metals in the earth's crust. It can occur in a number of forms, with Mn^{II} dominating in anaerobic environments, and Mn^{IV} in the presence of oxygen. Mn^{IV} forms an insoluble black precipitate, while Mn^{II} is quite soluble as Mn^{+2}. Surface water generally contains low levels of manganese (< 0.1 mg/L). Anaerobic groundwater can contain much higher levels, even above 1 mg/L. Dissolved manganese is often associated with iron, which is also soluble under anaerobic conditions.

Manganese is an essential element for humans, but a growing body of research suggests that exposure to high levels in drinking water can lead to adverse neurological effects (Wasserman et al, 2006). Because of possible health risks, WHO has set a GV of 0.4 mg/L. Normally, consumers are unlikely to drink water containing manganese at this level or higher because of a strong unpleasant metallic taste, however there are recorded situations, such as in Bangladesh, where people are regularly consuming water with manganese levels above the GV. Concentrations below 0.05–0.1 mg/L are usually acceptable to consumers from a taste perspective but may sometimes still give rise to the deposition of black deposits in pipes (see 2.4).

Molybdenum *Mo* *GV 0.07 mg/L*

Molybdenum is a relatively uncommon element in rocks and soils, with a global abundance of 1 mg/kg. Molybdenum is an essential trace nutrient for plants and animals, and is commonly used as an additive in agriculture. It is also used in the manufacture of steels, lubricants and pigments.

Molybdenum is an essential trace element for humans, but there is relatively little information about possible toxic effects at higher exposures. Molybdenum levels in drinking water are generally below 0.01 mg/L. Molybdenum, like arsenic and boron, forms a negatively charged species in water (MoO_4^{2-}) and is relatively mobile in groundwater.

The WHO GV is set on the basis of toxicological studies on animals. Cattle, in particular, are susceptible to molybdenum toxicity and show a range of symptoms including diarrhoea, greying of hair and lowered growth rate.

Selenium *Se* *GV 0.01 mg/L*

Selenium is a trace element in rocks, with an average concentration of less than 1 mg/kg. Sedimentary rocks (shales, limestone) may contain up to 100 mg/kg, while levels up to several thousand mg/kg have been reported in some coal deposits. Industrial sources of selenium are minor, though mining operations can release significant amounts to the environment.

Natural levels of selenium in drinking water are generally below 0.01 mg/L. A garlicky odour can be noted in waters containing 0.01 – 0.03 mg/L Se. The dominant species in water are all negatively charged: Se^{IV} (selenite: $HSeO_3^-$, SeO_3^{2-}) and Se^{VI} (selenate: SeO_4^{-2}).

Selenium is thought to be an essential trace nutrient for humans, and a number of conditions have been linked to selenium deficiency, including Keshan disease, a heart condition which primarily affects children. The recommended daily intake for adults is about 1 µg/kg of body weight, which in most cases can be met through food intake.

Human exposure to high levels of selenium (> 500 µg/day) has been linked with liver and kidney damage and hair and fingernail loss. Drinking water typically contributes a minor amount of selenium compared to dietary intake. In zones containing selenium-rich coals, significant exposure may also occur from household coal burning.

Uranium	*U*	*GV 0.015 mg/L (P,T)*

Uranium occurs naturally in rocks and sediments, with average concentration in soils and rocks of 3 mg/kg. Elevated levels are sometimes found in granites and shales. Drinking water typically contains up to 0.003 mg/L U, though levels of up to 0.78 mg/L have been reported (UNEP, 2003).

Natural uranium occurs as a mixture of three isotopes: ^{238}U is the dominant fraction, with ^{235}U and ^{234}U contributing 0.72% and 0.0054% respectively. All three isotopes decay by both alpha and gamma emissions. Depleted uranium (DU) contains only about a quarter as much ^{235}U and ^{234}U and as such is approximately 40% less radioactive than natural uranium.

Although the decay of uranium isotopes (especially ^{234}U) produces radioactivity, the main public health threat of uranium arises from its chemical toxicity as a heavy metal, with the kidneys being the main target organ. Uranium is not known to be carcinogenic. In 2004 the WHO raised the provisional guideline value for uranium in drinking water from 0.002 to 0.015 mg/L, to protect against kidney damage. A guideline value based on radiologic toxicity would be approximately ten times higher, at 0.14 mg/L (WHO, 2001).

Depleted uranium in war zones

Depleted uranium (DU) is used in armor-penetrating ammunition, and in war zones spent rounds might lead to contamination of soil or water, even after a few years. UNEP has conducted extensive surveys in the Balkans, and was able to detect DU in soil and dust particles, seven years after the end of the conflict. Transport of dissolved DU is very limited, as uranium (as UO_2^{2+}) adsorbs strongly to soil particles. Colloids or carbonate complexes can facilitate transport of uranium, and in one case, UNEP detected DU in a drinking-water well. The contamination (0.003 mg/L) was well below the WHO guideline value and radiologic contamination was negligible. Still, the finding shows that DU can contaminate drinking-water supplies, and it is possible that in other cases contamination might exceed the GV of 0.015 mg/L.

The media have raised concerns that DU used in war zones may have contributed to a variety of adverse health effects among combatants and civilians, including leukemia, lung cancer, kidney and liver disorders, respiratory ailments, chronic fatigue, skin spotting and joint pain. However, according to UNEP, "at low levels of exposure, as expected in most post-conflict situations, the additional risk of cancer is thought to be very low. Importantly, any radiation effects based on DU occur only in the long-term, requiring typically 10-20 years before symptoms appear – if ever" (UNEP, 2003).

Although epidemiological studies do not show a link between DU exposure and these conditions, UNEP recommends continued study – particularly in Iraq, following the US invasion – to identify "a number of remaining scientific uncertainties".

Those most likely to be affected are combatants and small children, who may ingest DU when playing in or near DU impact sites. People may also be exposed to DU by stripping scrap metal off destroyed vehicles. WHO recommends preventing children from playing near such sites; monitoring of DU contamination in food and drinking water following conflict; clean-up operations in impact zones; disposal of DU following appropriate national or international recommendations; and raising public awareness about the risks of exposure to DU.
Source: WHO (2001, 2003); UNEP (2003)

Naturally occurring chemicals with no guideline value

A number of naturally occurring chemicals are not known to have negative health effects at levels found in drinking water. These include chloride, hardness (the sum of polyvalent metallic ions in water – the principal components of which are calcium and magnesium), hydrogen sulfide, pH, sodium, sulfate, total dissolved solids (TDS). Many of these compounds have aesthetic effects (see 2.4).

Some evidence suggests that hardness in drinking water may be protective with respect to cardiovascular disease, but the data are inadequate to prove a causal association (see “Hardness” in 2.4). Vanadium can occur in natural waters at levels of up to 0.2 mg/L, and while limited evidence suggests that vanadium can affect animal and human health, available data do not warrant the setting of a guideline value.

2.3.2 Chemicals from industrial sources and human dwellings

Localized contamination of drinking-water resources can occur when chemicals are used in industries or in private households. Heavy metals, petroleum products, and chlorinated organic solvents are the main types of chemicals used in these settings. Heavy metals that occur naturally as well as in industrial settings are discussed in 2.3.1, while metals involved in drinking-water treatment or distribution (e.g., antimony, lead) are covered in 2.3.4.

Cadmium *Cd* *GV 0.003 mg/L*

Cadmium is used in metal plating, plastics, pigments and batteries. It is carcinogenic when inhaled, but there is no evidence that ingestion through drinking water can cause cancer. The WHO GV is set to protect against kidney damage.

Cyanide CN GV 0.07 mg/L

Cyanide is widely used in metal finishing and the production of plastics such as nylon. Cyanide is acutely toxic, primarily affecting the thyroid and the nervous system. Cyanide can occur naturally in some foods, such as cassava, but is rarely found in drinking water except due to industrial contamination.

Mercury Hg GV 0.006 mg/L

Mercury is used in the electrolytic production of chlorine; in electrical appliances such as dry-cell batteries, fluorescent light bulbs and switches; and in thermometers. Natural contamination can also occur in groundwater, but is rare.

Ingestion of mercury can cause serious damage to the kidneys, brain, and nervous system. Organic mercury compounds are significantly more toxic than inorganic mercury, but almost all mercury in uncontaminated drinking water is thought to be in the inorganic form. The guideline value is now given for inorganic mercury, not total mercury.

Other inorganic compounds

Perchlorate (ClO_4^-), the explosive main ingredient of rocket and missile fuel, is a powerful thyroid toxin, which can contaminate groundwater and soil. WHO has not determined a GV for perchlorate, but the USEPA is contemplating setting a standard of 1 µg/L.

Beryllium, a metal used in making metal alloys, can cause lung cancer when inhaled, but there are few data regarding its toxicity when ingested. WHO has not set a GV for beryllium, because it is unlikely to be found in drinking water. Likewise, WHO considers thallium, another toxic metal, unlikely to occur in drinking water.

Organic compounds

WHO lists GVs for a number of hydrocarbon products and solvents used in the household and in industry. Chelating agents may also have guideline values, because chronic ingestion can cause unhealthy deficiencies of trace metals such as zinc.

In recent years it has been recognized that pharmaceutical and personal care products (PPCPs) can be released to the environment, particularly through wastewater streams. Many of these biochemically active compounds are not removed with conventional water treatment, and can potentially make their way into drinking-water supplies. In most cases concentrations in drinking water are too low to cause a direct threat to human health. However, these compounds can pose a considerable environmental threat, in some cases by mimicking natural hormones and interfering with normal growth in aquatic animals (Daughton and Ternes, 1999).

Additional resources on PPCPs

USEPA PPCP website www.epa.gov/ppcp/

WHO/ILO/UNEP International Programme on Chemical Safety (IPCS)
www.who.int/ipcs/en/

2.3.3 Chemicals from agricultural activities

Most chemicals used in agriculture are either pesticides or fertilizers. Contamination of drinking-water resources may result following land application or from improper disposal.

Nitrate and nitrite	NO_3^- and NO_2^-	50 and 3 mg/L

When nitrogen fertilizer is applied to crops, nitrate (NO_3^-) can filter into shallow aquifers or be washed into surface waters. Disposal of human or animal waste can also be a source of nitrate. Nitrate can be converted to nitrite (NO_2^-) by bacteria in surface water, groundwater, piped distribution systems or the body. Both nitrate and nitrite are very mobile in water, and groundwater typically contains higher levels than surface water. Since nitrate is used in all fertilizers, contamination of water resources is relatively common. Some drinking-water utilities use chloramines rather than free chlorine for disinfection, to avoid formation of trihalomethanes in distribution systems (2.3.4). In chloraminated systems, microbial activity in the distribution system may lead to sporadic nitrification episodes, resulting in elevated levels of nitrite.

The main health concern regarding nitrate and nitrite is methaemoglobinaemia, or "blue-baby syndrome", which can lead to death by asphyxiation amongst bottle-fed infants when contaminated water is used to prepare formula (or where infants drink contaminated water directly). Methaemoglobinaemia is rare in industrialized countries, but there are few data regarding its prevalence in the developing world, and contamination from agricultural sources is known to be common.

When ingested, both nitrate and nitrite can oxidize blood haemoglobin (Hb) to methaemoglobin (metHb); nitrite is approximately ten times as potent as nitrate. MetHb cannot transport oxygen, and the oxygen-poor blood causes development of a blue colour in tissues (cyanosis). The abnormal colour is usually first noticed in the lips, followed by the fingers and toes, the face, and then the whole body. Infants below 6-12 months of age are particularly susceptible: their stomachs are less acidic than those of older children or adults, favoring the reduction of nitrate to nitrite. In addition, the haemoglobin of infants is more vulnerable to oxidation. Methaemoglobinaemia arises from short-term rather than chronic exposure to nitrate and nitrite.

WHO GVs for nitrate and nitrite are set at 50 and 3 mg/L, respectively, to protect against methaemoglobinaemia in bottle-fed infants. In addition, the sum of the ratios of the concentrations of each to its guideline value should not exceed 1. For example, drinking water containing 30 mg/L nitrate and 1.5 mg/L nitrite would exceed the guideline value.

There is some evidence that nitrite can react with amines or amides in the body to form nitrosamine, a known carcinogen. Chronic exposure to nitrite has produced changes in the adrenals, heart and lungs in laboratory animal studies. Accordingly, WHO provisionally recommends a GV of 0.2 mg/L nitrite for long-term exposure.

Units of concentrations

Nitrate and nitrite concentrations may be expressed either in terms of the mass of nitrate (NO_3^-) or nitrite (NO_2^-), or of total nitrogen. Since nitrate and nitrite are 23% and 30% nitrogen by weight, respectively, concentrations reported in terms of total nitrogen are much lower. WHO and many governments prefer reporting concentrations in terms of nitrate or nitrite.

mg/L NO_3^-	*mg/L* NO_3*-N*
50.0	11.3
44.3	10.0
mg/L NO_2^-	*mg/L* NO_2*-N*
3.3	1.00
3.0	0.91
0.2	0.06

Pesticides

Pesticides may enter surface water or groundwater primarily as runoff following application to crops, though inappropriate disposal or accidental release can also cause contamination. The potential of a pesticide to contaminate drinking water is affected by its solubility and biodegradability; the method of application; and environmental factors such as soil, weather, season and proximity to water resources.

Early pesticides were compounds of toxic metals such as arsenic, mercury, copper or lead. Use of such pesticides greatly decreased following the introduction of synthetic organic pesticides in the 1950s. The first organic pesticides were chlorinated hydrocarbons such as DDT, aldrin, dieldrin, chlordane, endrin, heptachlor, lindane and pentachlorophenol. These compounds are relatively insoluble, and tend to concentrate on soil surfaces instead of dissolving in water. However, they are resistant to biodegradation and can accumulate in food supplies, leading to toxic concentrations in some predator species. Accordingly, use of many of these chlorinated pesticides has been restricted over the last several decades. The most commonly used pesticides today include organophosphorus compounds (e.g., chlorpyrifos, diazinon and malathion) and carbamates (e.g., aldicarb, carbaryl, carbofuran and oxamyl), both of which are relatively soluble and biodegradable. See Table 2.7 for common trade names of these and other pesticides.

A number of pesticides have serious health impacts on humans and wildlife, including damage to internal organs and cancers. WHO has established guideline values for 32 pesticides: for detailed information see WHO GDWQ, section 8.5.3.
Guideline values have also been set for several larvicides applied for public health (e.g., mosquito control). See section 2.3.5, and WHO GDWQ, section 8.5.5.

Table 2.7 Common trade names for selected pesticides

Active Ingredient	Common Trade Names (partial listing)
aldicarb	Temik
aldrin	Aldrex; Altox; Drinox; Octalene; Toxadrin
carbaryl	Sevin, Vet-Tek
carbofuran	Furadan, Curater
chlordane	Belt, Corodane, Chlortox, Niran, Octachlor, Octa-Klor, Sym-klor, Toxichlor
chlorpyrifos	3M Livestock Premise Spray, Disvap Mec Klor, Pyrifos, Lorsban, Pyrinex, Dursban
DDT	Anofex, Cezarex, DinozideGesarol, DDT, Guesapan, Guesarol, Gyron, Ixodex, Neocide, Neocidol, Zerdane
diazinon	Basudin, Diazinon, DZN, Diazol, Protector, Proturf, Y-TEX Optimizer
dieldrin	Dieldrin, Alvit, Octalox, Panoram, Quintox
heptachlor	Drinox, Heptagram, Heptamul
lindane	Aphtiria, Chemlind, Lindacol, Maladane and many others
malathion	Cythion, Malathion, Grain Protectant, Fyfanon
methoprene	Altosid, Apex, Diacan, Dianex, Kabat, Minex, Pharorid, Precor
oxamyl	Vydate
pentachlorophenol	Dowicide 7, Pentachlorol, Pentacon, Penwar, Santophen, Sinituho
permethrin	Ambush, Cellutec, Dragnet, Ectiban, Eksmin, Exmin, Indothrin, Kafil, Kestrel, Pounce, Pramex, Qamlin
temephos	Abate, Anba, Chembat, Temephos

Sources: International Programme on Chemical Safety (IPCS) (2007) and Ministry of Agriculture and Lands (2007).

2.3.4 Chemicals from water treatment and distribution systems

The treatment and distribution of drinking water involves contact with chemicals and materials that may impart chemical residuals to the water. Residuals might be desired, in the case of disinfectants, or might be unwanted products of water treatment processes, or might result from corrosion and leaching of pipe materials.

Disinfectants

Free chlorine is the most commonly used disinfectant, with a target residual concentration in the range of 0.2 to 1 mg/L. There are no specific adverse health effects of exposure to free chlorine, but WHO has conservatively set a GV of 5 mg/L, which is well above the taste and odour threshold for most consumers. Chloramines (a mixture of monochloramine, dichloramine and trichloramine formed when ammonia is present in chlorinated water) are also commonly used disinfectants, with a typical final concentration of 0.5-2 mg/L in finished waters. The GV for monochloramine is 3 mg/L, no GV is set for di- and trichloramine.

Silver has a bacteriostatic effect and is sometimes used for emergency disinfection, or impregnated onto filter media to prevent bacterial growth. Excessive intake of silver can cause argyria, a condition in which skin and hair become discoloured, taking on a silvery hue. Argyria is not harmful, and there is no health-based GV for silver in drinking water.

Other disinfectants include chlorine dioxide, iodine, and ozone. WHO has not set guideline values for these compounds either because they decay rapidly in water or data are inadequate to recommend a health-based guideline value.

Disinfectant by-products (DBPs)

All chemical disinfectants have the potential to produce unwanted organic or inorganic by-products that may be of health concern. The first recognized disinfection by-products (DBPs) were the trihalomethanes, which are produced by the reaction of free chlorine with natural organic matter. When bromide is present in the source water, brominated DBPs may be formed along with chlorinated ones. Other chlorination DBPs include haloacetic acids, halogenated ketones and haloacetonitriles. The concentration of chlorination DBPs tends to increase with water age.

WHO has set GVs for 14 DBPs. Some of the DBPs have been found to be carcinogenic or cause reproductive or developmental effects in laboratory animals, but there is some uncertainty involving the risks to humans posed by chronic ingestion of DBPs.

Note on disinfection by-products

It is important to recognize that the health risk of developing cancer from long-term exposure to disinfection by-products is insignificant compared to the acute danger of ingesting pathogens from insufficiently disinfected water. While it is desirable to reduce DBP concentrations, this must be done while ensuring adequate disinfection and maintaining a disinfectant residual throughout the distribution system.

Contaminants from treatment chemicals

Polymer additives used in flocculation may contain residual levels of the monomers acrylamide and epichlorohydrin, which have been linked with tumour formation in rats. The WHO GVs for these compounds are 0.5 and 0.4 µg/L, respectively. Acrylamide and epichlorohydrin levels are controlled by product and dose specification.

Aluminium salts are widely used coagulants in drinking-water treatment, and may result in elevated aluminium levels in treated water, particularly if filtration is inadequate. High aluminium residuals may cause an undesirable colour and turbidity in treated water or precipitation of flocs (small solid particles) in distribution systems. There has been a good deal of controversy about health risks associated with aluminium levels in drinking water, particularly regarding a possible link with Alzheimer's disease (AD). The 1997 WHO EHC for aluminium concludes that:

> The relative risks for AD from exposure to aluminium in drinking-water above 100 µg/litre, are low (less than 2.0)…. Owing to the limitations of the animal data as a model for humans and the uncertainty surrounding the human data, a health-based guideline value for aluminium cannot be derived at this time.
>
> The beneficial effects of the use of aluminium as a coagulant in water treatment are recognized. Taking this into account, and considering the health concerns about aluminium (i.e., its potential neurotoxicity), a practicable approach is proposed, based on optimization of the coagulation process in drinking-water plants using aluminium-based coagulants, to minimize aluminium levels in finished water. Under good operating conditions, concentrations of aluminium of 0.1 mg/litre or less are achievable in large water treatment facilities. For small facilities, 0.2 mg/litre or less is a practicable level for aluminium in finished water (WHO, 1997a).

Likewise, iron salts are used as coagulants but iron is not a parameter of health concern, and as such has no GV.

Contaminants from pipes and fittings

A number of organic compounds and heavy metals present in pipes and fittings can leach into drinking water during distribution. Metal leaching is most common in acid water, though alkaline waters with high carbonate levels may also attack some metals. Hard water provides some protection against metal corrosion, since scale deposits within pipes can provide a physical barrier between the water and the pipe wall.

Natural waters and treated drinking water usually contain almost no lead. However, pipes in distribution systems and houses may well be made of lead, or may be joined together using lead solder, especially in older dwellings. Lead is a general toxicant that accumulates in the skeleton. The WHO GV of 10 µg/L is set to protect infants and children on the basis that lead is a cumulative poison and that there should be no accumulation of body burden of lead.

Corrosion of plumbing can also lead to high copper concentrations in drinking water. Copper is an essential nutrient, but excessive copper can cause gastrointestinal problems in some users, and some sub-populations may be genetically susceptible to metabolic disorders of copper homeostasis. Because of uncertainties regarding the effects on sensitive populations, the WHO GV of 2000 µg/L is provisional. Other heavy metals that can leach into drinking water include antimony and nickel (GV 20 µg/L and 70 µg/L respectively), which are present as alloys in some taps and fittings.

Coal-tar is sometimes used to coat drinking-water pipes or storage tanks to protect against corrosion. This practice can introduce polyaromatic hydrocarbons (PAHs) into the treated water. A GV of 0.7 µg/L has been set for the PAH benzo[a]pyrene. Unplasticized polyvinyl chloride (PVC) pipes may leach vinyl chloride (GV 0.3 µg/L), a human carcinogen, into drinking water.

Asbestos-cement pipes can release asbestos fibres into drinking water. Although asbestos is a known human carcinogen when inhaled, there is no consistent evidence that it is carcinogenic when ingested, so no GV has been set for asbestos in drinking water.

2.3.5 Pesticides used in water for public health purposes

A number of pesticides are used to control vectors such as mosquitoes. In some cases pesticides used for vector control may enter drinking water supplies, or even be added deliberately. There are currently five larvicides recommended by WHO for addition to drinking water: temephos, methoprene, pyriproxyfen, permethrin and *Bacillus thuringiensis israelensis* (see table 2.7 for trade names of some of these chemicals). Of these, only pyriproxyfen has been reviewed. It was found to be neither genotoxic nor carcinogenic, and given a GV of 0.3 mg/L.

Other pesticides (e.g. chlorpyrifos, DDT) which are not recommended for direct addition to drinking water may be used for control of aquatic vectors, and could potentially enter drinking water.

DDT and mosquito control

Malaria causes more than 300 million acute illnesses and kills at least one million people every year. Ninety percent of deaths due to malaria occur in Africa, south of the Sahara, and most deaths occur in children under the age of 5. Although agricultural use of DDT has been banned in most countries since the 1970s, indoor spraying of DDT can be highly effective and a comparatively inexpensive form of malaria control. For many malaria-affected countries, responsible DDT use is a vital strategy for preventing malaria transmission and controlling epidemics. In some cases, the introduction of less effective

DDT substitutes has compromised the efficacy of malaria-control programmes (WHO, 2007b). Consequently, a 2007 WHO position paper states that DDT should continue to be used for indoor spraying in a controlled fashion until cost-effective alternatives are available (WHO, 2007b).

2.3.6 Cyanobacterial toxins

An excess of nutrients, primarily phosphorus and in some cases nitrogen, can cause algal blooms in surface waters. The cyanobacteria (also known as blue-green algae) that are primarily responsible for these blooms produce a wide variety of biochemically active toxins, which can cause human health problems if ingested. Cyanobacterial toxins have only recently been recognized as a potential threat to the integrity of drinking water, and the magnitude of health impacts remains unclear. Because of the large number of cyanobacterial toxins, and the difficulty of laboratory analysis, chemical monitoring for these toxins is not recommended. Rather, source waters should be monitored for evidence of blooms, or bloom-forming potential. A provisional GV of 1 µg/L has been established for one of the more toxic and common toxins, microcystin-LR.

A WHO monograph describes in detail the state of knowledge regarding toxic cyanobacteria in drinking water (Chorus and Bartram, 1999).

Gastro-enteritis epidemic in the area of the Itaparica Dam

A severe epidemic of diarrhoeal disease in Brazil's Bahia state followed the flooding of the newly constructed Itaparica Dam reservoir in 1988. Some 2000 gastro-enteritis cases, 88 of which resulted in death, were reported over a 42-day period. Clinical data and water sample tests were reviewed, blood and faecal specimens from patients were subjected to bacteriological, virological and toxicological testing and drinking-water samples were examined for micro-organisms and heavy metals. The results demonstrated that the source of the outbreak was water impounded by the dam and pointed to toxin produced by cyanobacteria present in the water as the responsible agent. No other infectious agent or toxin was identified, and cases occurred in patients who had been drinking only boiled water. The cases were restricted to areas supplied with drinking water from the dam (Chorus and Bartram, 1999).

2.4 Physical and aesthetic water quality

Consumers of drinking water tend to base their perceptions of drinking-water quality on easily observed parameters such as visual appearance, taste and odour. This can lead to ingestion of water that is microbiologically or chemically unsafe, but appears clean. Conversely, a water of high microbiological and chemical quality with regard to health impacts may still appear dirty or have an unpleasant taste or odour, and can be rejected by consumers. The supply of aesthetically unpleasant water can and often does lead to the use of less safe, but more appealing, water resources; or may compel users to invest in costly (and possibly unreliable) alternatives such as bottled water or domestic water treatment devices. Thus, even in the absence of a direct threat to public health, water suppliers should seek to produce and deliver drinking water that is acceptable to consumers.

The concentration at which a parameter is objectionable to users will vary according to social, economic and cultural considerations. Therefore WHO does not set Guideline Values at specific levels, but rather indicates a typical concentration that might give rise to complaints from consumers. For detailed information see the WHO GDWQ Chapter 10.

Taste and odour

Unpleasant tastes and odours can arise from inorganic or organic compounds in water sources, occurring naturally or as a result of human activity. An unpleasant taste or odour may indicate a failure of drinking-water treatment, and should be investigated to ensure that microbial and chemical quality of the water is not compromised.

A major cause of taste and odour complaints is chemical disinfection. Utilities with large distribution systems may apply large chlorine doses to ensure a residual throughout the distribution system. In community or household settings, it can be difficult to ensure a consistent chlorine dose while maintaining the desired residual, typically near 0.5 mg/L. Above a residual free chlorine concentration of between 0.6 and 1.0 mg/L there is an increasing likelihood of complaints from consumers. Chloramines can also give rise to taste and odour problems.

A second major cause of taste and odour problem is dissolved inorganic compounds, especially metals. Naturally occurring iron and manganese commonly occur in groundwater; these may react with oxygen after exposure to air to form insoluble precipitates. Either as dissolved ions or as small particles, iron and manganese give a strong metallic taste to water. Iron is usually not detectable by users below 0.3 mg/L, and in some cases higher concentrations are acceptable. Manganese levels below 0.1 mg/L (well below the health-based GV of 0.4 mg/L) are usually acceptable to users.

Metals can also enter drinking water from pipes and fittings. Although copper can give rise to taste problems, the taste should be acceptable at the health-based provisional guideline value of 2 mg/L. Zinc levels above 3 mg/L can impart an undesirable astringent taste to water. Drinking water usually contains much lower levels of zinc, though older galvanized plumbing materials can leach zinc. There is no health-based GV for zinc.

Sulfate in drinking water can cause a noticeable taste above concentrations of about 250 mg/L. In the absence of oxygen and free chlorine, bacteria can convert sulfate to hydrogen sulfide, which causes a distinctive “rotten-egg” odour at concentrations as low as 0.05 mg/L. There are no health-based GVs for sulfate or sulfide.

Total dissolved solids (TDS) is a measure of salinity that can have an important effect on the taste of drinking-water. The palatability of water with a TDS level of less than 600 mg/L is generally considered to be good; drinking water becomes significantly unpalatable at TDS levels greater than 1000 mg/L. Dissolved ions increase the electrical conductivity (EC) of water, which is easily measured with a meter, so EC is often used as a surrogate for TDS. EC in microSiemens per centimetre (µS/cm) usually ranges from 1 to 2 times the TDS in mg/L. Excessive pumping or lack of rainfall in coastal areas can lead to saltwater intrusion, increasing the salinity in freshwater aquifers. Groundwater with high TDS may be too saline to be accepted by users; when drilling new wells salinity should be tested as early as possible, and certainly before well completion.

Sodium and chloride are principal components of TDS, and either ion can give water an unpleasantly salty taste at concentrations above 200-300 mg/L, depending on the associated counterion. Although some people with hypertension are sensitive to sodium, no health-based GV has been derived for either sodium or chloride.

The third major class of taste and odour compounds is organic material. Bacteria and fungi in surface water reservoirs can produce a number of organic compounds that can impart unpleasant earthy/musty odours to water. Geosmin and 2-methylisoborneol (MIB) are of particular concern, since they can cause acceptability problems at trace levels (below 10 ng/L, or 0.000010 mg/L). These compounds are most likely to be found in drinking water following algal bloom events.

Finally, synthetic organic compounds can impart tastes and odours to water. For many organic compounds, health-based GVs are below taste and odour thresholds. However, a number of low-molecular weight hydrocarbons found in petroleum oils and solvents may impart a very unpleasant "diesel-like" odour to water at levels well below health-based GVs.

Appearance

Ideally, drinking water should be free from colour and particulate matter.

Most consumers can detect colours above 15 true colour units (TCU), though more coloured waters may be acceptable according to local preference. Dissolved organic matter such as humic and fulvic acids is the main component of colour. Highly coloured waters may indicate a high potential for formation of byproducts following disinfection.

Turbidity, or cloudiness, is caused by suspended particles in water. Turbidity may result from insufficient filtration during water treatment or mobilization of sediments, mineral precipitates or biomass within the distribution system. Changes in turbidity following rainfall may indicate contamination with untreated surface water, and may contain pathogens. High levels of turbidity can shield pathogens from disinfectants, so effective disinfection requires that turbidity is less than 1 nephelometric turbidity unit (NTU); ideally, median turbidity should be below 0.1 NTU. Higher turbidity levels may be acceptable to consumers, but because of the possible screening of pathogens it is recommended that turbidity in treated water should be kept below 1 NTU.

Dissolved metals may contribute to colour in drinking water, and can stain laundry and plumbing fixtures. Metal precipitates may also form coatings on pipe walls that can slough off as fine particulates, contributing to turbidity. Iron and manganese above 0.3 and 0.1 mg/L, respectively, can cause staining, and may impact colour and turbidity at lower levels. Foods cooked in water (e.g., rice, plantains) containing high levels of iron and manganese may become unacceptably discoloured. Dissolved copper can stain laundry and sanitary ware at levels above 1 mg/L, which is below the taste threshold for most consumers, as well as the health-based GV of 2 mg/L.

High levels of aluminium in water following drinking-water treatment can lead to deposition of aluminium hydroxide flocs in distribution systems, and can interfere with discolouration of water by iron (see the discussion on contaminants from treatment chemicals in section 2.3.4 for more information on aluminium).

Hardness (calcium and magnesium)

Hardness is the sum of polyvalent metallic ions in water. Calcium and magnesium are the principal components, and hard waters are most common in groundwater, especially when derived from limestone, dolomite or chalk aquifers.

Hardness scale

Hardness is expressed in terms of milligrams of calcium carbonate equivalents per litre. A general hardness scale is:

Classification	mg/L CaCO3
Soft	0-60
Moderately hard	61-120
Hard	121-180
Very Hard	> 180

Hard water can be unacceptable to consumers. Hard water requires more soap to produce a lather, and can form scale deposits on pipes, basins, pots and hot water heaters (scale formation increases at higher temperatures). In contrast, soft water can lead to corrosion of metal pipes and elevated levels of heavy metals such as cadmium, copper, lead and zinc in drinking water.

The taste threshold for the calcium ion is in the range of 100–300 mg/L and the taste threshold for magnesium is probably lower. In some instances, consumers tolerate water hardness in excess of 500 mg/L. Soft water may also have a salty taste. There is some evidence that consumption of hard water is linked with lower rates of cardiovascular disease, but data are inadequate to show a causal relationship.

Additional resources on hardness

WHO Hardness Fact Sheet
www.who.int/water_sanitation_health/dwq/chemicals/hardness/en/

Corrosiveness

Corrosion is a complex process in which metals are oxidized through a variety of chemical, physical and biological reactions. Iron pipes and handpumps used in drinking-water systems are subject to corrosion, which can cause breakage or greatly reduce the efficiency of water transmission (McNeill and Edwards, 2001). A second important effect of corrosion is its negative impact on drinking-water quality: the high iron (and in some cases, zinc) levels resulting from corrosion can lead to consumer complaints of colour, turbidity or staining of laundry and sanitary ware.

Corrosion can occur under a variety of water conditions, but soft, acid waters tend to be the most aggressive (corrosive). Dissolved copper or high salinity can enhance some kinds of corrosion, but dissolved calcium and alkalinity can reduce corrosion by forming passive calcium carbonate coatings on metal surfaces. To some extent, corrosiveness can be predicted with corrosion indices, but because of the complexity of the corrosion process, metal pumps or pipes should be tested under field conditions in areas where corrosion is common. WHO recommends a pH of 6.5 or higher in drinking water to prevent corrosion. On the other hand, pH should be kept below 8.0 to allow more effective disinfection with chlorine.

Handpump corrosion in West Africa

In 1987 an investigation was conducted to identify the cause of well-known red water problems encountered by many handpump users in West Africa. A geochemical survey showed that natural groundwater quality was generally high, with iron levels typically below 1 mg/L, but that approximately half of the water samples had a pH below 6.5. However, water delivered from handpumps contained excessive levels of iron (over 20 mg/L in many cases) and most consumers were unwilling to drink water containing 5 mg/L iron or more.

The investigation concluded that aggressive water, especially with a pH < 6.5, was corroding handpump rods and rising mains. Up to two-thirds of handpump failures in the study area were directly or indirectly caused by corrosion, which even damaged galvanized rising mains and pump rods. As newly installed handpumps corroded, they produced red water that was unacceptable to users: over half of users reported that water taste deteriorated within a few months of installation.

Water quality was improved somewhat by encouraging villagers to use the handpumps more frequently. Although intensive and regular use of the handpumps does not stop corrosion, it significantly reduces red water problems by continuous flushing of corrosion products. When installing new wells in the project area, use of corrosion-resistant (e.g., stainless steel) rising mains was recommended for use below the water table. Less expensive galvanized materials could still be used for rising mains that will not be immersed in water (Langenegger, 1994).

Temperature

Consumers often tend to prefer cool water to warm water. This has been identified as a possible constraint for water treatment systems that rely on boiling or heating water, but in practice it does not appear to be a major problem (EAWAG, 2007; Islam and Johnston, 2006). High temperatures can also negatively impact water quality by enhancing micro-organism growth, and may increase taste, odour, colour and corrosion problems.

2.5 Radiological water quality

The contribution of drinking water to overall radioactive exposure is very small (typically less than 5%), and is principally due to the presence of naturally occurring elements in the uranium and thorium decay series.

Radioactive materials can be grouped into alpha, beta and photon emitters based on the particles or energy they emit. Rather than setting guideline values for individual radioactive compounds, WHO has set screening guideline values at 0.1 Bq/L for gross alpha activity and 1 Bq/L for gross beta activity. (The standard unit of radioactivity is the becquerel, where 1 Bq = 1 disintegration per second. Alpha particles consist of two protons and two neutrons, while beta particles are much smaller, and are equivalent to electrons.) Most alpha emitters occur naturally in the environment while beta emitters are principally products of the nuclear industry. If the screening GV for radiation in a water sample is exceeded, the radionuclides responsible for the radiation should be identified, and their individual activity concentrations measured.

Nearly half of the total natural radiation exposure we receive comes from a radioactive gas, radon, which is emitted by naturally occurring uranium, thorium and radium in rocks and soil. As radon (an alpha emitter) is quite volatile, radon concentrations in air are much higher than in water. Over 99% of radon exposure occurs from inhalation of radon naturally present in air, rather than from ingestion of drinking water.

Groundwater typically contains more radioactivity than surface water. Radium, a product of both uranium and thorium decay, is often the principal component of gross alpha activity in groundwater. Aquifers in granite or phosphate rocks can have elevated levels of uranium, and therefore thorium, radon and radium.

Additional resources on radiation

USEPA Radiation web page www.epa.gov/radiation

WHO Radiation web page www.who.int/ionizing_radiation/en

2.6 Key resources

US Agency for Toxic Substances and Disease Registry
www.atsdr.cdc.gov

USEPA Factsheets on Drinking Water Contaminants
www.epa.gov/OGWDW/hfacts.html

WHO (2006). Guidelines for Drinking-Water Quality. Third edition. Incorporating first addendum. Geneva: WHO.
In particular, Chapters 8 (Chemical aspects), 9 (Radiological quality), 10 (Acceptability aspects), and 12 (Chemical fact sheets).
www.who.int/water_sanitation_health/dwq/gdwq3/en/

WHO Environmental Health Criteria documents www.who.int/ipcs/publications/ehc/en/
Detailed monographs of individual chemicals designed for scientists and administrations responsible for the establishment of safety standards and regulations.

Chapter 3
Water Quality Monitoring and Surveillance

Safe water supplies are the result of informed and active governments and communities, properly constructed and managed systems, and the protection of systems from sources of contamination. Water quality monitoring and surveillance ensures that water continues to be safe throughout the life of the system and through changes in environmental conditions, watershed status and pollution patterns.

In many countries there is a trend towards the decentralization of government services and of water system management. Water quality monitoring and surveillance must follow this trend – technologies and methodologies for water quality control must increasingly be applicable at the community level. While national level activities such as strengthening legislation and developing supportive policies continue to be essential, governments and support agencies like UNICEF must stress the empowerment of community and local governments with the necessary tools and knowledge to assure the quality of their own water supplies.

Water quality monitoring and surveillance systems are an essential component of water safety plans (Chapter 4) and should be developed together with other components of the plan.

3.1 Methodologies

3.1.1 Rapid assessments and surveys

As the importance of water quality issues becomes increasingly recognized by national governments and external support agencies, special water quality assessment programmes are becoming more commonplace. Typically two types of rapid assessment are being carried out: comprehensive surveys of a range of key quality parameters and specific surveys of a single parameter.

A multi-parameter assessment has several goals. It is used to establish a water quality baseline, to help predict quality patterns and trends, to promote the establishment or improvement of routine monitoring systems and to influence the development of policy and legislation related to water source construction and national water quality standards.

In many developing countries good water quality data are not available, especially in rural and poor urban areas. Data are either not collected at all, collected sporadically or recorded in a format that makes it difficult to analyze (such as handwritten logs filed in provincial or district level government offices). A rapid assessment will often provide the very first set of usable information on water quality in a country. In most cases, such an assessment is a one-off event, but it can form the basis for the design of a national routine monitoring and surveillance programme.

A single-parameter assessment is usually carried out in response to an existing public health problem caused by a specific contaminant. The most common examples of this are the arsenic testing programmes in Asia. These surveys are used to quickly assess the extent of the contamination and the types or characteristics of the water sources affected. The information is used to help design mitigation programmes and to inform people about which specific sources, or type of sources, should be avoided.

Most multi- and single-parameter assessments are carried out on a sample basis (blanket arsenic surveys – where every source is tested in a particular area because of the unpredictable pattern of arsenic contamination – are an exception). There are several different ways of choosing statistically valid random samples, and it is beyond the scope of this handbook to explain them all. UNICEF and other organizations recommend the use of a cluster sample approach: the collection of water quality samples from groups of water sources that are close to one another. There are two main reasons for using this methodology: it is the same method by which most water, sanitation and public health-related information is gathered in developing countries (through the UNICEF/WHO Joint Monitoring Programme for Water Supply and Sanitation, the UNICEF Multiple Indicator Cluster Surveys and the USAID-supported Demographic Health Surveys), and it is logistically much easier and therefore less expensive and less time-consuming than other methods.

The choice of which water quality parameters to include in a multi-parameter assessment is dictated by the relative seriousness of a parameter in terms of health impact, whether or not a parameter is known (or suspected) to be present in a country and the existence of human activities that are known to potentially cause pollution of water supplies. Parameters affecting the acceptability of drinking water to users should also be prioritized. National standards and the WHO *Guidelines for Drinking-Water Quality* (see section 2.1) and any previous water quality surveys or data are important resources for defining the parameter set for a new assessment. Another resource is the methodology and parameter set developed through a recent rapid assessment pilot project conducted in six countries and replicated in an additional two countries under the auspices of the WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation (JMP, 2008).

Selection of parameters for assessment

The first priority in assessing drinking-water quality must be to check microbiological quality. This can be done by measuring, at a minimum, the "essential parameters" of drinking-water quality: faecal coliforms (or E. coli), and, when assessing treated water, chlorine residual, pH and turbidity (WHO, 2006, Section 4.2). Other important priorities are the aesthetic quality of the water and contamination with chemicals of known health risk. Table 3.1 lists parameters in order of decreasing priority. Level 1 parameters should be measured in any assessment, while level 2 and level 3 represent increasingly sophisticated and complete assessments.

Table 3.1 Levels of Assessment

Level of assessment	Microbiological and related	Inspections and risk assessments	Physical and chemical
Level 1	Thermotolerant coliforms (or *E. coli*) Turbidity (treated water) pH (treated water) Chlorine residual (treated water)	Sanitary inspection Pollution risk assessments Brief interviews at treatment works	Appearance (qualitative) Conductivity Priority inorganics (arsenic, fluoride, nitrate) unless known to be absent locally
Level 2	*E. coli* Faecal streptococci	Audit of treatment work records Catchment assessment Basic hydrogeological assessment	Alkalinity Copper (piped systems) Corrosivity Hardness Iron and manganese Odour (qualitative)
Level 3	Bacteriophages *Clostridia perfringens* Pathogen assessments Cyanobacterial toxins	Catchment assessment/EIA Full hydrogeological assessment Hazard analysis Microbial risk assessment Full chemical assessment	Inorganics: aluminium, ammonia, boron, cadmium, chromium, cyanide, lead, mercury, selenium Odour (quantitative) Organics: pesticides, disinfectant by-products Radiation

Source: Adapted from Howard, Ince and Smith (2003)

3.1.2 National monitoring and surveillance systems

Water quality monitoring refers to the routine and systematic inspection and testing of water supply systems by the water provider and, in some cases, by the consumer. In piped systems it involves the regular analysis of parameters related to both the quality of the water (including the quality of the intake water) and the functioning of the system itself (such as chlorine levels at tapstands in systems where chlorine is used and hydraulic pressure in pipelines). The key purpose of monitoring is to ensure that when a problem appears, system managers can take appropriate measures to correct it before unsafe water is delivered to the consumer.

In point sources, including both community and household systems, monitoring is often limited to sanitary inspections of water quality control measures such as well aprons and rooftop rainwater harvesting filters (see 3.1.4). It can also include some direct analysis of water quality through the use of field instruments (including, notably, H_2S strip vials for testing microbiological quality – see 3.2). In most cases, monitoring is carried out by system owners or designated community members, and not by private or government technicians.

Water quality surveillance refers to the oversight of water systems and water providers by independent agencies to ensure the consistent safety and acceptability of all national drinking-water supplies. All countries should have, or be working towards, a functional national water quality surveillance system. Ideally, the surveillance system should be based on established water quality standards and a national legislative and regulatory framework (see 2.1). In practice, many countries have neither national standards nor specific water quality legislation in place. In such cases, systems can be established that make use of existing legislation (e.g., in the areas of food safety, child rights, and health and welfare) and interim water quality standards. UNICEF and its partners (especially WHO) can be instrumental in supporting the establishment of a surveillance system along with national standards and legislation.

In practice the agency responsible for surveillance (e.g., a national ministry of health, a provincial water board or a municipal public health department) works closely with water providers, assisting them in the establishment of good systems management practices, reliable quality control processes and remedial procedures. The surveillance system should also provide a channel for third party audits of water supply systems, periodic testing of point sources in communities and mechanisms for notification and response in water quality emergencies (e.g., during a cholera outbreak). Finally, the surveillance system should have provisions for facilitating legal action in cases where it is necessary.

Water supply and surveillance agencies have an obligation to share water quality information with consumers. In some cases this obligation is formally defined in information rights legislation and in other cases it is implied. However, such rights do not ensure that people will be informed. Consumers may not be aware of their rights and some government agencies may be reluctant to provide the information. Even when attempts are made to inform people about water quality, poor communication infrastructure, large distances, limited budgets and illiteracy often mean that people are unaware of quality problems and continue to drink unsafe water.

Surveillance agencies must develop communication strategies to ensure that water quality messages are effectively transmitted to consumers (see Chapter 6). These strategies include the dissemination of information in formats understood by communities, establishing dialogues with communities through meetings and other means, involving local government bodies and NGOs, and in some cases, directly identifying problem sources (see box). UNICEF often has a role in this area, using its experience in programme communication to support these efforts.

Monitoring and surveillance programmes should not be allowed to become pointless exercises in data collection alone. The purpose of monitoring and surveillance is to ensure water systems are protected and, if problems emerge, to be the stimulus for corrective measures. There is little point in monitoring if there is no intention or capacity to act on the results. This means that monitoring and surveillance efforts should be fully incorporated into sectoral programmes at national, sub-national and community levels.

Communicating water quality information: marking wells

In the arsenic-affected countries in Asia, governments – in some cases with UNICEF support – are implementing blanket testing programmes to establish the status of each and every tubewell in suspect areas. Experience suggests that the most effective way of ensuring that contaminated wells are identified as such by consumers is by physically marking the wells – usually by painting the handpumps red or attaching a red band to the pump base – and implementing a comprehensive communication campaign to associate the marked wells with the health risks of arsenic. As a rights-based organisation, UNICEF should support efforts that inform and educate consumers about the safety of their water supplies (see also Chapter 6).

3.1.3 Community-based surveillance

National monitoring and surveillance systems are usually less effective in rural areas and poor urban areas than in cities and towns. Water Safety Plans, as discussed in the 2004 WHO Guidelines for Drinking Water Quality (and elsewhere, see Chapter 4), are more difficult to implement although they are relevant to such communities. Poor communication and transportation infrastructure, lack of resources, dispersed point source water systems and weak local government agencies contribute to this. Perhaps most importantly, poor and rural communities tend to have low awareness levels of the importance of water quality and thus do not typically demand water quality surveillance services.

Community-based surveillance systems are important in two ways: they extend the reach of national surveillance systems to poor and rural areas, and they directly involve the primary stakeholders in communities, thus helping to raise awareness on water quality. Improved local awareness and surveillance leads ultimately to safer water supplies.

Programmes to initiate and encourage community-based surveillance should include five components: awareness-raising on the importance of water quality; training of community members and source owners on sanitary inspection techniques (see 3.1.4); provision of field kits (including H_2S strips, see box) for water quality testing; establishment of links between the community and the national surveillance system and the development of a system for water quality problem remediation that involves both community-based interventions and, when necessary, interventions from government water services. In some cases, water quality surveillance can be introduced through ongoing hygiene education and promotion programmes and in all cases, awareness-raising on hygiene and water quality should go hand in hand (see Chapter 6).

The most important outcome of community-based surveillance is a "knowledge-empowered" community, that is, people with the knowledge to act as their own advocates for improved water services and the tools to improve the quality of their own water supplies.

Using H_2S kits for community-based water quality surveillance

H_2S kits (described in more detail in 3.2) are simple and inexpensive tests for bacteriological contamination of water supplies. While not as accurate as laboratory tests, they provide qualitative information on whether or not sources are likely to be contaminated with faecal material. Even in countries with functioning water quality surveillance systems, laboratory microbiological testing of small community water supplies is rarely carried out – this technology has the potential to help change the situation.

The test is very appropriate for community-based surveillance: it is inexpensive (as low as $0.20), portable, simple and provides a visible test result. In the test, prepared vials are filled with sample water and if the water turns black after 24 hours the source is likely to be contaminated. The vials are most commonly used in a simple presence/absence format, which provides no information about the degree of contamination. It is possible to use H_2S kits in a Most Probable Number format, but this is rarely done. H_2S testing was developed in India and is gaining popularity in other countries including South Africa, Ethiopia, Bangladesh, Myanmar, Thailand and Vietnam. In Thailand, for example, the Ministry of Public Health manufactures H_2S kits and other simple presence/absence kits for use within their own monitoring programme and for sale to consumers at low cost. H_2S testing has also been used in emergency situations to rapidly assess the safety of water sources. In some cases the test vials are provided through pilot projects, in others they are available in the marketplace. In Vietnam, the vials are sold in some pharmacies.

The tests can be used to empower communities with direct knowledge of the quality status of their own water points. This knowledge can be used to assess the quality of sources constructed by government or the private sector and to demand improvements or replacements when necessary. The technology allows communities to test sources throughout the year and to take remedial action, such as chlorination, when necessary.

H_2S kits are available from international chemical companies like Hach, and increasingly from manufacturers and distributors in developing countries. However, H_2S kits remain an emerging technology, and kit performance should be carefully evaluated and test results checked against more conventional laboratory methods.

3.1.4 Sanitary inspections

The analysis of water quality parameters alone cannot provide a complete picture of the water quality status of a community and its water supply systems. Periodic quality testing is only a snapshot: it provides limited information on the source of contamination and it can miss important seasonal quality fluctuations. Remediation of actual and potential water quality problems is only possible if information is available on the sources and pathways of contaminants, and this information can only be provided by sanitary inspections. Thus, sanitary inspections are an integral component of rapid assessments, routine monitoring and community- based systems (as well as water safety planning – see box in section 4.4).

A sanitary inspection is an on-site appraisal by trained people of actual and potential contamination hazards and pathways in and around water supply systems. Hazards are contamination sources that may be a risk to water systems, such as latrines too close to shallow point sources or stagnant surface water. Pathways are routes through which contamination may occur, such as leaking pipes or cracked well aprons. Hazards and pathways can be indirect or intermittent, such as a broken gate that allows animals into well enclosures or erosion that uncovers buried pipelines. Sanitary inspections focus on microbiological contamination sources. However, in some cases inspections can identify chemical hazards from local industries or agricultural activity such as intensive fertilization near a surface water source intake or effluents from a tannery near a point source.

Sanitary inspections are usually carried out using standardized checklists for observations and interviews with a scoring system to quantify overall risk. For a complete a set of recommended checklists, see Water Safety Plans: Managing drinking-water quality from catchment to consumer (Davison, A., G. Howard et al, 2005). In most cases checklists are modified to take into account specific country conditions. WHO recommends sanitary inspections annually for all water supply systems, including point sources, and for every new water system.

Sanitary inspections are traditionally carried out at different points in a water system, including the source, intake, distribution lines, treatment plant and at all point sources. Recently, the concept of sanitary inspections has been broadened to include not just systems and their immediate surroundings, but an analysis of contamination pathways, hazards and practices in communities and households (in some texts, this is referred to as “visual inspection”).

It is now well understood that contamination of water often occurs during the transportation of water to the home and in the home itself. Such contamination is linked to hygiene awareness and practices of water bearers and family members and, in some cases, to the availability of appropriate receptacles and utensils (e.g., closed water jars and long-handled ladles). Observing water handling and storage practices and interviewing community members can yield valuable information on the actual causes of poor water quality and contribute to plans for interventions to improve the water quality status of a community.

While training is essential, sanitary inspectors do not necessarily have to be water technicians. Community members with no formal technical background have been successfully trained in the sanitary inspection of point sources and small community systems. Local inspectors are often very effective as they are direct stakeholders in the water systems, are accountable to their peers and local authorities, and are in a position to carry out inspections on a regular basis.

Additional resources on water quality monitoring and surveillance

Howard, G. (2002a). Water Quality Surveillance - a practical guide. Loughborough: WEDC. www.lboro.ac.uk/watermark/practical-guide

Howard, G. (2002b). Water Supply Surveillance - a reference manual. Loughborough: WEDC. www.lboro.ac.uk/watermark/reference-manual

Davison, A., G. Howard et al (2005). Water Safety Plans: Managing drinking-water quality from catchment to consumer. Geneva: WHO. www.who.int/water_sanitation_health/dwq/wsp0506/en/index.html

WHO (2006). Guidelines for Drinking-Water Quality. Third edition. Incorporating first addendum. Geneva: WHO. Especially Chapter 4 (Water Safety Plans) and Chapter 5 (Surveillance). www.who.int/water_sanitation_health/dwq/gdwq3/en/

3.2 Measuring water quality

The aesthetic quality of water, by definition, is determined subjectively by the user. The safety of drinking water for public health, on the other hand, must be determined analytically: water that is pleasant-tasting and apparently clean may still contain dangerous numbers of pathogens or high levels of chemicals that can cause health effects.

Microbiological and chemical testing can be made either on-site, using field kits, or in laboratories. Where possible, field testing is preferred because it is logistically much easier, and in most cases significantly more cost effective. In addition, errors introduced from the preservation, transport and storage of samples for laboratory testing are eliminated. Properly trained field test kit operators can test a large number of water sources in a relatively short time, allowing the results to be obtained and shared with users within hours or days. In recent years technological innovations have improved the quality of field test kits, while further lowering costs. If this trend continues, field testing should be expected to become more prevalent in the future. All testing programmes – whether laboratory or field based – should be subject to quality assurance, as described in section 3.3.

3.2.1 Microbiological analyses

By far the most serious public health risk associated with drinking-water supplies is microbial contamination. Pathogens – bacteria, viruses and parasites – can cause a wide range of health problems when ingested in drinking water (see Chapter 2), but the primary concern is infectious diarrhoeal disease transmitted by the faecal-oral route.

It is impractical to analyze water for every individual pathogen, some of which can cause disease at very low doses. Instead, since most diarrhoea-causing pathogens are faecal in origin, it is more practical to analyze water for *indicator species* that are also present in faecal matter. The most commonly used indicator species are coliform bacteria, which include a wide range of bacteria, all of which can ferment lactose and produce gas at 35°C. Many but not all coliforms are faecal in origin, so the presence of **total coliforms** in water is not a good indicator of poor water quality.

Coliforms that come from faecal matter can tolerate higher temperatures than most environmental coliforms, so those that ferment lactose and produce gas at 45.5°C are called **thermotolerant coliforms**, or **faecal coliforms**. These are more closely associated with faecal pollution than total coliforms. The most specific indicator of faecal contamination is ***Escherichia coli*** **(*E. coli*)**, which unlike some faecal coliforms never multiplies in the aquatic environment. Either *E. coli* or faecal coliforms are acceptable for use as indicator species. Faecal coliforms have a number of characteristics of a good indicator species: they are universally present in faecal matter in high numbers, are not themselves pathogenic, and are relatively easy to measure using simple and inexpensive equipment. One drawback of coliform indicators is that they are significantly more susceptible to chlorine than some other pathogens (e.g., *Cryptosporidium,* viruses). Also, some treatment processes may remove coliforms but not viruses, which are much smaller. For these reasons, water without *E. coli* or faecal coliforms should be seen as low-risk, rather than completely safe.

Other indicator organisms sometimes used include **faecal enterococci** as an indicator of faecal pollution, and **heterotrophic plate count (HPC)** measurements, which are useful in assessing the effectiveness of treatment and distribution systems. ***Clostridia perfringens*** is a type of bacteria that can survive in the environment, and is resistant to standard disinfection. As such it may be a useful indicator for virus or parasites in water contaminated with faecal material. For detailed information about these and other indicator organisms refer to WHO (2006), Chapter 11.

When assessing faecal contamination, it is recommended to measure turbidity along with *E. coli* (or faecal coliforms), since pathogens can adsorb onto suspended particles, and to some extent be shielded from disinfection. When water has been disinfected, it is also important to measure chlorine residual and pH. These four parameters (*E. coli*/faecal coliforms, turbidity, disinfectant residual and pH) are considered the minimum set of “essential parameters” required to assess microbiological quality of drinking water (WHO, 2006).

Laboratory analysis is generally required for positive identification of specific pathogens (e.g., E. coli, viruses, protozoa) or non-coliform indicator species (e.g., faecal streptococci). Total and faecal coliforms, on the other hand, can be measured in the lab or in the field using portable kits. Field kit results are usually reliable, can be shared with users rapidly, and the testers can take advantage of their visit to advocate for improved sanitation and hygiene as needed. In developing countries lab facilities are often insufficient to support large-scale testing of rural water supply systems, so routine field testing may be the only practical option. As a quality assurance measure, some field analyses should be cross-checked with laboratory tests.

Since analysis involves culturing viable microbes in a hospitable nutrient broth, the results are very sensitive to sample type and incubation conditions. It is particularly important that standardized methods be used so that results are consistent and reliable.

Standardized methods

When making microbiological analyses, it is critical that standardized methods be followed so that results will be consistent and comparable to other analyses. Standardized methods may be obtained from a number of internationally recognized sources:

- ISO, the International Organization for Standardization, is a network of national standards institutes from 148 countries that produces and sells individual standards online (www.iso.org).
- Standard Methods for the Examination of Water and Wastewater (APHA/AWWA/WEF, 1998), widely used worldwide, is a classic compilation of standards and can be purchased online (www.standardmethods.org).
- Many microbiological methods are freely available from the USEPA microbiology home page: (www.epa.gov/nerlcwww/). A complete CD-ROM database of USEPA-approved methods for analysis of drinking water is available for purchase (USEPA, 1999).
- The US National Environmental Methods Inventory (www.nemi.gov) is a searchable database of analytical methods for environmental monitoring, including microbiological methods.

Sampling

Microbial analysis is fundamentally different from chemical analysis in that the goal is the detection of a very small number of viable microbes, which are not evenly distributed through the sample. Microbial contamination can change markedly over time, so frequent sampling is recommended. In piped water systems samples should cover the entire water system, particularly extremities where disinfectant residuals are likely to be lowest. However, it is easier and more practical to make multiple tests of disinfectant residual at different locations, in order to identify areas where faecal coliforms might be able to survive.

Field workers collecting samples for laboratory analysis must be properly trained in the collection and handling of samples to prevent contamination. Samples should be stored in the dark, be kept chilled (ideally between 4° and 10°C), and be analyzed within 6 hours. If the water has been chlorinated, a quenching agent such as sodium thiosulfate should be added to the sample bottle at the laboratory before sample collection. When sampling chlorinated waters, pH and chlorine residual should also be measured.

Laboratory analysis has some advantages over field testing: samples can be processed more rapidly, and the environment is cleaner. However, significant challenges are presented by preservation and transport of samples from field sites to laboratories. Field-based methods, especially using the membrane filtration method (see below) can produce results of a quality comparable to laboratory methods, as long as staff are properly trained in aseptic techniques. For these reasons, field analysis of microbiological quality is generally recommended.

Methods

The two classic methods for measuring coliform bacteria in drinking water are the multiple tube and membrane filtration methods. In recent years two alternatives, the enzyme substrate and H_2S methods, have been gaining increasing popularity.

Multiple tube fermentation (MTF)[1]: multiple samples of the water being tested are added to a nutrient broth in sterile tubes and incubated at a particular temperature for a fixed time (usually 24 hours). If the water source is unprotected or contamination is suspected, serial dilutions of the water (usually 10, 1, and 0.1 mL) may be made. Three or five tubes per dilution are commonly used, though ten tubes may be used for greater sensitivity. As coliform bacteria grow, they produce acid and gas, changing the broth colour and producing bubbles, which are captured in a small inverted tube. By counting the number of tubes showing a positive result, and comparing with standard tables, a statistical estimate of the *most probable number* (MPN) of bacteria can be made, with results reported as MPN per 100 mL.

Since some noncoliform bacteria can also ferment lactose, this first test is called a “presumptive” test. Bacteria from a positive tube can be inoculated into a medium that selects more specifically for coliforms, leading to “confirmed” results. Finally, the test can be “completed” by subjecting positive samples from the confirmed test to a number of additional identification steps. Each of the three steps (presumptive, confirmed and completed) requires 1-2 days of incubation. Typically only the first two steps are performed in coliform and faecal coliform analysis, while all three phases are done for periodic quality control or for positive identification of *E. coli*.

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[1] This method is sometimes called the ‘most probable number’ method, but that term is more properly applied to any method which involves incubation of multiple samples to give a statistical estimate of bacterial density

This method is easy and requires little specialized equipment, and has the advantage of being applicable to turbid or highly contaminated samples. Disadvantages include the large number of tubes needed and the long time requirement for the full test. Accordingly, this test is most conveniently applied in a laboratory setting, though the presumptive test is sometimes made with field kits. Another disadvantage of this method (and other MPN methods) is that the result is a statistical approximation with fairly low precision, and as such should only be considered semi-quantitative.

Membrane filtration (MF): A water sample (typically 100-mL) is filtered through a cellulose membrane with a pore size of 0.45 microns, which screens out all coliform bacteria. The membrane is then incubated in a growth medium at a particular temperature. Bacteria that are favoured by the growth medium will grow into colonies that can be counted after 24 to 48 hours. Results are reported as *colony-forming units* (CFU) per 100 mL. As with the MTF method, positive test results should be considered as presumptive, and confirmed with subsequent inoculations into more selective growth media.

This is a very commonly used method in laboratories, and forms the basis of the most widely used field kits. One advantage is that it gives a direct count of bacteria, rather than the statistical estimate of MPN methods. For waters of low turbidity, large volumes can be filtered, increasing the test's sensitivity. However, this method is inappropriate for turbid waters, which can clog the membrane or prevent the growth of target bacteria on the filter. Another concern with this method is that it may not detect stressed or injured coliforms.

Commercially available field kits*

A number of field kits, or portable laboratories, have been widely used for field microbiological analysis. All allow measurement of essential physical and chemical parameters (pH, turbidity, chlorine residual), and some have modules for colorimetric measurement of various inorganic chemicals (e.g., ammonia, arsenic, fluoride, nitrate). All kits are able to run from mains electricity or on built-in batteries, which can be charged with solar panels. Some of the more commonly used kits are listed below.

- ELE Paqualab www.ele.com/env/int/
- Hach MEL portable laboratory series[2] www.hach.com
- Oxfam/DelAgua kit www.rcpeh.com
- Wagtech Potakit www.wagtech.co.uk

* This list does not constitute an endorsement of the companies or products.

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[2] The Hach MEL laboratories incorporate enzyme substrate assays with conventional MF or MTF methods.

Enzyme substrate methods

In recent years tests have been developed that chemically identify specific enzymes produced by particular pathogens. These enzymes react with specific substrates in the nutrient medium, and generally produce a striking colour change that is easy to identify. These tests are more rapid than conventional methods: some can produce results in 24 hours or less. Furthermore, they are more specific than conventional tests, so confirmatory tests are generally not necessary. Two of the most relevant enzyme tests for drinking water are described briefly below.

> *Beta-galactosidase:* Coliform bacteria produce the beta-galactosidase enzyme. A number of specific substrates have been developed which react with this enzyme to produce a strong colour, usually yellow or deep red.
>
> *Beta-glucuronidase:* Over 95% of *E. coli* produce the beta-glucuronidase enzyme.[3] This enzyme reacts with the substrate 4-methylumbelliferyl-beta-D-glucoside (MUG) to produce a chemical that glows blue upon exposure to ultraviolet light. Other substrates can produce a visible colour, typically blue.

Assays using substrates that react with these two enzymes have been certified by the USEPA and ISO. Many commercially available assay kits test for both enzymes, allowing simultaneous determination of total coliforms and *E. coli*.

Enzyme methods can easily be used in a qualitative way to measure the presence (P) or absence (A) of coliforms or *E. coli* (P/A test). A single sample of undiluted water is incubated for the appropriate time, with a positive result indicating contamination, but giving no information regarding the level of contamination. P/A tests are useful for screening, especially in settings where most samples are expected to give negative results (e.g., treated water).

Enzyme methods can also be employed semi-quantitatively, using multiple samples and serial dilutions, to obtain a most probable number (MPN) estimate, as in multiple-tube fermentation. Sometimes a tray with multiple small wells is used instead of multiple tubes, significantly simplifying the procedure. The P/A test can easily be applied in the field, while the semi-quantitative MPN method is more readily performed in a laboratory. Advantages of these methods are simplicity, speed and specificity. Disadvantages are the relatively high cost of reagents, and the relatively small number of commercially available products (see box).

Commercially available enzyme-based pathogen tests*

Company	*Product*
Charm Sciences 36 Franklin Street Malden, MA USA 02148 www.charm.com	E*Colite

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[3] One exception is the enterohemorrhagic E. coli (EHEC) strain O157:H7.

Company	Product
CHROMagar 4, Place du 18 juin 1940 75006 Paris France www.chromagar.com	CHROMAgar E. Coli CHROMAgar Vibrio CHROMAgar Salmonella
EMD Chemicals (an affiliate of Merck) 480 S. Democrat Road Gibbstown, NJ USA 08027 www.emdchemicals.com	Readycult Chromocult
Hach Company 100 Dayton Avenue Ames, IA USA 50010 www.hach.com	m-ColiBlue24
IDEXX Laboratories One IDEXX Drive Westbrook, ME USA 04092 www.idexx.com	Colilert Colisure Enterolert

* This list does not constitute an endorsement of the companies or products.

Enzymatic methods typically require an incubation period of 18 to 36 hours. However, recent studies have shown that shorter incubation periods (<12 hours) can give good results, and if water is highly contaminated, coliforms can be detected rapidly, without a growth phase (Tryland et al., 2001).

A number of other enzyme substrate assays exist for important water-borne pathogens (e.g. enterococci, *Salmonella*, *V. cholera*, *E. coli* O157), though these are not as well-developed as the coliform tests, and have been for the most part applied to food or stool samples. Still, it is likely that they could facilitate drinking-water analysis in the future.

Hydrogen sulfide (H_2S) test

In 1982 Manja et al. reported a simple method for detection of faecal contamination in drinking water (Manja et al., 1982). The authors noted that waters containing coliform bacteria also consistently contained organisms producing hydrogen sulfide (H_2S). H_2S reacts rapidly with iron to form a black iron sulfide precipitate, so the authors developed an iron-rich growth medium. When water samples are incubated in the medium at 30°-37°C for 12 to18 hours, production of a black colour indicates contamination with H_2S-producing organisms. Over the last 20 years a number of modifications have been made to the method proposed by Manja et al., in an attempt to improve its performance. The method has been applied as in presence/absence, most probable number, and membrane filter formats. Most commonly it is used qualitatively, as a presence/absence test with a 20 mL sample.

The H_2S test does not specifically test for standard indicator species such as total coliforms, faecal coliforms or *E. coli*. Rather, a large number of bacteria can lead to H_2S production (e.g. *Citrobacter, Enterobacter, Salmonella, Clostridium perfringens*). Most of these are faecal in origin. Both human and animal faeces contain H_2S-producing organisms, so the H_2S test, like the total coliform test, is not specific for human faecal contamination.

The H_2S method was reviewed in a WHO report (Sobsey and Pfaender, 2002), which found the test to be reasonably accurate, simple and inexpensive – approximately one fifth the cost of standard coliform tests. A review of the literature indicates that the test detects faecally contaminated water with about the same frequency and magnitude as the conventional methods (MTF and MF). However, the authors caution that some conditions (in particular, the presence of sulfate-reducing bacteria) may lead to false positive results. False positives are of less public health concern than false negatives, and the advantages of the method (speed, simplicity and low cost) still make the H_2S test an attractive option. The H_2S test is not mature enough to replace conventional methods, but can serve a valuable role in screening water supplies. Testing water for faecal contamination with the H_2S method is certainly preferable to not testing at all.

H_2S kits may be purchased from a few international chemical companies (e.g., Hach Company's Pathoscreen Field Kit). As the reagents are all commonly available in developing countries, kits may also be produced locally (see box in section 3.1.3). A joint research project between UNICEF and the Rajiv Gandhi National Drinking Water Mission in India has produced specifications for a field kit that are available from the Rural Water Supply Network (RWSN) at:
www.rwsn.ch/documentation/skatdocumentation.2005-11-18.4373711451/file

3.2.2 Chemical analyses

Chemical parameters can be analyzed much more rapidly than microbiological ones, because there is no need for incubation. Analysis time generally ranges from a few seconds to hours. Most parameters must be analyzed in a laboratory, at least for quantitative results. Some parameters, though, might change during storage and transport (e.g., pH, alkalinity) and should be measured at the sampling site. Inexpensive field kits are available for semi-quantitative determination of many parameters, and in some cases sophisticated equipment can be made portable for field analysis.

Laboratory methods

A full review of laboratory methods for measuring the various parameters important to drinking-water quality is beyond the scope of this document. The reader is referred to the

WHO GDWQ (WHO, 2006, Section 8.3) for a comprehensive listing of laboratory methods for specific chemicals that have guideline values. The main laboratory techniques are briefly summarized below, in order of increasing complexity.

Colorimetric methods: Chemicals are added which react with the parameter of interest to form a product that absorbs light at a particular wavelength. Samples are then analyzed in a colorimeter or spectrophotometer[4] and compared to known standards. Colorimetric methods are available for many inorganic compounds.

Electrode methods: Ion-selective electrodes can measure the concentration of certain ions in the water sample. pH is readily measured with an electrode and meter.

Chromatography: Samples are passed through a column containing a specific packing or coating that selectively retains certain types of chemicals. Different compounds pass through the column at different speeds, depending on their affinity to the packing or coating. Ion exchange resin is used in ion chromatography (IC) for charged inorganic compounds. Volatile organic compounds are analyzed in gas chromatography (GC), while non-volatile organics are analyzed with high performance liquid chromatography (HPLC). HPLC can also be used for some inorganic compounds. A suitable detector at the column exit allows quantification.

Atomic absorption spectrometry (AAS): Most metals and metalloids can be analyzed with AAS. Samples are heated either in a flame (F-AAS) or electrically in a graphite furnace (GF-AAS), and concentration is determined by the metal atom's absorption of light at a characteristic wavelength. Flame AAS is used for moderate concentrations (generally 0.1 – 100 mg/L) while GF-AAS is used for trace determination, on the order of 0.001 mg/L.

Inductively Coupled Plasma (ICP): Like AAS, ICP is used for analysis of metals. Samples are atomized and detected either through atomic emission spectroscopy (ICP-AES) or mass spectroscopy (ICP-MS).

Colorimetric and electrode methods can be implemented in basic laboratories with relative ease. Chromatography and atomic absorption are considerably more expensive and complex, and are more appropriate for central or reference laboratories. ICP methods are very costly and difficult, and are uncommon in developing countries.

Some parameters require special procedures during collection (e.g., filtration) or storage and transport (e.g., preservation with acid or a chelating agent to prevent precipitation of iron, which can remove metals). Procedures for sample collection and preservation should be documented as part of a quality assurance program (see 3.3).

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[4] Colorimeters and spectrophotometers do the same thing: measure the amount of light of a certain wavelength that passes through a sample. The main difference is that colorimeters direct a broad band of the light spectrum onto the sample, while spectrophotometers use a tight band around the wavelength of interest. Spectrophotometers can achieve lower detection limits, but are more expensive.

Field kits

Many inorganic compounds can be measured at concentrations of interest using field test kits. Analysis of most organic contaminants requires laboratory equipment. Some field test kits involve chemical reactions that change the colour of a paper strip, which is compared to a colour chart. Others change the colour of the water sample, and use a colour-disk or portable colorimeter to determine the concentration.

The priority chemical contaminants of health concern in drinking water are arsenic, fluoride and nitrate. Unfortunately, these contaminants – especially arsenic and fluoride – are relatively difficult to measure at concentrations of health interest. Still, because of their public health importance, significant efforts have been applied to design robust and reliable field test kits for these parameters.

Kits may be procured from international suppliers or produced domestically. Large international firms have excellent quality assurance programs, so kit quality is generally high. Domestically produced kits may suffer from substandard design and/or reagents, especially if the company does not have extensive experience in field kit production. However, domestic kits can be significantly less expensive, are easier to procure and can be more easily adapted to local needs.

For any kind of field kit, it is of critical importance that kit operators receive proper training and supervision, and that field results are regularly validated with quality control samples and cross-checks with more sophisticated methods (see section 3.3).

Sensitivity and specificity

Two important concepts in judging the quality of a test kit are its sensitivity and specificity.

Sensitivity refers to the probability that the test correctly identifies contaminated samples, while *specificity* is the likelihood that the test correctly identifies non-contaminated samples. A highly sensitive test will have very few false negative results, while a highly specific test will not produce false positives.

		True value	
		YES	NO
Test result	YES	True Positive (TP)	False Positive (FP)
	NO	False Negative (FN)	True Negative (TN)

Sensitivity = TP/(TP+FN)
Specificity = TN/(FP+TN)

Positive Predictive Value = TP/(TP+FP)
Negative predictive value = TN/(FN+TN)

Strictly speaking, sensitivity and selectivity only apply to tests where the results are of a YES/NO format. These terms are sometimes applied to quantitative or semi-quantitative results, by using a reference value to group quantitative results into YES/NO categories. For example, say the drinking-water standard for arsenic in a particular country is 50 µg/L. Test results indicating 51 µg/L arsenic or more could be defined as positive results, and results of 50 µg/L or less as negative. When this is done, the kit sensitivity and specificity will depend on the actual concentrations being tested, and will be lowest near the reference value. For example, if the actual value of a sample being tested was 52 µg/L and a test indicated 48 µg/L, the test would be counted as a false negative even though the measurement is actually quite accurate. If the actual value was 500 µg/L, and the test kit indicated only 48 µg/L, this would be a serious false negative, and could indicate that the kit is insufficiently sensitive.

Arsenic *As* *WHO GV 10 µg/L (P)*

Quantitative measurement of arsenic, especially at the µg/L level, is difficult, and no simple paper-strip or colour-disk field kits are available. However, as a result of the discovery of significant arsenic contamination of groundwater in Asia and elsewhere, a variety of field kits are now available. All of these rely on the Gutzeit method, which consists of several steps (United Nations, 2002, Chapter 2):

1. Pre-reduction. Arsenic(V) is converted to arsenic (III) in the water sample. Strong reducing agents such as potassium iodide (KI) and stannous chloride ($SnCl_2$) or ascorbic acid are added to the water sample. Reaction takes about 15 minutes.

2. Arsine generation. Arsenic (III) is further reduced to arsine gas (AsH_3), which bubbles out of the sample. In the classical test, liquid hydrochloric acid is added to zinc metal, producing hydrogen gas, which reduces arsenic to arsine. The hydrogen also acts as a carrier gas, transporting the arsine to a piece of paper impregnated with mercuric bromide. This step is problematic: hydrochloric acid is dangerous to handle in the field; zinc metal often contains significant amounts of arsenic as impurities; and the generation of arsine is slow, taking at least 30 minutes. Arsine generation is also very sensitive to zinc grain size.

   Several modifications have been proposed to improve arsine generation. Hydrochloric acid can be replaced with a solid acid such as sulfamic or amidosulfonic acid, in powder or tablet form. An alternate to zinc is sodium borohydride ($NaBH_4$), which is used in laboratories for hydride generation. When mixed with acid, sodium borohydride produces hydrogen gas, and reportedly reduces arsenic to arsine more rapidly than when zinc is used. Use of borohydride may make a pre-reduction step unnecessary (some of these modifications have been incorporated into the Arsenator kits, see box below).

3. Sulfide removal. If the water sample contains sulfide, this will be transported to the mercuric bromide paper, and will react to form a black precipitate. This would ruin the test, so sulfide must be removed. This is most commonly done by passing the gas stream through material (paper or glass wool) impregnated with lead acetate. Some kits remove sulfide prior to arsine generation, by oxidation to sulfate. Sulfide removal is an important step, as arsenic is most commonly found in anaerobic groundwaters which may also contain significant amounts of sulfide.

4. Arsine trapping. Arsine gas reacts with mercuric bromide to form a yellowish-brown compound. Most kits use paper impregnated with mercuric bromide to trap the arsine gas. As more arsine gas is trapped, the pale yellow colour produced becomes darker and brownish. Arsenic concentration is measured semi-quantitatively by comparison with colour charts. Early kit designs inserted a long mercuric bromide paper strip into the reaction vessel, where the arsine gas can pass over the paper surface. A significant design improvement is a vessel design that forces the arsine gas to pass through the reagent paper. This produces a deeper colour, allowing a lower detection limit.

Most commercially available field test kits typically provide colour reference charts, with reported detection limits on the order of 10 µg/L. However, evaluations have shown that results are semi-quantitative at best, especially at lower levels (<100 µg/L) (Van Geen et al, 2005). The kits are most effectively used in a positive/negative format with a reference value of 50 µg/L, which is the drinking-water standard in many countries. At this level, most samples containing 50-99 µg/L are identified as positive, and nearly all samples containing 100 µg/L or more result in positive test results, though the quantitative assessment may be incorrect. With a reference level of 50 µg/L, there is still a significant risk of false negatives (~10%), but most false negatives occur in samples containing low levels of arsenic (10-49 µg/L), rather than the complete absence of arsenic. Since even 10 µg/L is not considered safe, this type of false negative can be tolerated. The field kits rarely give false positive results, though they may quantitatively overestimate actual concentrations. Currently available field kits cannot reliably measure arsenic at the 10 µg/L level, so they would not be effective if this were chosen as the reference value. However, in recent years manufacturers have modified designs in an effort to lower detection limits. The newer kits are probably still not capable of reliably quantifying arsenic at such low levels, but should have lower false negative rates when used in a positive/negative format.

It has been argued that field kits are inappropriate for arsenic analysis, because they lack the sensitivity to reliably detect arsenic at levels of health interest (10-50 µg/L) (Rahman et al., 2002). However, there are three main obstacles to the exclusive use of laboratory methods in large screening exercises (Kinniburgh and Kosmus, 2002): first, the lack of sufficient laboratories of the required quality to reliably process large numbers of samples; second, the lack of management experience to organize the collection and tracking of samples and reporting of results on a large scale; and finally, logistical problems associated with the transport of samples from the field to laboratory, and ensuring that results are in turn relayed back to the field.

Evidence now shows that well-designed and implemented survey programmes using field test kits can be accurate. An analysis in Bangladesh of 6,341 sample pairs from Merck kits and laboratory tests demonstrated a field kit sensitivity of 88 percent and specificity of 84 percent (16 false positives out of every 100 negative tests, and 12 false negatives out of every 100 positives) (Rosenboom, 2004). And a 2006 study analyzing newer generation test kits in the USA demonstrated a high correlations to laboratory results (Steinmaus et al, 2006).

At least in the short term, field kits remain the best available option for large-scale screening. It is critical, however, to implement QC checks on field kit analyses such as analysis of QC samples (blanks, known standards) and cross-checking a subset of results (typically 2-10%) in reference laboratories.

A separate criticism of arsenic field test kits is that they expose the analyst to unsafe levels of the toxic arsine gas. One study found that nearly half of the arsine generated escaped the reaction vessel (Hussam et al., 1999). Newer kit designs that force arsine gas through rather than around reagent paper strips should greatly reduce arsine escape, but analysis should still always be conducted in a well-ventilated area (e.g., outdoors).

Commercially available arsenic test kits*

- Acustrip Inc. (www.acustrip.com) markets five different arsenic test kits. The main product, the Arsenic Check test (#481396) has a range of 5-500 µg/L, while the lower-priced, less sensitive version (#481298) has a range of 10-1000 µg/L. The company also markets a low-range kit (#481297) with a range of 2-160 µg/L and two "individual" kits for household use. The Acustrip kits have a reported reaction time of only 12 minutes.
- The Asia Arsenic Network (www.asia-arsenic.net), an early player in arsenic testing and kit development, continues to market an inexpensive kit with a range of 20-700 µg/L in Bangladesh (through NIPSOM – National Institute of Preventative and Social Medicine – www.nipsom.org) and Nepal (through ENPHO - Environment and Public Health Organization, www.enpho.org). Kit specifications are available online.
- Hach (www.hach.com) produces two arsenic test kits. The EZ Arsenic Kit (# 2822800) has a range up to 4000 ppb, takes fewer steps, and is more economical. The Low Range Kit (# 2800000) has a range up to 500 ppb and is best for samples containing sulfide or arsenic-iron particles.
- Merck (www.merck-chemicals.com) has produced arsenic test kits for many years. Currently the company markets two colorimetric (colour chart) kits: the standard Merckoquant arsenic test kit (#117917) with a reported detection range of 20-3000 µg/L and the newer more sensitive kit (#117927) with a reported detection range of 5-500 µg/L. Merck has also released a new digital optical photometer Spectroquant arsenic kit (#101747) with a reported range of 1-100 µg/L. This kit is used with Merck's photometers to digitally measure colour results for better accuracy and precision. These photometers are typically used in a laboratory setting, but one model,

the Nova 60A (# 1.09751.0001) comes with a battery pack and can be used as a "portable field station" (although it is much larger and heavier than the arsenator, below).

- A joint project between UNICEF and the Rajiv Gandhi National Drinking Water Mission in India has developed specifications for a field kit that does not use the conventional mercuric-bromide paper. Instead, a detector tube is filled with a granular media coated with a secondary colour reagent that reacts with arsenic and mercuric bromide to produce a pink colour. Following completion of the test, arsenic concentration (10-110 µg/L) is read directly by measuring the extent of pink colour penetration in the detector tube. Specifications for the kit are available from the Rural Water Supply Network (RWSN) at: www.rwsn.ch/documentation/skatdocumentation.2005-11-18.2902656953/file
- UNICEF also supported the development of locally manufactured arsenic test kits in China, Thailand and Vietnam, and the former two are still in use. The Thai kit, developed and marketed by Mahidol University (www.mahidol.ac.th), has a detection range of 10-110 µg/L and is used both in Thailand and in other countries in the region.
- Wagtech International Ltd (www.wagtech.co.uk), produces the Digital Arsenator. Like the Merck photometer kit (above), it uses an optical photometer to digitally measure the colour change on mercuric bromide filter paper, however, it is much more portable. It detects arsenic within a reported range of 2-100 µg/L. The Arsenator is significantly more expensive than manual colour comparison kits, but is more accurate and precise. A recent UNICEF-commissioned study from India comparing the Arsenator with laboratory AAS-HG showed a very high correlation of 0.998 (Shriram Institute, 2006). Wagtech also produces a Visual Arsenic Detection Kit, which uses a visual reference colour chart instead of the optical photometer. It has a reported range of 10-500 µg/L.

* This list does not include all available kits, and it also does not constitute an endorsement of the companies or products that are listed.

All of these kits have incorporated design improvements such as forcing arsine gas through rather than around the reagent filter paper. Most kits, in addition, have replaced liquid hydrochloric acid with some solid acid, supplied in tablets or pre-measured sachets. Many of these kits have been extensively used in the field, and evaluated in independent reports. Earlier versions of the Acustrip test kits and the Arsenator were evaluated through the USEPA's Environmental Technology Verification project (www.epa.gov/etv), and generally met manufacturer's specifications. The Arsenator consistently performs well in evaluations (Milton, 1999), (Kinniburgh and Kosmus, 2002), (Swash, 2003), (Shriram Institute, 2006), and should be considered as an intermediate technology between visual field kits and more sophisticated laboratory methods.

Fluoride *F* *WHO GV 1.5 mg/L*

Like arsenic, fluoride is somewhat difficult to measure. Laboratories commonly use an ion-selective electrode, or a colorimetric procedure based on fluoride's reaction with zirconium or lanthanum. The zirconium method uses an organic chemical (SPADNS), which forms a red complex with zirconium. When fluoride is present in the sample, it binds to the zirconium ions, resulting in a loss of red colour that can be measured with a colorimeter. The lanthanum method relies on a similar reaction, except that as fluoride reacts with lanthanum ions, a blue colour is produced, which is then measured colorimetrically. See Chapter 6 of the WHO Fluoride in Drinking-water monograph for additional discussion on analytical methods (Fawell et al, 2006).

Major international companies (e.g., Hach, Merck, Chemetrics) produce fluoride field test kits that require a portable digital colorimeter. These can provide reliable, quantitative measurements of fluoride, but like the Arsenator are relatively expensive. However, unlike the Arsenator, portable digital colorimeters can be used to analyze a number of different chemicals, for which colorimetric methods are available. Currently there are no commercially available field kits that allow visual quantification with colour comparator charts or disks.

A new procedure for field analysis was proposed by India's National Chemical Laboratory in conjunction with a joint project by UNICEF and the Rajiv Gandhi National Drinking Water Mission. The procedure is essentially a modification of the proposed field kit for nitrate (see below). It is a novel method for measurement of fluoride and should be carefully evaluated before wide application in the field. If the new test kit proves to be reliable, it will represent a substantial advance, as it does not require the use of an electronic colorimeter.

It might be possible to use an ion-selective electrode for fluoride measurement in the field, but most electrodes require a meter, which is not designed for battery operation or field use.

Nitrate and nitrite NO_3^- *and* NO_2^- *WHO GVs* 50 and 3 mg/L (11.3 and 0.9 mg/L as nitrogen)

Field measurement of nitrate is difficult because of the relatively complex procedures required, the possibility of interference from other dissolved ions, and the limited linear range (APHA/AWWA/WEF, 1998). Nitrate can be measured directly by absorption of ultraviolet light at 220 nm, but this is recommended for screening purposes only, and is subject to interference from dissolved organic matter.

Most field (and laboratory) methods are based on the reduction of nitrate (NO_3^-) to nitrite (NO_2^-) in the presence of cadmium. Nitrite then reacts with a colour reagent to form a reddish purple colour, which can be measured visually or with a colorimeter. This method is subject to interference from nitrite, but this is not a major disadvantage since the WHO GV for nitrite is lower than that for nitrate. Kits are easily modified to measure nitrite alone by elimination of the cadmium reagent.

Commercially available nitrate/nitrite test kits*

Chemetrics (www.chemetrics.com) produces a number of different kits, which use vacuum ampoules that are quantified either in a colorimeter or by visual comparison with liquid colour standards.

Hach Company (www.hach.com) produces a variety of kits to measure nitrate and nitrite, listed in order of increasing complexity, accuracy and cost:

- test strips that are simply dipped in water and compared to reference colour charts
- kits that involve addition of powdered reagents to the sample to produce a colour change, which is measured against a reference colour chart (Cube kits) or a colour disc
- kits that use powdered reagents or vacuum ampoules and quantify results using a pocket colorimeter
- a probe that directly measures nitrate measurement using absorption of ultraviolet light.
- portable water quality laboratories

Merck (www.merck-chemicals.com), like Hach, offers a range of kits:

- Merckoquant test strips, for simultaneous measurement of nitrate and nitrite
- Aquamerck kits, which require addition of reagents to samples and comparison to a reference colour chart. The Microquant kit is a similar design with a slightly lower detection limit.
- Reflectoquant kits use an electronic device to measure colour change on a paper strip, allowing greater sensitivity than the Merckoquant strips
- Spectroquant kits use a portable colorimeter to measure colour change in a reaction cell

The joint project between UNICEF and the Rajiv Gandhi National Drinking Water Mission has developed specifications for a field kit based on the cadmium reduction method. Samples are compared against a reference colour chart. Specifications are available from the Rural Water Supply Network (RWSN) at: www.rwsn.ch/documentation/skatdocumentation.2005-11-18.5970441980/file

* This list does not constitute an endorsement of the companies or products.

Nitrate, like fluoride, can also be measured with an ion-selective electrode, but these have not often been adapted for field use.

Other kits

Some chemical parameters (pH, residual chlorine, dissolved oxygen, alkalinity) should be measured in the field because they can change significantly during sample collection and storage. Field kits are available for these parameters, as well as for many metals and many other inorganic compounds (e.g., chloride, hardness, phosphate, sulfate), ranging in sophistication from simple semi-quantitative test strips to portable colorimeters. The choice of a method will be determined primarily by the required accuracy and detection limit, though simplicity of operation, susceptibility and cost are also important considerations.

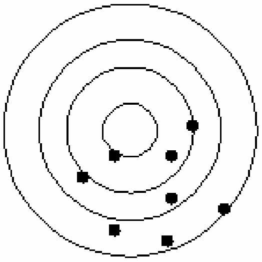
3.3 Quality assurance

Water quality data, whether collected in the field using kits or in a sophisticated laboratory, must be subject to quality assurance procedures to ensure accuracy and reliability. Approximate or incorrect results can be worse than no result at all: false positive results could lead to the unnecessary closure of a safe water system, while false negative results could lead to continued use of an unsafe water source. If the public becomes aware that UNICEF-sponsored water analyses are of poor quality, confidence could be lost in the broader water and sanitation programme. For these reasons, quality assurance is critical when testing for drinking-water quality.

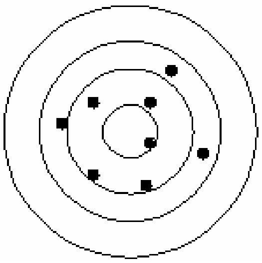
Quality assurance (QA) is a broad term referring to a management programme that specifies the measures required to produce defensible data of known precision and accuracy (APHA/AWWA/WEF, 1998). **Quality control (QC)** measures are specific technical steps that are taken in the laboratory to allow a quantitative assessment of the parameter being measured, along with the precision and accuracy of the measurement. Quality control measures are one important component of a quality assurance plan.

Precision and accuracy

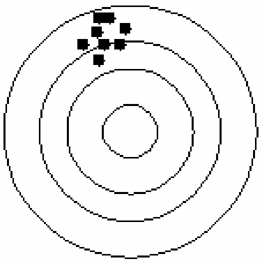
In all experimental measurements, there is a degree of uncertainty or error. When reporting data, the degree of uncertainty can be measured by considering the *precision* and *accuracy* of the analysis. The precision simply means the reproducibility of the analysis: if the same sample is analyzed multiple times, how much will the results vary? Accuracy, on the other hand, refers to how close the measurement is to the true value.



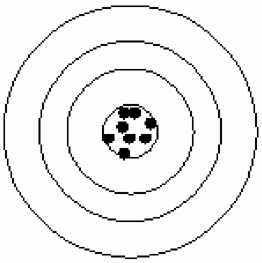
Not precise, not accurate



Accurate, not precise



Precise, not accurate



Accurate and precise

Analytical precision can be assessed by making repeat measurements and calculating the ratio of the standard deviation to the average. This is called the coefficient of variation, and as a rule of thumb should be less than 10% for laboratory measurements. Precision will depend primarily upon the instrument and method, but also on the operator and quality control procedures.

Quality assurance programs involve planning, supervision, and systematic review of data collected and their use in decision-making. Examples of QA components might include the following (APHA/AWWA/WEF, 1998):

- Establishment of a written quality assurance plan, identifying QA/QC activities and personnel responsible for ensuring policies are followed
- Policies for analyst background and training requirements
- Policies for purchasing, handling and storage of reagents
- Policies for sample collection, preservation and handling
- Procedures for measurement of method detection levels and data precision and accuracy
- Procedures for documentation of analytical results, including a system for management and archiving of records and preparation of summary reports on a regular basis

Examples of QC activities are:

- Consistently following standard procedures for sample collection, handling and transport
- Proper cleaning and use of glassware
- Identifying detection limits for analytical methods and reporting results below the detection limit as “none detected” or “below detection limit”, rather than “0”.
- Use of standard operating procedures for instruments, which describe in detail all routine laboratory operations (e.g., preparation of standards, instrument calibration, analytical methods)
- Analysis of QC samples such as blanks, known standards and field samples spiked with known standards at regular, established intervals. As a rule of thumb, at least one QC sample should be analyzed for every ten samples
- Periodic replicate analyses of samples
- Periodic external validation of results by sending samples to reference laboratories

UNICEF Project Officers are not expected to be experts in QA/QC procedures, but should be familiar with their basic components. When contracting laboratories for water analysis, it is recommended to request a copy of the laboratory's QA plan and QC procedures for the specific analyses being made. If laboratories do not have such policies documented, the data that they generate should not be considered reliable. An informal assessment of a laboratory's precision and accuracy can be made by sending QC samples such as blanks, known standards or replicate samples to the laboratory.

Most QA/QC resources are designed for a laboratory setting, but quality assurance is even more important for field test kits. Field kits are often less precise and accurate than laboratory methods; conditions in the field are more variable and challenging; and operators may have less technical training and experience than laboratory technicians. Quality assurance begins with field kit design and procurement of materials. In too many cases, field kit prototypes have been developed which performed well, but when the manufacturer began producing large numbers of kits, lack of quality assurance led to use of inferior reagents and resulted in substandard products. Quality problems can be avoided to a large extent by purchasing kits from large international companies (e.g., Hach, Merck), which have excellent QA programmes. However, domestic production of field test kits has a number of advantages, including simpler procurement procedures and costs that are potentially much lower.

Given a high-quality field kit, critical components of a QA plan include the proper training and supervision of kit operators, well-defined systems for data collection and analysis and the regular use of QC samples. Finally, it is critical to check for false positive and false negative results by confirming a proportion of field test kit results using laboratory methods.

Additional resources for quality management in laboratories

APHA/AWWA/WEF (1998). Standard methods for the examination of water and wastewater. Washington, D.C.: American Public Health Association, American Water Works Association, Water Environment Federation. www.standardmethods.org

Martin, B. (2002). An Introduction to Standards and Quality Control for the Laboratory (lit 2426). Loveland, CO: Hach Company. http://www.hach.com/hc/static.template/templateName=HcLearningLibrary.HcLearningLibraryLabPractice.htm

Quevauviller, P. (2002). Quality Assurance for Water Analysis. New York: Wiley.

USEPA (1979). Handbook for Analytical Quality Control in Water and Wastewater Laboratories. EPA/600/4-79-019. Cincinnati, OH: USEPA. www.epa.gov/nscep/

USEPA (1996). ICR Microbial Laboratory Manual. EPA/600/R-95/178. Washington, D.C.: USEPA. www.epa.gov/nerlcwww/icrmicro.pdf

Standards

ANSI/ASQC E4-1994: Specifications and Guidelines for Quality Systems for Environmental Data Collection and Technology Programs.

ISO/IEC 17025:1999: General Requirements for the Competence of Testing and Calibration Laboratories.

3.4 Key resources

APHA/AWWA/WEF (1998). Standard methods for the examination of water and wastewater. Washington, D.C.: American Public Health Association, American Water Works Association, Water Environment Federation. www.standardmethods.org

Davison, A., G. Howard et al (2005). Water Safety Plans: Managing drinking-water quality from catchment to consumer. Geneva: WHO.
www.who.int/water_sanitation_health/dwq/wsp0506/en/index.html

WHO (1997b). Guidelines for Drinking-Water Quality: Volume 3, Surveillance and control of community supplies. Geneva: WHO.

WHO (2006). Guidelines for Drinking-Water Quality. Third edition. Incorporating first addendum. Geneva: WHO.
Especially Chapters 7 (Microbial aspects) and 8 (Chemical aspects).
www.who.int/water_sanitation_health/dwq/gdwq3/en/

Chapter 4
Preventing Contamination

Preventing contamination of water supplies through the protection of water resources is the first step in any programme to provide safe water to consumers. Removing contaminants from water supplies to make them safe for domestic use is usually a much more expensive and complex process than preventing contamination in the first place.

Contamination prevention is a two-pronged process: reducing the amount of pollution entering the environment as a whole and erecting barriers to prevent any contamination that is present in the environment from reaching water supplies. Water should be protected at all stages in the supply chain: at the watershed and micro-watershed level, at system and point sources, during transportation and while being stored in the home.

UNICEF and the protection of freshwater resources

The 2006 UNICEF WASH Strategy Paper acknowledges the importance of protecting freshwater resources and outlines UNICEF responsibilities in this area. Below is an extract:

"*Though UNICEF involvement will vary depending on factors such as water scarcity and pollution problems, all UNICEF WASH programmes in every priority country should include an element of water protection and conservation. Specific support will focus on community management of local water resources, including rainwater harvesting (for use by households and schools, and groundwater recharge), micro-watershed management and operational research...*

UNICEF will ensure that supported approaches in improved management of water resources equally benefit poor and disadvantaged communities and households, and that interventions do not in any way deteriorate the quality of the water environment. UNICEF will use its position as one of the leading agencies in the WASH sector to bring the needs of the sector to the table in water resource management forums, as well as to catalyze and facilitate the involvement of other WASH actors in such forums" (UNICEF, 2006).

This chapter covers all aspects of water protection, starting with a description of contamination sources and pathways. It goes on to discuss the ways to prevent contamination, focusing mainly on community and household level interventions: how to protect small systems, point sources and water stored in the home. Although chemical contamination is discussed here (and elsewhere in this handbook), the chapter emphasizes prevention of faecal contamination of water supplies – in most cases the single most serious threat to water at all stages in the supply chain.

4.1 Sources and pathways of contamination

No natural water is absolutely pure – the chemical and physical characteristics of water are constantly changing through interaction with the environment. These changes can be positive: water is purified as its percolates down to aquifers and some adsorbed minerals can improve the taste and perceived value of water. Sometimes the changes can result in water that remains safe, but is unacceptable to consumers for aesthetic reasons (taste, smell or colour). And in some cases water can become unsafe for human consumption through contamination by naturally occurring chemicals (such as arsenic) or through pollution from human activities (such as pesticides).

As discussed in Chapter 2, there are two categories of contamination, microbiological and chemical. While the chemical contamination of water supplies can cause very serious problems, microbiological contamination is the largest public health threat, especially in developing countries and in poor communities. And the most serious water-borne diseases (such as dysentery and cholera) are caused by the ingestion of faeces, both human and animal.

4.1.1 Sources and pathways of chemical contamination

There are two sources of chemical contamination: naturally occurring chemicals and anthropogenic (caused by human activity) pollutants.

As discussed in 2.1.1 there are nine naturally occurring chemical compounds that pose a threat to human health, the most serious being arsenic and fluoride. Other natural chemicals affect the aesthetic quality of water and cause health problems indirectly by forcing people to use alternative sources that may be less safe. Iron is the most common such contaminant. Groundwater sources are typically the most affected by natural chemical contamination although there are cases of seriously contaminated surface water as well. In these cases, the chemical contaminant is present in the rocks and soils of the aquifer and is absorbed by the groundwater through a variety of chemical processes.

Natural chemical contaminants often affect large areas and multiple water sources, although there may be significant variation in contamination levels from source to source. Arsenic contamination levels, for example, are highly variable due to the complexity of the affected aquifers and the chemical processes involved. The level of contamination may also be influenced by the depth of the water source and whether or not it is capped.

In general, natural contamination cannot be prevented. If an aquifer is affected, the only remedial measure is to tap another, unaffected aquifer (e.g., a deeper aquifer), use another source such as surface water or use filters or other treatment measures to remove the contaminant from the pumped water. In addition, there are techniques that can improve the water quality *in situ,* in the aquifer itself. This involves reducing the contamination concentration levels through dilution by injecting uncontaminated water into the aquifer, or by inducing a chemical state in the aquifer that minimizes the adsorption of the contaminant in the water. These techniques are in general not fully developed, and used on a limited basis.

Pollutants are harmful chemicals released into the environment from agricultural activities, industrial processes and household wastes (see 2.3.2 and 2.3.3). There are two types of pollution: point source (such as effluents from factories) and non-point source, including run-off from fields and emissions of chemicals into the atmosphere. All types of water sources can be affected by pollution. Groundwater is contaminated though seepage from non-point source pollutants and from point sources such as leaking chemical storage tanks. Surface water is often contaminated through the release of industrial and domestic effluents directly into lakes and rivers, and from pesticide run-off from fields. Even harvested rainwater is sometimes at risk: rain can absorb and retain contaminates from air pollution, especially near certain types of industries. Pollution, especially point source pollution, can be prevented, as it is easier to identify and isolate.

4.1.2 Pathways for faecal contamination of water sources

Faeces are the most serious water contaminant affecting people’s health and the interruption of the fecal-oral cycle is the key objective of most water and sanitation programmes in developing countries. Both animal and human faeces are health threats; however human faeces are generally the most dangerous (see Table 2.4). As discussed in 2.2, there are other sources of microbiological contamination besides faeces, but because faeces are by far the most common and the most dangerous, this section focuses on faecal contamination pathways.

When water sources are contaminated by human and animal faeces, water-borne diseases can be transmitted: the many pathogens that can be present in faeces are ingested by humans through drinking and cooking water (and water is only one of the transmission pathways – see 4.2 on sanitation and hygiene below).

Table 4.1 Sources and pathways for the faecal contamination of water sources

Point Sources: tubewells, dug wells and springs (see also 4.3 for more details on groundwater pathways and sanitary sealing)

- Latrines close to the source*
- Latrines uphill of the source*
- Other potential sources of faecal contamination close to or uphill from the source (e.g., open defecation, septic tanks, corrals, intensive grazing, abandoned dug wells, garbage pits)
- Standing water at or near the source due to poor drainage*
- Poorly constructed or maintained headworks (concrete apron and drain, headwall, pump seal) and below-ground sanitary sealing
- Irregular maintenance and cleaning of apron and source surrounding
- Bucket used in windlass system allowed to touch the ground, buckets from homes dipped in well or in spring reservoir

- Animals with access to source (fencing missing or broken)
- Erosion around protected spring, dug well or tubewell

* The minimum safe distance (MSD) between contamination sources and water sources varies, depending on local hydrogeology and other factors. In some countries rule-of-thumb figures (e.g., 10 m minimum distance between a dug well and a latrine) are used as a guide but, as detailed in 4.3.3, there are cases where these distances should be more carefully estimated to better protect water sources.

Rainwater Harvesting Tanks

- Bird and small animal faeces from rooftops and gutters
- Cracked tanks, poorly sealed access holes allow entry of animal and insect vectors
- Inadequate or poorly maintained filters and/or 'first flush' system

Piped Systems

- Groundwater source inadequately protected from contamination (see above)
- Surface water intake inadequately protected from local sources of contamination (e.g., no fencing, broken fencing, poorly constructed or damaged intake structures, inadequate screening)
- Treatment plant non-operational, operates intermittently (e.g., broken equipment, no treatment chemicals) or inadequately maintained and supervised (e.g., process control tests not carried out regularly, record keeping inadequate, poorly trained operators, incorrect storage of treatment chemicals)
- Cracked storage tanks and reservoirs
- Tank access covers or vents improperly sealed
- Infrequent cleaning of storage tanks and reservoirs
- Broken or leaking pipes, exposed pipes due to erosion or poor construction
- Service interruptions causing pressure loss and thus potentially allowing the entry of contaminated surface and groundwater into system via pipes and fittings
- Standing water around tapstands (standpipes) due to poor drainage
- Open defecation near tapstands

As is the case for all water contaminants, preventing contamination and interrupting the transmission cycle is more efficient than purifying the water at the source or in the home.

4.1.3 Pathways for faecal contamination during transport and storage

Protected water sources do not ensure that water used for drinking and cooking in the home is safe. Household water storage – a practice common in developing countries – contributes to drinking-water contamination. Water stored in homes is often faecally contaminated at levels far above the contamination level at the source. Studies show that water stored in homes routinely have faecal coliform levels hundreds of times higher than is present in the source – some studies have documented thousand-fold increases in faecal coliforms.

A review of literature worldwide between 1980 and 2001 (Sobsey, 2002) cited 20 studies from Africa, Asia and the Americas that showed a deterioration of water quality between the source and stored water and 5 studies that documented increased water-related disease morbidity among family members in households. In all cases the problem was linked to inadequately stored water.

There are three reasons water quality deteriorates during the storage and transport of water:

- poor hygiene knowledge prevents people from taking basic steps to minimize contamination (see 4.2)
- inadequate household latrines, hand-washing facilities and poor community environmental sanitation results in more faeces in and around households (see 4.2)
- commonly used transport and storage containers are easily contaminated (see 4.4)

Table 4.2 Pathways for the faecal contamination of water during collection, transport and storage

Water collection and transport

- use of wide-mouth containers that allow hands to come into contact with water
- use of leaves or other material in buckets to prevent water spillage during transport
- containers used not clean
- containers ‘washed’ with contaminated hands or cloths
- contaminated cups, bowls, ladles or buckets used to draw water
- dirty source surroundings and pump/tap spouts

Water Storage

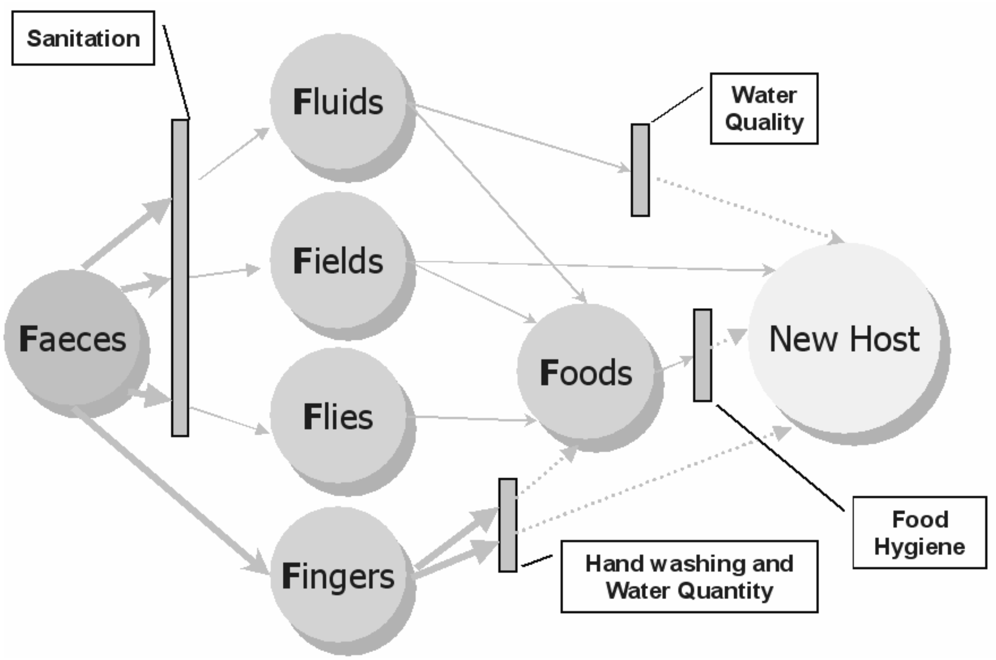
- use of wide-mouth containers for storage that allow hands, cups/ladles and insect and animal vectors to come into contact with water
- uncovered containers
- no spigot or spout on containers – water drawn with cups or ladles
- containers stored on floor, allowing more easy access to water by children and animals
- infrequent cleaning of storage containers

4.2 Sanitation and hygiene promotion

Adequate sanitation and good hygiene knowledge and practice are more important for protecting water supplies than any other factor. Removing faeces safely from the environment eliminates the main source of water pollution. The proper use and maintenance of water facilities and the hygienic transport and storage of water protects the water supply chain from faecal contamination. But the importance of sanitation and hygiene goes far beyond protecting water quality because water is not the only transmission route in the faecal oral cycle (see Figure 4.1).

Faeces can be transmitted from one person to another through direct contact, by exposed faeces in fields and streets, through contaminated food and by insect and animal vectors. Sanitation and hygiene can act as transmission barriers on all of these pathways.

Figure 4.1 The F-diagram: faecal contamination paths and barriers



Source: modified from Wagner and Lanois, 1958

Improving the quality of water in sources, systems and homes can result in significant health benefits. However, one of the most important lessons learned from water supply programmes worldwide is that maximum health benefits are achieved if water interventions are accompanied by sanitation and hygiene promotion.

This handbook provides a short introduction to the subjects of sanitation and hygiene. See the list of resources at the end of this chapter for further reference.

4.2.1 Sanitation

The importance of sanitation

Sanitation is the management and disposal of solid wastes and waste water in and around communities and households. The most dangerous waste product – and thus the focus of sanitation programmes – is human faeces.

Faeces: the most dangerous contaminant

One gram of faeces can contain:
10,000,000 viruses
1,000,000 bacteria
1,000 parasite cysts
100 parasite eggs

The safe disposal of human faeces is essential for the health of families and the community as a whole. But improved health is not the only benefit of sanitation. Privacy, convenience, reduced smells and flies and improved security for women (who, without latrines, often have to wait until after dark to defecate) are very important benefits in communities. Improved sanitation can be an important factor for improved education: lack of sanitary facilities can prevent girls from attending schools, and the helminth infections caused by poor sanitation can impair learning retention.

Sanitation promotion

Despite the benefits, sanitation coverage lags far behind water supply coverage. Forty percent of the world's population – 2.4 billion people – still do not have access to basic sanitation facilities. The most important reason for this is that in many circumstances there is far less demand for sanitation than there is for water and other services, both among communities and decision makers. Successful and sustainable sanitation programmes begin with demand creation – at both the political and household level.

The slow pace of improving sanitation coverage demonstrates that so far promotion efforts have been insufficient. New sanitation promotion initiatives rely on a variety of techniques to accelerate coverage. These include improved research and baseline surveys to better assess awareness levels and motivation of target audiences, using a wide variety of communication methods and media, and using social marketing approaches to better package and promote sanitation to communities.

Community-led total sanitation

Community-led total sanitation (CLTS) is an approach to sanitation promotion that encourages community self-analysis of existing defecation patterns and threats, and promotes local solutions to reduce and ultimately eliminate the practice of open defecation. CLTS initiatives do not stress latrine construction per se, and avoid the use of hardware subsidies. Instead, mobilisation efforts focus on helping communities and individuals understand the health risks of open defecation and use disgust and shame as "triggers" to promote action, which ultimately lead to the construction and exclusive use of locally-built low-cost household latrines. The ultimate goal of CLTS are communities that achieve and maintain "open defecation-free" status.

The CLTS approach has been especially successful in Bangladesh. Largely as a result of the rapid spread of the CLTS approach in the country, Bangladesh is now set to exceed its MDG target for sanitation. CLTS has also been introduced with successful results in Cambodia, Ethiopia, Indonesia and other countries.

Design and technologies

There are two categories of sanitation technologies: on-site and off-site. On-site technologies, which include latrines and septic tanks, dispose of faeces at or near households. Off-site technologies like water-borne sewage systems transport faeces away. While off-site systems generally provide better protection to communities and households by removing faeces from the local environment, the opposite can be true when systems are poorly operated and maintained. And of course, removing faeces from a community can sometimes mean transferring the problem downstream to the next community.

On-site solutions are chosen primarily because they are more economical than off-site systems. The most commonly used on-site systems are simple pit latrines, ventilated pit latrines, pour-flush latrines and septic tanks. As shown in Table 4.3, each has its advantages and disadvantages, and the reasons a household chooses one technology over another are often complex.

Table 4.3 Advantages and disadvantages of common on-site sanitation technologies

Technology	Advantages	Disadvantages
Simple pit latrine	o lowest cost o usually can be constructed by family members o does not require water	o does not reduce flies o smells o can collapse if slab is made of traditional materials
Ventilated pit latrine	o low cost o minimizes flies o minimizes smells o does not require water	o interior of latrine must be dark to function correctly, which can be a detriment to use, especially among children o requires some materials (screening and vent pipe) which may not available in all communities o requires some skilled labour to construct
Pour-flush latrine	o eliminates flies o eliminates smells o pit can be offset from pan and trap, allowing placement of toilet in a house	o higher cost o requires a regular supply of small volumes of water o requires some skilled labour to construct

Technology	Advantages	Disadvantages
	o contents of pit not visible o can be connected to a sewer if it becomes available	o cannot be used in areas where solid anal cleaning materials (e.g., maize husks) are used o requires permeable soil o requires periodic sludging
Septic tanks	o as above o provides the equivalent convenience of a flush toilet connected to a sewer	o highest cost o requires a regular supply of high volumes of water o skilled labour required o requires permeable soil o requires periodic sludging

Although many government and agency-supported sanitation programmes continue to subsidize the cost of family latrines at least for the poor, household latrines are usually paid for primarily by families themselves. Sanitation promotion programmes are generally more successful when families have a choice of technologies to buy. Sanitation programmes facilitate the development and production of a range of technologies (sometimes called “sanitation ladders”), allowing consumers to choose an option depending on their preferences and ability to pay and providing an avenue to upgrade service in the future.

Latrine designs vary widely in response to cultural, geographic and socio-economic factors. Designs that work well in some countries do not necessarily work well elsewhere. In some countries standard designs are promoted nationwide while in others designs vary from region to region. In all cases, the two most important design criteria are safety and usability: latrines should safely remove faeces from the community and household environments and they should be attractive to all users, especially women and children.

School toilets and latrines are in a special category. Sanitation facilities in schools not only contribute to increased enrolment and improved learning, but together with hygiene promotion they encourage children to be sanitation advocates in their communities. It is therefore critically important that the latrines’ design encourage their use. Privacy is a key consideration, especially for girls: designs must include secure doors and other privacy features. Studies show that separate facilities for girls increase their usage. Children’s size is another factor that should be taken into account in designs. The most successful latrine and toilet designs are those in which children themselves have participated in the design process.

Ecological sanitation

A step beyond the safe removal of faeces from households and communities is using faeces (and urine) as a resource. Ecological sanitation promotes practices and technologies that take advantage of the nutrients in human excreta and urine to improve agricultural production (or “closing-the-loop”) and to protect local environments and freshwater resources. Although not a new concept (human faeces have been used as fertilizer for thousands of years), improved promotion, technologies and methods have sparked increasing interest in ecological sanitation in some countries.

Ecological sanitation involves the composting and/or desiccation of faeces which, if functioning correctly, can eliminate pathogens from faeces much faster than a pit latrine. The technique therefore has the potential of being safer than more traditional on-site methods. On the other hand, ecological sanitation does mean that people must to a certain degree handle human faeces. If done incorrectly, this can pose serious health risks. Other disadvantages of ecological sanitation include, in some cases, higher technology costs and the difficulties in overcoming cultural taboos on the use of faeces to fertilize food crops.

Sanitation and groundwater quality

Properly designed, constructed and maintained sanitation facilities protect water sources from faecal contamination. But the opposite can also be true: some sanitation systems are a major source of water pollution.

Off-site systems become sources of pollution in a variety of situations. Many urban sewer systems release untreated sewage directly into the environment. And even sewage treatment plants themselves are a problem if they do not function regularly due to electricity shortages or other operational problems, or they are too small to deal with increased flows.

Sewage pollution is a worldwide problem

India: The city of New Delhi produces 3 billion litres a day of waste water, of which only about half is treated, and the rest is released untreated into the Yamuna River.
Mozambique: During months-long power cuts in the 1980s and 1990s the city of Beira’s sewage pumping network was non-operational. Large volumes of sewage leaked from clogged pipes into groundwater, contaminating dug wells and increasing cholera and diarrhoea rates.
USA: In 2003, health authorities closed beaches in California on 59 separate occasions (for a cumulative total of over 700 days), due to untreated sewage releases or spills.

On-site sanitation can also be a source of pollution. In general, properly sited and constructed latrines do not pose a threat to groundwater. However there are cases, especially in densely populated areas, where on-site sanitation facilities have been implicated in a deterioration in groundwater quality. While the use of minimum safe distances (MSD) between latrines and water sources can reduce the chances of contamination, more rigorous methods for well and latrine siting are often necessary, as described in 4.3.3.

Although there is a potential for contamination to occur with all types of sanitation systems, the health and other benefits of sanitation far outweigh the disadvantages.

4.2.2 Hygiene

The importance of hygiene

Improving access to safe water and sanitation facilities leads to improved health in families and communities. However, when people are also motivated to practice good hygiene practices, health benefits are significantly increased. Hand-washing with soap can result in major health improvements: one review of studies worldwide documented a 45- percent reduction in diarrhoeal morbidity from improved hand-washing (Curtis and Cairncross, 2003) and another documented over 50 percent reductions in the incidence of both diarrhoea and pneumonia when children washed their hands with soap (Luby *et al*, 2005). Good hygiene practices are the most effective barriers in the faecal-oral cycle.

Hygiene is especially important for the survival and development of young children. Good hygiene practices among mothers and other caregivers (especially hand-washing with soap after defecating and before preparing food, and the safe disposal of children's faeces) prevent diarrhoea..

Disposal of children's faeces

Children's faeces are often not disposed of safely even though they are more likely to contain diarrhoeal pathogens than adult faeces. Children often do not use latrines, because there are none, they are not allowed to use them, or they are dark, smelly or otherwise unattractive.

Caregivers in some countries do not dispose of toddlers' and babies' excreta because traditionally these faeces have been regarded as harmless. The UNICEF Multiple Indicator Cluster Surveys (MICS) carried out in 2000 in 17 African countries found that in more than half of households surveyed in rural areas the faeces of children under three years old were not disposed of safely.

Promoting behavioural change

Education and communication are important components of a hygiene promotion programme. All people have a right to know about the relationship between water, sanitation, hygiene and the health of themselves and their families. However, education alone does not necessarily result in improved practices. Knowing about the causes of disease may help, but new hygiene practices may be too unfamiliar, too difficult, or take too much time, especially for poor people. Promoting behavioural change is a gradual process that involves working closely with communities, studying existing beliefs, defining motivation strategies, designing appropriate communication tools and finally encouraging practical steps towards positive practices. Communities should be fully engaged in the process at all stages using participatory processes, and special attention should be given to building on local knowledge and promoting existing positive traditional practices.

Behavioural change is necessary not only at the community level, but among decision makers as well. All stakeholders -- from politicians and government officials to field workers and people themselves – must be encouraged to recognize the importance of hygiene.

Facts for Life: What every family and community has a right to know about hygiene

1. All faeces should be disposed of safely. Using a toilet or latrine is the best way.
2. All family members, including children, need to wash their hands thoroughly with soap and water or ash and water after contact with faeces, before touching food and before feeding children.
3. Washing the face with soap and water every day helps to prevent eye infections. In some parts of the world, eye infections can lead to trachoma, which can cause blindness.
4. Only use water that is from a safe source or is purified. Water containers need to be kept covered to keep the water clean.
5. Raw or leftover food can be dangerous. Raw food should be washed or cooked. Cooked food should be eaten without delay or thoroughly reheated.
6. Food, utensils and food preparation surfaces should be kept clean. Food should be stored in covered containers.
7. Safe disposal of all household refuse helps prevent illness.

Source: Facts for Life (2002)

Hygiene and water

Without water there is no hygiene. Research shows that the less readily available water is, the less likely that good hygiene will be practised in households. In rural areas and some poor urban areas, the most important factor determining the availability of water in households is the distance that must be travelled to the water source. As shown in Table 4.4, hygiene can only be assured when water is readily available nearby.

Table 4.4 Service level descriptors of water in relation to hygiene

Service level description	Distance/time measure	Likely quantities collected	Level of health concern
No access	More than 1000m or 30 minutes total collection time.	Very low (often less than 5 l/c/d).	Very high as hygiene not assured and consumption needs may be at risk. Quality difficult to assure; emphasis on effective use and water handling hygiene.
Basic access	Between 100 and 1000m (5 to 30 minutes total collection time).	Low. Average is unlikely to exceed 20 l/c/d; laundry and/or bathing may occur at water source with additional volumes of water.	Medium. Not all requirements may be met. Quality difficult to assure.
Intermediate access	On-plot, (e.g. single tap in house or yard).	Medium, likely to be around 50 l/c/d, higher volumes unlikely as energy/time requirements still significant.	Low. Most basic hygiene and consumption needs met. Bathing and laundry possible on-site, which may increase frequency of laundering. Issues of effective use still important. Quality more readily assured.
Optimal access	Water is piped into the home through multiple taps.	Varies significantly but likely above 100 l/c/d and may be up to 300l/c/d.	Very low. All uses can be met, quality readily assured.

Source: Howard and Bartram (2003)

The importance of well-designed and located hand-washing facilities

Although knowledge and motivation plus access to water are the most important factors influencing hand-washing practices, the existence, type, location and cost of hand-washing facilities are also important. Designing hygienic low-cost hand-washing facilities is especially difficult in poor communities where water in the home is scarce because it is expensive (such as in some slum areas) or must be fetched by hand from distant sources.

The hand-washing facilities must be hygienic (usually by providing a stream of water for hand-washing), use very little water, be easily made at low or no cost and be easily installed at or near latrines and in homes. Several designs including “tippy-taps”, modified soft-drink bottles, and hollowed out gourds have been used to meet this challenge.

Hand-washing facilities must also be accessible to children. Taps and other facilities must be low enough for children to reach, easily operable, clean, attractive and very close to latrines and toilets. In schools, facilities must be robust and provide enough water to accommodate many users in a short period of time.

Good hygiene practices prevent the contamination of water sources and the contamination of water during transport and storage. Water sources, especially open point sources, are easily contaminated with faeces from hands, buckets and other vectors. Knowledge about the dangers of polluting water is the first step towards eliminating contamination sources and blocking contamination pathways. Community managed maintenance of water sources and systems is effective and sustainable only if based on good hygiene knowledge and practices. As discussed in detail in 4.4, hygiene is especially important in the transport and storage of water.

4.3 Water source and system protection

4.3.1 Watershed management

The protection of water sources begins with the management of the watershed itself, including the prevention of industrial and agricultural pollution that can threaten water safety.

Water resource management at the watershed level involves the development and implementation of a set of national policy and legislative measures to ensure that freshwater resources are protected from a variety of threats, including not just threats to quality but to depletion through over-extraction. Progressive policies and laws – based on the premise that domestic water comes first – protect domestic water supplies from water competitors, such as large-scale cash crop irrigation, and from polluters. The process for developing and implementing such legal and policy instruments is complex. It involves:

- detailed hydrology assessments
- consideration of all water uses (including not just economic uses but uses involving the maintenance of ecosystems)
- participation of and negotiations among key national and international stakeholders on water use priorities
- the definition of quality standards for different uses
- the definition of acceptable pollution limits
- the creation of national institutions to implement plans and monitor implementation.

Few developing countries have comprehensive water resource management legislation and fewer have the means to enforce them. Advocacy and awareness-raising on water quality and the effects on communities (see Chapter Six) can be an important first step encouraging the initiation of the process.

Even in countries with laws protecting watersheds and domestic water sources, micro-watershed management by communities is an important facet of protecting water supplies. At this level sources of pollution are usually more easily identified and water uses more readily inventoried. But, as is the case with macro-watershed management, the prioritization of water uses is a complex process that must involve meaningful participation by all water stakeholders.

4.3.2 Water source choice and protection

Minimizing contamination of a water systems begins with the choice of the system itself, and especially the choice of the water source. Systems and sources are chosen for a variety of reasons, but the relative susceptibility to contamination is a primary factor.

In many countries, groundwater is the most common water source, especially in rural areas. Groundwater is chosen over surface water because it is often more widely available and less expensive to extract, and it is inherently safer from faecal contamination. Groundwater is not always safe, however. Population pressures and other factors can increase the possibility of faecal contamination and sources must be carefully chosen and protected, as discussed in detail in the next section. Groundwater sources are also vulnerable to chemical contamination (see 2.3). The wide-scale arsenic and fluoride contamination of tubewells – as well as other chemical contamination problems – has underlined the fact that groundwater is not the best option everywhere.

Surface water is widely used throughout the world as the source for domestic water systems. It is often the source for larger piped water systems because the large volumes of water required are not available from groundwater sources. In almost every case, surface water must be treated before reaching consumers since lakes and rivers are highly susceptible to faecal contamination. This treatment requirement increases the cost of surface water, making it a less common choice for small rural and peri-urban systems. Surface sources are best protected through management of the watershed itself, as discussed above. Local protective measures to prevent pollution of the source in the area immediately surrounding the intake is also a requirement for surface systems.

In theory, rainwater is the safest of all water sources. Although rainwater can become contaminated through the absorption of atmospheric pollutants, it is usually very pure as it hits the earth. The problem with rainwater is that the surfaces that are used to collect it, such as rooftops, are often not clean. And more seriously, the fact that rainwater must be stored for relatively long periods of time increases its susceptibility to contamination from a variety of sources. The challenges of safely collecting and storing rainwater are discussed in 4.4.

The systems used for conveying water to the consumer are also susceptible to contamination and must be protected. Although all systems, including point source systems (such as a handpump installed on a tubewell), are at risk of contamination, piped systems present the greatest risk simply because there are more points on the system where contamination can occur (see Table 4.1). A well-designed and constructed system will minimize the potential for contamination. More important is how the system is operated and maintained. Breakdowns, intermittent service, illegal connections, poorly trained operators, and the lack of a regular supply of water treatment chemicals can all result in contaminated water.

Family dug wells and tubewells

The private family dug wells and tubewells that are common in many parts of the world are usually outside of any national water quality regulatory and monitoring framework. The sources are often poorly constructed and are rarely well-sealed against contamination. Exacerbating the problem is the fact that many household compounds, because of lack of space and knowledge, have family latrines and garbage pits dug close to the dug well or tubewell.

There are three strategies to improve the quality of water in households with private sources: encouraging families to use safer community water sources for drinking and cooking purposes, promoting home water treatment and facilitating (sometimes with subsidies) improvements to better protect the private dug well or tubewell. All strategies have merit, depending on the local situation.

In the 1990s in Zimbabwe, government and NGO-sponsored programmes assisted in the construction of 45,000 improved family wells, each with aprons, well capping and a special windlass system. Extensive microbiological testing showed that these wells were a significant improvement over traditional family wells but still more contaminated on average than community wells with handpumps.

Proponents of family wells in Zimbabwe and elsewhere argue that people will continue to construct and use family wells because of their convenience, and helping to improve the wells is a valid use of public funds. The health and economic benefits of water close to the home are also cited.

Until household connections to public systems become common, private wells and tubewells will increase in number, even in areas where coverage in community systems is high. In some Indian states, for example, more than half the population use private tubewells even though public water supply coverage exceeds 90 percent. An increasing number of water and sanitation sector professionals acknowledge the importance of household sources and the need to work with families to improve their quality.

4.3.3 Interrupting faecal contamination pathways in groundwater-based systems

In rural and peri-urban regions of developing countries, groundwater-based systems for domestic water supply continue to be the most common. And the most serious threat to water quality in these systems is faecal contamination. It is thus important to focus in more depth on groundwater systems in this text.

Contamination pathways for groundwater systems were introduced in 4.1.2. To understand how pathways are interrupted, it is useful to categorize them into two types:

- natural or aquifer pathways: pathways that are naturally present in the rock in and overlying the aquifer, including cracks, fissures and the permeability of the material itself
- local or system pathways: pathways created by shortcomings in the design, construction and maintenance of groundwater sources.

Natural pathways

There are always natural pathways in the geological environment. Where water is drawn from groundwater and there are sources of contamination such as latrines, there is always a potential route for contamination to enter the aquifer. Most micro-organisms become harmless – or are reduced in numbers – through natural processes as they travel through water, soil and rocks. In general, the longer they spend in the environment, the more harmless they become.

Micro-organisms spend more time in the environment if the distance between the contamination source and the well or spring is large (both lateral distance and depth), if the permeability of the aquifer and the overlying material is low and if direct pathways (cracks, fissures) are not present or are long. Empirical evidence suggests that there is a significant risk of contamination of water sources if micro-organism travel time is less than 25 days (Lawrence et al., 2001).

It is not easy to calculate or even estimate micro-organism travel times, and it is rarely done. In many countries, groundwater source siting is carried out using a handful of rule-of-thumb figures that specify minimum lateral distances (minimum safe distances – MSDs) to sources of contamination and minimum depths to water tables. These figures are useful in the absence of other information, but do not reflect the range of pathway variation within countries. And even these inadequate figures are loosely applied, especially in rural water supply programmes.

Due to growing population densities and increasing use of latrines and other on-site sanitation facilities there is a concern in some countries that faecal pollution of groundwater is becoming a serious problem. Although in most cases it is likely that the benefits of improved sanitation far outweigh any potential risks to groundwater, the issue should be more comprehensively addressed than in the past. The old rule-of-thumb MSD figures for safe source siting are becoming obsolete.

The first step in going beyond these figures is recognizing the situations where they may not apply, where dangers are more serious and where more investigation is necessary. Table 4.5 describes such situations.

Table 4.5 Contamination of groundwater from on-site sanitation

The following are situations in which there is a significant risk of contamination of groundwater sources from on-site sanitation:

- population densities are high (greater than 10 people per hectare)
- septic tanks, aqua privies or high use pour-flush latrines are common
- high water tables (depth to water table is less than 5 metres)
- area is prone to flooding
- rock types (in aquifer or in overlying material) is primarily composed of medium to coarse particles (medium to coarse sands, gravels, sandstones) or is fractured/fissured
- latrines and water sources are constructed very close to one another (e.g., where households have their own latrines and dug wells or tubewells in small plots)

In cases where contamination is more likely, or in situations where major new water supply or sanitation programmes are planned, a more detailed investigation should be carried out (see box).

ARGOSS - Guidelines for assessing the risk to groundwater from on-site sanitation

In 2001 the British Geological Survey published the ARGOSS manual, which was the result of a comprehensive programme funded by DFID to develop a useable methodology to assess the risk of contamination of groundwater supplies from on-site sanitation. The guidelines are aimed at sector professionals responsible for planning and managing low-cost water and sanitation programmes in developing countries. They provide detailed step-by-step procedures for assessing the risk of microbiological contamination of groundwater under various scenarios and use methodologies that do not rely on detailed hydrogeological data. The manual also provides information and guidance on assessing the risk of nitrate contamination and of carrying out monitoring programmes.

The procedures presented in the manual, while simplified, are still too complex to apply in each and every situation. They are most useful in situations where new large-scale water programmes are being planned in areas with existing on-site sanitation, where new sanitation programmes are being planned in areas with existing groundwater supplies and when there is some reason to suspect that existing supplies are being contaminated (see Table 4.4).

The manual is available on-line at: www.bgs.ac.uk/hydrogeology/argoss/manual.html

In new water system construction projects, the characteristics of natural pathways in an area should be a primary determinant of the type of system chosen. Dug wells should not be chosen, for example, if water tables are very high or if the rock type is predominantly coarse sand. In practice, other criteria – especially cost considerations – become equally or more important in determining the choice of a system.

Local pathways

Minimizing contamination pathways associated with the water source itself (local pathways) is always important. It becomes even more important when there is a greater risk of contamination through natural pathways or when the local environment becomes more stressed with new sources of pollution and/or population pressures.

Groundwater sources are protected by sealing the sources against ingress of contaminated surface water, and by ensuring that the immediate surroundings are kept clean. Properly designed, constructed and maintained sources can be very well protected from contamination from the local environment. Even dug wells, the most vulnerable of sources because of their shallow depth, can be made very safe. Table 4.6 lists the sanitary sealing design features of tubewells, dug wells and protected springs that are necessary to prevent contamination.

Table 4.6 Sanitary sealing of groundwater sources

	Sanitary protective measures: below ground	**Sanitary protective measures: above ground**
Tubewells	o use of high quality well casing pipes and riser mains (only pipes designed for this purpose should be used) o if possible, annular space between casing pipe and borehole sealed with cement or clay from the surface down to the level of the filter screen (usually not possible when hand-drilling methods are used) o in all cases, the top 3 m of the annular space must be sealed with concrete o filter screen installed as deep as possible o non-return valve incorporated into pumping system to prevent pumped water returning to the aquifer	o concrete foundation for pump thick enough to prevent pump from coming loose (depending on pump design, usually about 40 to 50 cm) o tight seal between handpump and base/apron o circular concrete apron to prevent ingress of contaminated water from surface: at least 1.5 m in diameter with a smooth surface and sufficient slope (1:50) o concrete drain at least 3 m long to direct water away from apron o soak pit, extended drain or garden constructed or utilized at end of concrete drain o fresh cement and clean sand and gravel used for all concrete works using a strong mix (preferably 1:2:4)
Dug wells	o design incorporates a filter: either a 30 cm-thick sand/gravel pack at the bottom of the well and/or a porous concrete ring or plug	o well capped and sealed with a concrete slab o access hole with a raised lip and tightly fitting cover to prevent

	Sanitary protective measures: below ground	**Sanitary protective measures: above ground**
	o well as deep as possible o if possible, the entire well should be lined with concrete rings o in all cases, the top 3 m of the well must be lined with concrete rings or thick masonry and any joints sealed with concrete	water ingress o handpump installed on cap correctly mounted and sealed o in cases where a bucket system must be used: a single designated bucket affixed to the well should be used (a windlass system can help to minimize the frequency that both the rope/chain and the bucket touch the ground) o headwall of well 30 to 80 cm high depending on type of water drawing system is used (handpumps usually require lower headwalls) o apron, drain, and concrete quality standards as for tubewells above
Protected springs	o spring box or retaining wall completely sealed against surface water ingress o backfill (above gravel/sand filter media) of impervious clay	o appropriate groundcover (usually grass) planted over all excavated and backfilled areas to prevent erosion and water ingress o spring box access hole sealed as per dug wells above o pipe (sometimes with tap) installed provides enough flow to quickly fill buckets, minimizing possibility that people will fill buckets directly from spring box o splash pad and drain to minimize water ponding around spring

Sanitary sealing of groundwater sources should be regulated and enforced by the government agency responsible for water supply. Sanitary sealing standards should be included in contracts and a system for supervising implementing agencies should be set up. This system must include provisions for supervising contractors during construction (because most below-ground sanitary sealing measures cannot be confirmed after construction has finished) and inspecting the finished source.

As important as sanitary sealing is ensuring that the immediate source surroundings are kept clean and free of contaminants. This involves, in some cases, the construction of physical barriers (fences and gates) to prevent the entry of animals. More importantly, it involves the establishment of a community management system that ensures the surroundings are clean and the source headworks are maintained to eliminate local contamination pathways detailed in Table 4.1..

All water supply programmes should include provisions for the establishment of local maintenance systems. These can take many forms, from the use of local voluntary well caretakers to professional maintenance teams paid for by water tariffs. The most important factor is that the maintenance system is chosen and managed by the community itself. The water supply programme should facilitate this process through awareness-raising, education and, in some cases, direct support such as the provision of mobile teams for performing major maintenance and repairs.

4.4 Safe handling and household storage of water

Hundreds of millions of people do not have household water connections and must transport water from point sources or standpipes and store it in their homes. Protecting water from contamination during transport and storage is at least as important as protecting the source itself. There are a variety of pathways for faeces to enter stored water in the home, and stored water is often more contaminated than the source (see 4.1). Extending water quality protection from sources to point-of-use is an increasingly common strategy in water safety programmes worldwide.

As already noted, minimizing the amount of faeces in the household environment through sanitation interventions and raising awareness on safe water handling and personal hygiene are prerequisites for improving water quality in homes. However, the design of storage and transport receptacles is also an important factor in reducing faecal coliform levels in storage water and in the levels of household diarrhoea and other diseases. Studies show clear correlations between the type of container used and both faecal coliform levels and diarrhoea incidence in the home (Roberts et al, 2001; Sobsey, 2002).

Many types of vessels are used to store and transport water in developing countries, including traditional clay or metal containers, plastic and metal buckets, jerry cans, collapsible containers, beverage bottles and barrels. But to safely store water in homes containers should have narrow openings that can be sealed, should be made of an easily cleaned material and should have narrow spouts or taps to minimize contamination of water through hands, ladles or other vectors.

These safety criteria are not necessarily the most important from many users’ point of view. Usability and user acceptance criteria are sometimes contradictory to safety criteria. For example, in many countries people prefer wide openings to make cleaning easier and thick-walled earthenware containers (which are not sealable) to keep water cool. Cost and availability are also key issues. Safe water storage containers often cost more than the alternatives or are simply not available in local markets.

An important factor is that many poor families cannot afford separate containers for transporting and storing water and therefore water storage containers must also meet users’ criteria for portability – including size, shape and weight – and durability. As shown in Table 4.7, this will inevitably mean a compromise in design characteristics. Poor families also do not necessarily use containers exclusively for water storage and transport, which means that there may be even more compromises on the water safety criteria (an open bucket is a more useful receptacle for carrying a variety of material than is a plastic jerry can with a small opening).

Table 4.7 Criteria for home water storage containers

x – somewhat important xx – important xxx – very important	**Importance for water storage containers**	**Importance for water transport containers**
Criteria for minimizing contamination		
Made of easily cleaned material (plastics, most metals, ceramics, polished concrete)	xxx	xxx
Tap to draw water (must not leak or stick) or narrow spout from which to pour water	xxx	
Top opening large enough to pour water into but small enough to discourage the entry of hands, ladles and other faeces vectors (about 8 cm)*	xxx	xxx
Cap for top opening (preferably screw type)	xxx	xx
Stable with a flat bottom (so that container does not tip over allowing contaminants to enter opening)**	xxx	xxx
Usability / user acceptance criteria		
Durable	xxx	xxx
Impact resistant (some plastics are not)	x	xxx
Corrosion resistant (plastics, coated/treated metal)	xxx	xx
Portable: lightweight, less than 25-litre capacity, suitable for local methods of carrying water (e.g., handles, flat bottom for head carrying, not too tall)	x	xxx
Inexpensive	xxx	xxx
Available in local markets	xxx	xxx

* Sometimes 8 cm is too small an opening for transport containers – larger openings are required to capture the water stream when taps or pumps are mounted too high (e.g., tall handpumps mounted on dug well caps), when it is windy, when there are long queues (and so every pump stroke counts) and when water is scarce (and no water can be wasted).

** For example, collapsible plastic containers (sometimes supplied to families during emergencies) are not stable.

Rainwater harvesting tanks are a special category of home water storage containers. They tend to be larger, situated outside the home and they store water over much longer periods of time than typical home water storage tanks. The fact that rainwater tanks are large means that there are more potential contamination routes (e.g., cracks, difficult-to-seal manhole covers) and being outside, they are often more prone to animal and insect vectors. Long storage times can cause quality problems including algae growth (if not protected from light) and mosquito larvae.

Table 4.8 Water quality criteria for household rainwater storage tanks

- rainwater harvesting system (from rooftops) should include a mesh filter at the gutter, a first flush bypass system (that diverts the first few minutes of flow away from the tank – allowing the roof to be flushed of most contaminants) and a sand filter
- access hole to allow cleaning, with a tight-fitting cap
- all openings sealed to prevent light penetration and the entry of insect vectors
- tap(s) at least 5 cm above the tank floor
- drainage pipe to remove sump water
- smooth interior finish to facilitate cleaning

The safe handling and storage of water, while very important, will not, of course, improve the quality of water from contaminated sources. And contaminated sources for domestic water supply are still very common in developing countries. In situations where sources cannot be protected, the treatment of water in the home (as discussed in 5.3.3) may become the only viable option for consumers.

The safe handling and storage of water at the household level is receiving greater attention from sector professionals. This is due to a growing body of research indicating that both household storage and treatment is among the most effective of water, sanitation and health interventions (WHO, 2007a). One forum for discussion and resources on the issue is the International Network to Promote Household Water Treatment and Safe Storage (www.who.int/household_water/en).

See also section 5.3.3 for a discussion on household water treatment.

Water safety plans

The WHO guidelines for drinking-water quality include a new emphasis on the process of protecting drinking water over the entire water supply cycle from the catchment basin to individual consumers. This Water Safety Plan (WSP) approach makes use of Hazard Analysis and Critical Control Points (HACCP), which are used extensively in the area of food safety. This approach represents a shift in thinking towards the use of risk-based and process-oriented techniques for ensuring drinking-water quality.

Water safety plans should be developed by water system owners and operators together with national or regional authorities. The plans focus attention on minimizing risk rather than on testing the quality of water at the point of delivery.

Steps for formulating and operationalizing water safety plans, as described in the new water quality guidelines, are:

- development of an understanding of the specific system and its capability to supply water that meets water quality targets
- identification of potential sources of contamination, and how they can be controlled
- validation of control measures employed to control hazards
- implementing a system for monitoring the control measures within the water system and initiating timely corrective actions to ensure that safe water is consistently supplied
- undertaking verification of water quality to ensure that the water safety plan is being implemented correctly and is achieving the performance required to meet relevant national water quality objectives.

It is expected that government authorities and support agencies will contribute to the process by developing a set of basic “model” water safety plans for different types of systems that can be used and revised by system operators. In the case of small community water supplies, plan implementation will be accompanied by capacity building.

Water safety plans are a fairly new concept, and relatively few have been developed to date in developing countries. However, initial experiences are positive (see, for example, the Kampala case study in Godfrey and Howard, 2005c) and various initiatives are underway to promote the practical adoption of the report (including an AusAid, UNICEF, WHO, WSP initiative to pilot water safety approaches in the East Asia region).

For more information on water safety plans, see Chapter 4 of the WHO Guidelines for Drinking Water Quality, the Davison WHO document specifically on water safety planning and the WEDC water safety plan series, all listed below in section 4.5.

4.5 Key resources

Water contamination and protection

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Schmoll, O. et al, eds (2006). Protecting Ground Water for Health: Managing the Quality of Drinking-water Sources. Geneva: WHO. (a comprehensive new resource on groundwater quality)

Sobsey, M. (2002). Managing water in the home: accelerated health gains from improved water supply. WHO/SDE/WSH/02.07 www.who.int/water_sanitation_health/dwq/wsh0207/en/

UNICEF (1999). Water, Environment and Sanitation Guidelines: Water Handbook. New York: UNICEF. www.unicef.org/wes/files/Wat_e.pdf

WEDC Water Safety Plan Series:
(all available on line: go to the online catalogue and search for water safety plans: wedc.lboro.ac.uk/publications/online-catalogue.php)

> Godfrey, S. and G. Howard (2005a). Water Safety Plans Book 1: Planning water safety management in urban piped water supplies in developing countries. Loughborough: WEDC, Loughborough University.
>
> Godfrey, S. and G. Howard (2005b). Water Safety Plans Book 2: Supporting Water Safety Management for Urban Piped Water Supplies in Developing Countries. Loughborough: WEDC, Loughborough University.
>
> Vairavamoorthy, K., S. D. Gorantiwar, J. Yan et al. (2005). Water Safety Plans Book 3: Risk Assessment of Contaminant Intrusion into Water Distribution Systems. Loughborough: WEDC, Loughborough University.
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Sanitation and hygiene

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Chapter 5
Improving Water Quality

Ideally, a well-designed water supply point (as discussed in Chapter 4) will provide water that is microbiologically safe and free from chemical contamination by humans – although naturally occurring chemical contamination may still be a concern. In practice, the ideal water supply point is hardly ever achieved, and even well-built water supply points degrade over time. Furthermore, water from a clean source may easily become contaminated with pathogens during collection, transport and household storage. In an urban context, water may be of high quality leaving a treatment plant, but become highly contaminated with faecal bacteria before reaching the user's tap, due to low pressure and leaks in distribution systems. In developing countries, especially in rural areas, it is nearly impossible to find water supplies that consistently provide water that is completely free of faecal contamination. In industrialized countries, enormous resources are invested in drinking-water treatment and delivery, yet chemical and microbiological contamination can still occur on occasion.

Clearly, the first line of defence should be to use the highest-quality source available. Surface water can be grossly contaminated with faecal pathogens, especially in densely populated countries with limited waste-water treatment. Groundwater is of much higher microbiological quality, due to the filtering action of the sediments, and can provide a good alternative to surface water in some cases. However, groundwater can also be susceptible to faecal contamination from on-site sanitation (ARGOSS, 2001), and may contain minerals or salts that are harmful or make the water taste unacceptable to users. Good quality water may also be obtained by collecting rainwater from rooftops (see box). While high-quality source waters may require little or no treatment, it is still recommended that any water used for drinking be disinfected to ensure microbiological safety.

This chapter briefly summarizes the main technologies for drinking-water treatment and provides the reader with references to more detailed sources. The approaches taken for microbiological and chemical treatment are different, although some technologies can be applied for either purpose. Implementation of treatment technologies is then discussed at the municipal, community and household levels.

Resources for rainwater harvesting and water quality

Rainwater collected from rooftops can be of excellent quality, though animal faeces may contaminate the water. This can be minimized by clearing trees and overhanging branches away from the rooftop, ensuring that gutters are cleaned regularly and designing a "first-flush" diversion system for rinsing the rooftop before rainwater is collected. Some chemicals (e.g., zinc and possibly lead) may be leached from metal rooftops, especially if the rainwater is acidic, and atmospheric pollution can also be a source of contamination. However, serious chemical contamination of rainwater is rare (Pathak and Heijnen, 2006).

A number of resources are available detailing the design and implementation of rainwater collection systems. See Gould (1991), IRC (1990, 2002, Chapter 7), Pacey and Cullis (1986), Cullis and Pacey (1991), Gould and Nissen-Petersen (1999). Additional resources are available from the International Rainwater Catchment Systems Association: (www.ircsa.org) and the Indian Centre for Environment and Science website on rainwater harvesting (www.rainwaterharvesting.org).

There is an increasing body of work on water quality and rainwater harvesting. Appendix B of the WHO Water Safety Plans book (Davison and Howard, 2005: www.who.int/water_sanitation_health/dwq/wsp0506/en/index.html) presents a model rainwater harvesting water safety plan and the Bangladesh University of Engineering & Technology (BUET) has drafted a specific plan for Bangladesh (BUET, 2006: www.buet.ac.bd/itn/pages/outcomes/RWH_WSP_2nd_version.pdf). For a more general discussion on water quality and rainwater harvesting see "Health and Hygiene Aspects of Rainwater for Drinking" (Pathak and Heijnen, 2006: wedc.lboro.ac.uk/conferences/pdfs/32/Pathak.pdf). Finally, WHO is planning on issuing a new guidance document on water safety and health aspects of rainwater harvesting and storage.

5.1 Improving microbiological quality

Unprotected water supplies can be heavily contaminated with faecal matter from humans and animals. Table 5.1 gives an idea of typical contamination levels and illustrates that, as expected, contamination is most severe in unprotected sources. It can be assumed that people who must use unprotected surface water or open wells are often drinking water containing more than a thousand faecal coliforms/100 mL. Even people using protected sources are probably regularly exposed to water containing from ten to several hundred faecal coliforms/100 mL.

Table 5.1 Faecal coliforms in untreated domestic water sources in selected countries

Country	Source	Faecal coliforms/100 mL
Gambia	Open hand-dug wells, 15-18 m deep	Up to 100,000
Indonesia	Canals in central Jakarta	3,100 – 3,100,000
Lesotho	Streams	5000
	Unprotected springs	900
	Water holes	860
	Protected springs	200
	Borehole	1
Uganda	Rivers	500-8,000
	Streams	2-1000

Country	Source	Faecal coliforms/100 mL
	Unprotected springs	0-2000
	Protected springs	0-200
	Hand-dug wells	8-200
	Boreholes	0-60

Source: Cairncross and Feachem (1993)

Because the infectious dose for many faecal pathogens is low (as little as a single virus can cause infection), treatment should be designed to remove the vast majority of pathogens. Treatment is generally designed with a particular **log removal** rate for particular pathogens: 90% removal constitutes 1 log, 99% 2 logs, and so on. Table 5.2 lists representative pathogens (bacteria, viruses and protozoa) that are likely to be present in a typical surface water source and treatment-based goals that would reduce the disease burden to an acceptable level[5] (WHO, 2006). These values serve as examples only; case-specific targets should be calculated based on the actual concentration in the source water and a locally acceptable risk level.

Table 5.2 Treatment of pathogens in surface water

Pathogen	Typical number per litre of raw water	Target removal
Cryptosporidium	10	99.994% (4.2 log)
Rotavirus	10	99.99968% (5.5 log)
Campylobacter	100	99.99987% (5.9 log)

Water quality and diarrhoea

Water quality is only one of the water- and sanitation-related causes of diarrhoea. Diarrhoea morbidity is generally linked more to poor sanitation conditions and hygiene practices than to water supply. However, newer studies that take into account household level (point-of-use) water treatment suggest that water quality interventions are more effective than previously thought in reducing diarrhoeal disease (Fewtrell et al, 2005; Clasen et al, 2007; WHO, 2007a). See sections 4.4 and 5.3.3 on household storage and treatment for further discussion.

A 2004 meta-analysis of higher-quality research studies (Table 5.3) confirms that sanitation and hygiene interventions (especially hand-washing with soap) continue to be very important strategies for reducing diarrhoea. But the study also shows that water quality interventions – including point-of-use treatment – can reduce diarrhoea morbidity by as much as 39 percent. Earlier meta-studies that considered only system and community-level water treatment estimated that water quality interventions accounted for only 15 per cent of diarrhoea reduction (Esrey et al, 1991).

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[5] For this example, a tolerable risk level was set at 10^{-6} Disability-Adjusted Life Years (DALYs) per year.

Table 5.3 Median percent reduction in diarrhoeal disease morbidity by intervention

Intervention	Percent reduction
Sanitation	24
Hygiene	42
Water quantity	23
Water quality	39

Source: Fewtrell and Colford (2004)

While rigorous data is limited on the combined effect of water, sanitation and hygiene interventions on reducing diarrhoea, most sectoral programmes (and certainly those supported by UNICEF) recognize the need to have balanced programmes including all effective interventions.

Pathogens differ in their susceptibility to various treatments. For example, *Cryptosporidium* cysts may be retained by filters, but are resistant to chlorination; the opposite is true of many viruses. Furthermore, all treatment systems are subject to occasional failures, which may not be recognized by operators. The key to developing a robust and reliable system for providing safe water is to implement **multiple barriers** for pathogen control. Different pathogens can be removed in different stages, according to their particular weaknesses, resulting in water of progressively higher quality. The multiple barrier approach protects against the transmission of pathogens in the event that one barrier should fail. A typical multiple barrier system for treating surface water might include sedimentation, some type of filtration (slow sand filtration or coagulation followed by rapid filtration) and disinfection.

5.1.1 Sedimentation

Sedimentation is the removal of suspended solids by gravity. Sedimentation, or **gravity settling**, is often the first stage of surface water treatment, with the goal of to removing coarse suspended solids that might clog filters or reduce disinfection efficiency. This is especially needed in tropical areas where rivers often have high silt loads.

Sedimentation most commonly takes place in horizontal-flow tanks, where water slowly moves from one end to the other. Preliminary sedimentation tanks can remove at least 50%, and up to 90% of turbidity and suspended solids, depending on the nature of the solids in suspension. If the tanks are open to the atmosphere, sunlight may promote algae growth. Preliminary sedimentation may be followed by a primary disinfectant dose to enhance colour removal, improve subsequent coagulation and to prevent the growth of algae and slime in treatment tanks. This also lowers pathogen loads prior to the main treatment phase.

5.1.2 Coagulation

Coagulation is a process which enables small particles suspended in water to stick to each other, forming larger particles that can be more easily removed through sedimentation or filtration.

When chemical coagulants are added to the water, they form small solid particles (flocs), which aggregate (flocculate) and settle out of suspension. Following sedimentation, the remaining suspended solids are removed by rapid sand filtration.

The most common coagulants are alum and ferric salts (chloride or sulfate). In some cultures, plant products are used as natural coagulants. The crushed seeds of moringa trees (*Moringa oleifera lam* and *Moringa peregrina fiori*) are particularly effective coagulants, comparing favorably with alum in terms of removal of turbidity. A dosing rate of 200 mg crushed seeds per litre of water is suggested as optimal (IRC, 1982a).

5.1.3 Filtration

Filtration is the passing of water through a porous material. Filtration can improve both physical and microbiological quality.

Rapid filtration

Suspended solids can be removed by filtering the water through beds of sand or anthracite coal. Rapid sand filtration uses filtration rates of 5 m/h to 20 m/h, depending on the turbidity, to achieve 90% to >99% reduction in suspended solids.

Rapid sand filtration alone can remove large pathogens (e.g., *Giardia* cysts, helminths) and bacteria (50%-90%), but viruses are small enough to pass through the filter beds. If the filter media is chemically modified to give the surface a positive charge, removal of bacteria and viruses can increase to > 99%. This can be done by combining sand or anthracite with metal salts such as alum, iron, lime or manganese (Sobsey, 2002).

More typically, rapid filtration is used following coagulation. In a well-operated system, this can lead to removal of 90% to 99% of bacteria and viruses, and over 90% of protozoa (Salvato, 1992, p. 346). Coagulation and filtration can also remove dissolved constituents such as phosphorus, metal ions and natural organic matter, under correct operating conditions.

Slow sand filtration

Slow sand filtration is an inexpensive alternate to coagulation and filtration, and one of the oldest technologies for surface water treatment. The first stage in slow sand filtration is some sort of coarse prefiltration (often through gravel or coconut husk) to remove large particles such as leaves. The pre-filter feeds into the main tank, which contains a thick bed of sand. The water level in the tank is always kept well above the sand bed, providing a driving pressure and preventing the filter from drying out. Water moves through the sand beds slowly (typically 0.04 - 0.4 m/h) and passes into a storage tank, fitted with taps for users to draw water from.

Slow sand filtration removes pathogens through a combination of physical, chemical and biological processes, the last of which is the most important. After the filter has been in operation for some time, a layer of microbes develops near the top of the sand bed. In this zone, called the *schmutzdecke*, predatory microbes attack and consume pathogens such as viruses, bacteria and protozoal cysts (including *Giardia*, and *Cryptosporidium,* which is resistant to chlorination), and helminth eggs (Bellamy et al., 1985a; Cairncross and Feachem, 1993). In a well-operated slow sand filter, pathogen removal may exceed 99%. Still, slow sand filtration is typically followed by a safety disinfection with chlorine (IRC, 1978; IRC, 1982b).

After some time (up to several months, depending on inlet water turbidity), slow sand filters can become clogged, and the flow must be restored by scraping off the top few centimetres of sand, including the *schmutzdecke.* After this scraping, the filter will require several days to "ripen" and become effective again, depending on the water quality and temperature. After ripening the filter can be commissioned again.

Table 5.5 Typical removal efficiencies in slow sand filtration

Water quality parameter	Effluent or removal efficiency	Comments
Turbidity	< 1 NTU	The level of turbidity and the nature and distribution of particles affect the treatment efficiency
Faecal bacteria	90 to 99.9%	Affected by temperature, filtration rate, size, uniformity and depth of sand bed, cleaning operation
Faecal viruses and *Giardia* cysts	99 to 99.99%	High removal efficiencies, even directly after cleaning (removal of the *schmutzdecke*)
Schistosomiasis *Cercaria*	100%	In good operation and maintenance conditions virtual complete removal is obtained
Colour	25 to 30%	True colour is associated with organic material and humic acids
Organic carbon	< 15 - 25%	Total organic carbon
THM precursors	< 25%	Precursors of trihalomethanes
Microcystins	85 to > 95%	Cyanobacteria and their toxins extracted from a cyanobacterial bloom
Iron, manganese	30 to 90%	Iron levels above 1 mg/l reduce filter run length

Sources: Bellamy et al. (1985b), Grutzmacher et al. (2002), IRC (2002)

Several overviews of slow sand filtration are available: (Huisman, 1974; IRC, 1982b; IRC, 2002; Raman et al., 1987).

Slow sand filtration works best with relatively clear source waters. An influent turbidity of under10 NTU is recommended, though somewhat higher levels can be tolerated for short periods (IRC, 1982b). Surface water with higher turbidity and pathogen loads can be treated by using rapid sand filters before the slow sand filtration step. In this context, rapid sand filters are called pre-filters, or roughing filters, and the combined system is called **multi-stage filtration** (MSF) (IRC, 2002, Chapter 16).

Bank infiltration

An alternative to constructing engineered sand filters to remove suspended solids and pathogens from surface water is to make use of naturally occurring sediments in the subsurface. In bank filtration (also called induced recharge), a shallow well or series of wells are installed in the vicinity of a river or lake. When water is pumped from the well(s), the local groundwater flow patterns are changed, and surface water enters the aquifer and flows towards the well.

In order to allow sufficient filtration and bacterial purification to take place, wells should be installed at least 20 m, and preferably 50 m or more away from the surface water source. Underground travel times should be at least three weeks, and preferably longer. One benefit of bank infiltration is that water can be abstracted from the well even during the dry season, when the surface water source may dry up, if the well screen is located below the dry season water table.

Cloth and membrane filtration

In many cultures water is filtered through cloth to improve the appearance of the water; this also improves the microbiological quality to some degree. Bacteria and viruses are small enough to pass through holes in the cloth, but some of these pathogens will be attached to larger particles that are removed by the cloth. Cloth filtration can very effectively remove larger pathogens such as parasites (especially helminths) and is an essential intervention in the eradication of guinea worm.

Vibrio cholerae on their own are too small to be removed through coarse filters. However, the bacteria tend to attach themselves onto the egg-cases and mouths of copepods – microscopic crustaceans a thousand times larger than the bacteria. Studies in Bangladesh have shown that when water is filtered through locally available cloth (old *sari* fabric) folded over several times, over 99% of *V. cholera* cells are removed. In a field study, cholera rates were reduced by about half in households that used *sari* cloth filtration. This simple (and free) treatment technique was easily accepted culturally (Colwell et al., 2003).

Membrane filtration makes use of the same process, but uses synthetic membranes with much smaller pores, which are large enough to allow water to pass through but small enough to keep out particles or large molecules. Membranes with larger pores can be operated at low pressures, but more restrictive (or tight) membranes require high pressures. Nanofiltration and reverse osmosis are examples of tight membrane treatment methods that can remove viruses and even some chemical contaminants. However, these methods create large volumes of waste water (typically only 10%-20% of the raw water passes through the membrane), require a great deal of electricity, and are relatively expensive. As such they are not well suited for use in developing countries. Looser membranes (e.g., microfiltration, ultrafiltration) are less expensive to operate and can remove bacteria and parasites, if not viruses.

Ceramic filtration

Porous ceramic filters are widely used for household treatment of water, most commonly in the form of candle filters. Ceramic filter pore size varies widely, but most can reduce turbidity and parasites by at least 90% and substantially lower bacterial concentrations. Viruses are small enough to pass through most ceramics, though the surface of some ceramics can bind viruses. Many ceramic filters are impregnated with silver, which prevents bacteria from forming biofilms on the filter surface (Sobsey, 2002). Ceramic filters can be easily manufactured in developing countries using inexpensive, locally available materials. The NGO, Potters for Peace (www.pottersforpeace.org), has developed silver-impregnated ceramic water filters in Latin America, Africa and Asia.

While ceramic filters can substantially improve water quality, they can be prone to failure or clogging, and require regular cleaning (Chaudhuri et al., 1994). A 2002-2006 comprehensive study in Cambodia sponsored by UNICEF (and conducted by the University of North Carolina) demonstrated that locally-produced ceramic filters, used regularly, can significantly improve household water quality (up to 99.99% less E. coli in treated versus untreated water) and reduce diarrhoea morbidity (households using the filter reported nearly half the cases of diarrhoea compared to control households). The study also highlighted the importance of a spare parts supply chain and the need for complimentary education programmes on correct filter use to reduce breakage and unsafe water handling practices.
(Brown et al, 2007: www.wsp.org/filez/pubs/926200724252_eap_cambodia_filter.pdf)

5.1.4 Disinfection

The various forms of filtration discussed above can greatly reduce the number of pathogens present in water, but none of them is 100% effective, especially against viruses. And with any treatment technology, there is the possibility of failure, which may go undetected. Accordingly, water should always be disinfected after other treatment. Disinfection (physical or chemical) is the most effective and reliable way to ensure that any pathogens present in drinking water are removed to acceptable levels.

Physical disinfection

Boiling: Bacteria, viruses and protozoan eggs and cysts present in water can be killed by bringing the water to a full rolling boil. Boiling is generally not recommended for several reasons: it requires a large amount of fuel; it may give the water a flat, unpleasant taste; and there is a risk that people may heat the water without boiling, and consider the water purified. Large-scale boiling is not a feasible option for drinking water in most cases because fuel costs would be prohibitive.

Pasteurization: Unlike boiling, pasteurization (heating) cannot kill all pathogens in water. Instead, pasteurization aims to achieve a logarithmic reduction in the number of pathogens to the point where they are less likely to cause disease. The effectiveness of the pasteurization process is dependent on temperature, contact time, and heat resistance of the pathogen. Pasteurization is widely used in the food industry (especially for milk) but is not yet commonly used for water purification. However pasteurization has been shown to significantly improved the quality of water in projects in developing countries (Iijima et al, 2001; Islam and Johnston, 2006), and is a component of the widely used solar disinfection method (below). An important design consideration for any water pasteurization is ensuring that the system used achieves sufficiently high temperatures and retention times: this is achieved by setting minimum exposure times (e.g. in solar-based systems) or by adjusting flow rates (see box below).

Chulli household pasteurization system

A UNICEF-sponsored pilot initiative in Bangladesh has supported the development of a simple flow-through system that utilizes waste-heat from household stoves (chullis) to pasteurize water for drinking.

The apparatus draws raw water from an elevated reservoir (with sand filter) through an aluminium tube coiled within the wall of the clay oven. By adjusting the flow rate, the effluent temperature can be maintained at 70 degrees Celsius. Influent and effluent laboratory testing on 420 chullis in six pilot communities showed that the system completely inactivated thermotolerant coliforms.

The chulli system can produce 90 litres of treated water per day. It is inexpensive (about $6), easy to fabricate and has no operation and maintenance costs. In the pilot area, the chullis were well accepted by users. Although developed as an alternative in an arsenic-affected area, the chulli system has the potential for wider application.

See Household Pasteurization of Drinking-water: The Chulli Water-treatment System (Islam and Johnston, 2006) for additional information.
www.icddrb.org/images/jhpn243_Household-Pasteurization.pdf

Ultraviolet radiation: Ultraviolet radiation can effectively kill pathogens. Electric ultraviolet lamps have been used to irradiate water, and several schemes have been developed to utilize solar energy for disinfection (see 5.3.3).

Solar Disinfection: The Swiss research centre, EAWAG, has shown that over 99% bacterial inactivation can be achieved by storing water in clear plastic bottles (usually used drinking-water bottles) and exposing them to at least 6 hours of sunlight.. Bacteria, viruses, *Giardia* and *Cryptosporidium* cysts, and parasite eggs can all be effectively inactivated through the combination of ultraviolet radiation and elevated water temperature (pasteurization). Raw water must have low turbidity (<30 NTU), for radiation to penetrate sufficiently. This technique, called SODIS (Solar Disinfection) involves minimal capital and operational costs and is a promising household treatment option. Field tests of SODIS in a number of different countries have shown both significant water quality improvements and drops in diarrhoea morbidity (EAWAG, 2007).

Chemical disinfection

The most widely used method for ensuring pathogens in water are killed is to add a chemical disinfectant. The extent of disinfection is determined by the pathogen's sensitivity to the particular disinfectant, disinfectant concentration and the length of time pathogens are exposed to the disinfectant. Disinfectant doses are usually designed to achieve a particular combination of concentration (C) and time (T), or CT.

An ideal disinfectant would have the following properties:

- inexpensive and widely available in rural areas of developing countries
- easy to handle, with a long shelf life
- highly toxic to bacteria, viruses, helminths and parasite cysts under a range of water conditions
- non-toxic to humans and animals
- does not produce any unwanted disinfection by-products
- stable in water, to provide a residual protection against recontamination

No single disinfectant meets all of these criteria, but chlorine compounds satisfy most, and are the most widely used disinfectants.

In rural areas, the most common forms of chlorine are liquid bleach (sodium hypochlorite, about 1% available chlorine); bleaching powder (calcium hypochlorite, up to 30% available chlorine); and high-test hypochlorite powder (50%-70% available chlorine as calcium hypochlorite). Sodium dichloroisocyanurate (NaDCC) is also used in emergency situations, but must be imported. Chlorine compounds are very reactive and if improperly stored, available chlorine levels can be much lower than expected. The appropriate chlorine dose will depend on the chemical and physical composition of the water, and should be sufficient to satisfy both the chlorine demand and to produce a free residual of 0.5 mg/L. A minimum contact time of 30 minutes is recommended.

Local production of chlorine disinfectant

Chlorine in powdered forms (bleaching powder, high-test hypochlorite) is highly caustic and can be dangerous to handle. Furthermore, it can be difficult to make up a solution of the desired concentration, especially using locally available products. In general, liquid solutions are easier and safer to handle than concentrated powders. Commercially available bleach may be used, but the chlorine concentration may be inconsistent, or it may contain additives. Users may be reluctant to add bleach, a known household cleanser, to drinking water.

An emerging alternative is to generate chlorine disinfectant locally, by electrolysis of an ordinary salt solution. Simple hypochlorite generators produce a consistent free chlorine concentration, and can be operated by locals without extensive technical backgrounds. The disinfectant can then be bottled and marketed locally for drinking-water treatment. Local production minimizes transport costs while creating jobs. The process is inexpensive: in projects implemented in Zambia, Madagascar and Kenya, a month's supply of disinfectant sold for between $0.10 and $0.20 (CDC, 2001).

Various systems have been developed for chlorination at community and household levels (WHO, 1997b; WRC, 1989). Chlorine disinfection has several obvious advantages: it is very effective at pathogen reduction and the free residual provides some protection against contamination during storage or transportation. However, if too little or too much chlorine is added, serious problems can arise: in the former case, users may incorrectly believe that the water is pathogen-free, while in the latter, the water may be unpalatable because of a strong chlorine taste. Especially at community and household levels, it can be very difficult to ensure that the correct dose of chlorine is delivered. Even when the optimal dose of chlorine is achieved, water users unaccustomed to chlorinated water may find the taste unpleasant and may choose to abandon chlorination. In both industrialized and developing countries, experience has shown that users have chosen unsafe sources over safe waters with too strong a chlorine taste.

Chlorination at any stage of treatment can produce harmful disinfection by-products, depending upon the dose and composition of the treated water. The health risks posed by these by-products are smaller than the risks posed by pathogens, so disinfection should not be neglected simply to avoid by-product formation.

Other disinfectants

Ozone is highly toxic to many pathogens (including *Cryptosporidium*), but it is relatively difficult and expensive to produce and leaves no residual. It is not practical for household use and would be difficult to implement in developing countries.

Iodine is an effective disinfectant. It is applied either in liquid form or impregnated on ion exchange resins. Because of its high cost compared to chlorine, it is generally used only for short-term treatment or in emergency situations. Another halogen, bromine, is a powerful disinfectant, but it is difficult to obtain and more costly and dangerous to handle than chlorine. Iodine and bromine are not recommended for standard use as disinfectants.

Some dissolved metals (e.g., gold, silver, copper, mercury) can either kill pathogens or prevent them from growing. However, some are expensive or toxic to humans. Silver is the most widely used, as the required dose is low and it is not very toxic to humans. Silver provides a stable residual, and does not produce taste, odours or disinfection by-products. However, its action is slower than that of chlorine and it is not very effective against viruses or parasite cysts. Silver is not recommended for use as a primary disinfectant, but can be used as a secondary barrier, for example when impregnated onto filter media or walls of storage vessels. It can also be used to prevent *Legionella* growth in distribution systems.

5.2 Improving chemical quality

Some chemical contaminants can be destroyed or converted to benign forms, in particular organic compounds such as pesticides or solvents. In general, organic compounds can be removed from water by air stripping, adsorption onto activated carbon, or biological or chemical transformation. However, partially transformed organic compounds may be as toxic as, or more toxic than, the parent compound. Since organic contaminants are likely to result from local contamination by humans, they are not considered in detail here.

Inorganic contaminants present a different challenge, as they cannot be destroyed, and in most cases are not volatile. Treatment generally involves forming a bond between the inorganic ion and a solid surface, either a granular media (e.g., activated alumina, ion exchange resin) or a suspension that can be removed with conventional sedimentation and filtration. Some chemicals may become insoluble by changing the pH or adding an oxidant; they may then be removed by filtration. In some cases, biological treatment is known to catalyze the removal process.

Tight membranes, such as those used in the reverse osmosis process, in principle can remove any organic or inorganic contaminant. However, because of the expense, tight membranes are rarely used for chemical removal, except for desalination of brackish or ocean water.

Table 5.6 Technologies for removing chemical contaminants

Contaminant (selected)	**Oxidation**	**Coagulation**	**Ion exchange**	**Precipitation/ softening**	**Adsorption**	**Membranes**	**Biological Treatment**
Arsenic		+++ <0.005	+++ <0.005	+++ <0.005	+++ <0.005	+++ <0.005	+++ <0.005
Fluoride		++			+++ <1	+++ <1	
Iron	+++ <0.1	+++ <0.1				+++ <0.1	+++ <0.1
Manganese	+++ <0.05	++				+++ <0.05	+++ <0.05
Nitrate			+++ <5			+++ <5	+++ <5
Nitrite	+++ <0.1						
Uranium		++	+++ <0.001	++	+++ <0.001		

++ > 50% removal +++ > 80% removal

Source: After WHO (2006, Chapter 8)

Removal of priority inorganics

Arsenic, fluoride and nitrate/nitrite are the primary inorganic compounds of health concern in drinking water.

Arsenic presents a challenge because the treatment target is so low, on the order of 5 to 50 µg/L. In highly contaminated areas, these targets could require a reduction of > 99%, which is difficult to achieve easily and economically with any technology. The most common treatments are coagulation with alum or iron salts; adsorption onto activated alumina; and ion exchange. Most removal processes are more effective for As^V than As^{III}, so pre-oxidation is usually required. Biologically activated reactors can improve removal of As^{III}.

Target concentrations for removal of *fluoride* are much higher, on the order of 1 mg/l, but fluoride is not extensively removed in conventional coagulation. Alum/lime coagulation (the Nalgonda process) is more effective, but requires a lot of chemical addition and produces a large amount of waste sludge. Adsorption onto activated alumina or bone char is also an option.

Nitrate is perhaps the most difficult to remove from drinking water, because of its chemical inertness. In municipal plants, biological removal (denitrification) is possible. At the community or household level, ion exchange is the most practical option. *Nitrite* is generally removed following oxidation to nitrate.

Nitrate is a priority inorganic because of the risk of methaemoglobinaemia “blue baby syndrome” to infants when contaminated water is used to prepare formula (see section 2.3.3). Because it is difficult to remove nitrate from drinking water and because the at-risk group is bottle-fed babies, the best mitigation for nitrate in drinking water in rural areas of developing countries may very well be breast-feeding promotion programmes.

5.2.1 Source substitution

Before any engineered water treatment is attempted, source substitution should be considered. Switching to an alternate source may be the best long-term solution for a safe and reliable water supply, even if initial costs are relatively high. Source substitution measures could include switching from groundwater to surface water (or vice versa); screening or casing wells at certain depths; rainwater harvesting; and sharing or blending of safe supplies. Piped distribution systems should also be considered, either to bring water from a safe source or to maximize the impact of a large treatment plant.

Alternate water sources should be carefully chosen to ensure that the risks from the new source are not greater than from the old source. The relative risks of all available options should also be carefully assessed. For example, when a rigorous risk assessment based on DALYs was conducted for alternatives to arsenic-contaminated groundwater in Bangladesh during both dry and wet seasons, one alternative water source (deep tubewells tapping arsenic-free aquifers) had a significantly lower potential disease burden than the other three sources (dug wells, filtered surface water and rain water) (Howard and Ahmed, 2007).

5.2.2 Coagulation

Coagulation, discussed above for removal of suspended solids, also removes many dissolved ions, which are trapped by or bound to the charged floc surfaces. Coagulation can remove some heavy metals, anions (e.g., arsenate, chromate) and some low-solubility organic contaminants, such as chlorinated pesticides. Doses of coagulants (alum or ferric salts) may be higher for chemical treatment than for removal of suspended solids, on the order of 2-5 mg/L Al or 4-10 mg/L as Fe. Higher doses may be required in the presence of competing solutes: for example, phosphate, bicarbonate and silicate all compete with arsenic.

Coagulation is usually followed by sedimentation and filtration to remove residual solids.

5.2.3 Precipitation

Some metals become insoluble at high pH, or in the presence of high levels of carbonate. The most common use of precipitation is lime softening: calcium and magnesium, the principal components of hardness, both form insoluble solids. When lime is added to water, the pH rises, and magnesium precipitates out as magnesium hydroxide. Addition of soda ash (sodium carbonate) is usually required to allow formation of the insoluble calcium carbonate precipitate. Precipitation is followed by sedimentation and filtration to remove sludge. While the principal application is hardness removal, chemical precipitation can also remove metals (iron, manganese, cadmium, barium), anions (arsenic, chromium, selenium), radionuclides and viruses.

Precipitation requires large amounts of chemicals (primarily lime), and produces large volumes of waste sludge. Following softening, water pH is generally above 10, and must be lowered prior to distribution or consumption. This is most commonly achieved by addition of carbon dioxide.

The Nalgonda process

The Nalgonda process, developed in India, makes use of coagulation and precipitation to remove fluoride from water. Alum and lime are added to form polymeric aluminium hydroxide species at high pH. Fluoride reacts with these aluminium species, and is removed along with aluminium flocs that settle out of solution. Calcium fluoride precipitates may also form. If the raw water is very hard, or low in alkalinity, more lime must be added to allow efficient floc formation.

Table 5.7 Approximate alum dose in mg/L required to achieve 1 mg/L residual fluoride

Fluoride concentration, mg/L	**Alkalinity, mg/L as $CaCO_3$**							
	125	**200**	**300**	**400**	**500**	**600**	**800**	**1000**
2	145	220	275	310	350	405	470	520
3	220	300	350	405	510	520	585	765
4	*	400	415	470	560	600	690	935
5	*	*	510	600	690	715	885	1010
6	*	*	610	715	780	935	1065	1210
8	*	*	*	*	990	1120	1300	1430
10	*	*	*	*	*	*	1510	1690

* Alkalinity must be increased with lime prior to treatment
Source: UNICEF/RGNDWM (2002)

5.2.4 Oxidation

Strong oxidants can help to break down organic chemicals, and can in some cases convert inorganic chemicals to a form that is easier to remove. Atmospheric oxygen is the most widely available oxidant, but it is weaker than other chemical oxidants such as free chlorine, permanganate and ozone.

The use of groundwater for drinking water is in many cases limited by the presence of dissolved iron and, to a lesser extent, manganese. These give the water an unpleasant metallic taste and stain food, sanitary ware and laundry. Both metals can be oxidized to form an insoluble precipitate, which can then be removed by filtration. Oxygen can in some cases be used for the oxidation of dissolved iron, but oxidation is slow below pH 7, or if the iron is bound with organic matter. Sometimes the water pH is increased by using alkaline filter media, such as limestone. Chemical oxidants are generally required to oxidize dissolved manganese or to achieve more rapid oxidation of iron: potassium permanganate is used most commonly.

Much effort has been spent on developing simple methods to remove iron and manganese from water. Most are based on oxidation followed by filtration, though biological processes probably contribute significantly to removal efficiency. While small community-based plants often work well initially, long-term success is less common, due to inadequate maintenance. Examples of community-level iron and manganese removal plants are provided by Hartmann (2001) and Cairncross and Feachem (1993). The inexpensive well-head iron removal filters developed by Finnida and UNICEF in 1989 in Sri Lanka are an example of a successful application of this technology. Iron removal filters have also been extensively used in India. Specifications for an iron removal plant based on a design tested in Uganda are available from the Cranfield University Institute of Water and Environment, at www.silsoe.cranfield.ac.uk/iwe/iron.htm.

5.2.5 Adsorption

Adsorption is the formation of bonds between dissolved species or small particles and the surface of a solid. Usually the solid is in the form of granular media, and water is treated by passage through packed beds. Powdered adsorbents may also be used, and adsorption is a key process during coagulation. Ion exchange can be considered as a special form of adsorption, though it is often considered separately.

The efficiency of adsorption depends primarily on the attraction of the contaminant for the media being used and the extent of contact between water and surfaces (controlled by particle size and loading rates). Water chemistry may also be important: positively charged species (like most metals) are more easily removed at high pH, while negatively charged species (like arsenate) are best removed at lower pH. Competition from other dissolved species or clogging of the media by particles can also greatly reduce adsorption of the target chemical. All adsorption media have a limited number of sites where adsorption occurs, and as these sites are filled the media becomes exhausted and must be replaced or regenerated.

Water treatment with granular adsorption media is relatively easy to implement: water is simply passed through packed beds containing the media. Adsorption may be improved by pre-treatment such as pH adjustment, oxidation or turbidity removal. One drawback of adsorption treatment systems is that it is not easy to tell when media have become exhausted.

Activated carbon/charcoal

Black carbon can remove many organic contaminants, including natural organic compounds that cause taste and odour problems. Wood charcoal is a convenient source of black carbon in developing countries. Activated carbon is chemically very similar to charcoal, but with a much greater surface area. Most toxic synthetic organic chemicals (pesticides, solvents) will be adsorbed by carbon. Fresh activated carbon can adsorb microbes, including pathogens, from water, but these tend to form biofilms on the carbon surface, reducing its capacity. Activated carbon also removes chlorine residuals, so biofilms can grow even when disinfectants are applied. Activated carbon is sometimes impregnated with silver to prevent biofilm formation. However, biofilms can improve removal of some organic compounds, by biological oxidation.

Carbon does not remove most inorganic contaminants. However, the carbon-based adsorbent **bone char** is known to remove a number of heavy metals and has a high adsorption capacity for fluoride.

Activated alumina

Like activated carbon, activated alumina has a very high surface area, giving it a relatively high adsorption capacity. The alumina surface has a strong attraction for many inorganic anions, and is commonly used for the removal of arsenic and fluoride. Activated alumina can also be used to remove other anions, including silica, selenium, uranium (as uranyl carbonate) and natural organic matter from water. Surprisingly, arsenite is also removed, even though it is neutrally charged below pH 9.2. Of course, the presence of competing anions, especially natural organic matter and sulfate, will reduce the adsorption capacity for the target anion.

Adsorption onto activated alumina is sensitive to pH, and is optimal in the 5.0-6.0 range. Above pH 8 activated alumina is ineffective. Ideally water would be acidified prior to treatment, but significant removal is still likely with untreated water, if the pH is near neutral.

Exhausted media may be regenerated with strong alkali, followed by strong acid to re-establish a positive surface charge. However, regeneration is inefficient, and adsorption capacity deteriorates with each regeneration cycle. Regeneration produces strong alkali and acid wastes and potentially high arsenic or fluoride levels.

In spite of the drawbacks of activated alumina it remains a viable technology for the removal of arsenic and fluoride, especially in community or household systems. Granular media are inherently easier to work with than chemical methods, since operation and maintenance is easier. In the case of fluoride, there are few competing technologies: the fluoride ion is much more strongly attracted to the alumina surface than to synthetic anion exchange resins, and activated alumina is simpler to implement than coagulation/precipitation methods (see boxes, “The Nalgonda process” and “Fluoride removal in India”). And since arsenic occurs at much lower levels, the media can be used for a long time before regeneration or replacement. The ability to remove As^{III} without a pre-oxidation step is also a significant advantage.

Other adsorbent media

Many inorganic chemicals bind to the surface of iron oxides, much as they do to activated alumina or during coagulation with iron salts. Iron-based media are beginning to become commercially available in granular form (e.g., granular ferric hydroxide). These reportedly have a high affinity for heavy metals and arsenic, and have a wider effective pH range than activated alumina. At present, these are only available from a few producers. Low-cost iron-based media can be made locally by coating sand or other materials with iron oxide.

Metallic iron also is increasingly used in drinking-water treatment and undergoes a complex series of reactions that are not yet well understood. Still, metallic iron shows great promise in the treatment of many organic compounds, as well as inorganic compounds such as arsenic.

5.2.6 Ion exchange

Ion exchange is very similar to adsorption, in that it involves passing water through beds of granular media which remove the target contaminant. The difference is that ion exchange media is made of synthetic resins, which forms easily reversible bonds with ions. This allows much better regeneration than, for example, activated alumina, and ion exchange resins can be reused many times. Salt solutions (brines) are used for regeneration.

The most common application of ion exchange resins is for removal of cations (positively charged ions) that cause hardness, chiefly calcium and magnesium. Cation exchange resins can also remove barium and radium. Other resins target anions (negatively charged ions) and are used to remove nitrate, arsenate, chromate, selenium and uranium. Molybdenum and boron may also be removed to some extent. Anion exchange is the most readily available technology for nitrate removal.

Ion exchange resin should not be used in waters with high salinity or sulfate, because competing ions will quickly exhaust the media. Also, iron removal may be necessary to prevent fouling of the media with oxide precipitates.

5.2.7 Membrane filtration

Synthetic membranes with small pores can remove large molecules while allowing water to pass through. Reverse osmosis, the main technology used for desalination, can effectively remove most inorganic contaminants but requires a lot of electricity to create the pressure needed to drive water through. Nanofiltration, which uses membranes with slightly larger pores, can also remove many ions from water, including arsenic. Electrodialysis is a related removal process that uses an electrical potential rather than water pressure to drive ions through membranes with relatively large pores.

Membranes can easily be fouled by organic matter or iron, so water usually is pretreated. Because of the complexity of operation and high cost, membrane processes are not generally appropriate for use in developing countries.

5.2.8 Biological removal processes

Microbes, especially bacteria, can play an important role in catalyzing many of the above processes, which may go unrecognized. Iron removal plants, for example, are often designed for treatment by physical and chemical processes. But iron-oxidizing bacteria, which are found everywhere in the environment, typically colonize the filtration media, and may end up being responsible for the majority of iron removal.

Other treatment systems are explicitly designed to use biological processes. Many organic contaminants can be broken down by bacteria, given the right conditions. Bacterial denitrification is the principal technology for nitrate removal in large municipal treatment plants.

5.2.9 Management of residuals

All treatment technologies will result in some kind of waste product, which should be handled and disposed of safely. Many wastes are harmless and can simply be disposed of locally. Some residuals, though, may contain elevated levels of chemicals that require special management.

Residual management is more of an issue in municipal or community-level treatment systems: household treatment generates small waste streams, which in most cases can be disposed of locally. Small amounts of waste can be safely disposed in sanitary latrines, where they will not recontaminate drinking-water supplies. If household waste is very toxic (e.g., concentrated arsenic waste accumulated over months) it may be collected for central treatment or landfill disposal.

Potentially hazardous wastes might leach toxic chemicals into the environment after disposal. The stability of a waste can be evaluated using chemical tests such as the USEPA’s Toxicity Characteristic Leaching Procedure (TCLP) test (USEPA, 2002, Chapter 8). If testing shows that the waste is likely to leach, it may be stabilized by mixing with cement or blending with glass.

5.3 Water quality interventions

Even when there are established technologies for reducing a given contaminant, implementation of water treatment schemes is a major challenge. Different approaches are appropriate in different contexts. One useful categorization of interventions is by the level of centralization: municipal, community-based or household-based.

5.3.1 Municipal (centralized) treatment

Cities and large towns may have substantial infrastructure for treatment and delivery of drinking water. These are conventionally operated by government employees, though privatization of water supply is a growing trend (see Lobina and Hall, 2000; Palmer et al., 2003; Rivera, 1997; Sansom et al., 2003). Wagner and Pinheiro (2001) offer a useful resource for optimizing and upgrading municipal treatment plants.

Municipal treatment allows relatively complex technologies to be applied by operators with technical backgrounds in engineering and chemistry. Water quality can be monitored at various points during treatment, and conditions can be optimized as needed by adjusting process parameters. In many developing countries, however, treatment is less of a problem than delivery. Distribution networks may be poorly constructed and sporadically maintained, and unauthorized connections are commonplace. Public water supply points and mains are frequently damaged. Typically, at least 30% and as much as 60% of water produced can be lost during distribution (Cairncross and Feachem, 1993). Distribution loss is not only inefficient and economically unsustainable, but leads to low pressure and infiltration of surface water heavily polluted with faecal material (Farley, 2001). Thus, it would be a mistake to spend a lot of money on producing top-quality water, for example using reverse osmosis, only to have it be contaminated during distribution (e.g., Semenza et al., 1998). The World Plumbing Council/WHO publication Health Aspects of Plumbing (2006) provides a comprehensive and useful guide for ensuring water safety in both production and distribution systems in developing countries.

5.3.2 Community-level treatment

While municipal water treatment and piped water are available in most urban settings, in small towns, peri-urban and rural areas, people must usually collect water on their own, either from community-managed or private sources. Some community-managed systems include piped distribution systems and even in-home taps.

The fundamental difference between municipal and community water supply is in the management structure. Municipal supplies are managed and run by government employees (or private sector contractors), with little input from beneficiaries. Community supplies designed along this model tend to fail, because systems are not maintained and operated in a professional manner. Community level treatment systems are more likely to work when community members are involved in the selection, design, construction, and operation and maintenance of water supply systems. Beneficiaries should contribute some or all of the start-up and operating and maintenance costs of any treatment project.

The design of sustainable mechanisms for community participation and management is critical, but beyond the scope of this document. See the UNICEF Water Handbook (UNICEF, 1999) for more in-depth discussion. Other useful references are IRC (2002), Appelton and Evans (1993), van Wijk-Sijbesma (1995, 1998), Bolt and Fonseca (2001), Brikké (2000) and WHO (1996).

Ideally, it would be possible to identify a source of water that would require little or no treatment after construction. Water treatment at the community level should only be considered if no sufficiently pure water sources are available, and if community members want the new source and are willing and able to contribute to its construction, operation and maintenance.

If treatment is required, simple technologies are preferable. Chemical addition, apart from chlorination, should be avoided if possible. Slow sand filtration can be implemented successfully and is preferable to coagulation and filtration. Likewise, chemical treatment using adsorption (or ion exchange) in filter beds is more easily applied than coagulation or precipitation methods.

Disinfection is recommended after any treatment process. Liquid hypochlorite solutions are easily applied at the community level and many designs are available for automatic delivery of chlorine (Cairncross and Feachem, 1993). However, it is difficult to ensure a constant disinfection rate with on-site disinfection. Too much chlorine and the water will be undrinkable, too little chlorine and users will have a false sense of security. Household disinfection, discussed below, may be more effective.

5.3.3 Household level treatment

Properly protected water resources and water sources (Chapter 4) and well-managed municipal and community treatment systems should result in safe water for consumers. In reality, this is often hard to achieve, especially in rural and poor urban areas in developing countries. Leaky and sporadically functioning distribution systems allow re-contamination to occur, as do poor hygiene, water transport and storage practices. Another reason water is unsafe is that in many countries safe water is simply not available and people rely on unimproved, contaminated water sources. In some cases, the only alternative is to treat water in the home.

Home treatment (also known as household treatment or point-of-use treatment) is an option increasingly adopted by householders themselves. In urban settings (both in developing and industrialized countries) it is now common for middle class and richer households to boil, filter or use ultraviolet disinfection systems to treat real or perceived threats to the quality of water in piped systems. In rural settings some form of treatment – usually filtration – is also common in some areas.

There is an increasing body of evidence demonstrating that home water treatment (coupled with improved storage and handling) significantly improves microbial water quality and has a greater impact on diarrhoea morbidity than previously thought (Fewtrell et al, 2005; Clasen et al, 2007). Because home water treatment can also be very cost effective and rapidly deployed, it is now thought to be amongst the most effective of water, sanitation and health interventions (WHO, 2007a). In recognition of this, the new UNICEF WASH strategy paper highlights the need for UNICEF country programmes to promote improved water safety at the household level including the development of point-of-use water treatment systems.

Although people have been using home-based treatment for years, governments and support agencies have in the past focused on community and municipal-based solutions for both water production and treatment. But this is now changing. Decision-makers and sector professionals are increasingly acknowledging that home treatment is a viable alternative to community-based solutions, especially in areas where water coverage is low or where even improved water sources are contaminated (e.g., in India, a country with water coverage rates above 90%, a recent study estimated that 22 % of public water sources – most of which are deep tubewells – are faecally contaminated). Home treatment is also a viable alternative in areas with chronic emergencies or instability.

Home-based treatment can be a more sustainable solution than communal systems because people are more motivated to correctly operate and maintain their own systems than they are communal ones. Also contributing to the movement towards home-based treatment is the availability of new low-cost treatment technologies specifically designed for poor households in rural or peri-urban areas (as discussed below).

But home water treatment is not about technology alone. To reliably improve water quality, the technologies and techniques must be used correctly and consistently. This means that users must be motivated, skilled and have the resources to purchase products and consumables throughout the year. It also means that large-scale programmes are successful only when technologies are affordable and a strong emphasis is placed on marketing. Most importantly, home water treatment on its own cannot significantly and sustainably reduce the incidence of water-related diseases unless water is stored and used safely and all household members practice good hygiene (see Chapter 4 for discussions on hygiene and water storage).

Microbiological treatment methods

Many of the methods described in 5.1 are applicable in the home setting. This discussion focuses on a selection of low-cost technologies that are widely promoted in rural and peri-urban areas, and their applicability for poor households. See section 5.1 for additional details.

At the household level, simple sedimentation can significantly reduce turbidity, though clay particles may be too fine to settle. Large pathogens such as protozoa may also settle if stored overnight or longer. Bacteria and viruses are too small to settle by gravity, but these pathogens may be attached to suspended solids which do settle. In the absence of light and a food source, pathogens will slowly die off during storage. However, household storage can also lead to greater contamination if faecal contamination is high and water is kept in inappropriate container.

Additional resources on household water treatment

In order to promote increased use of household-based water treatment methods, WHO has established the International Network to Promote Household Water Treatment and Safe Storage, which includes over 100 participant organizations including UNICEF. (www.who.int/household_water/en/).

One output from this network (available on the above website) is the detailed report describing home treatment and storage of water, *Managing water in the home: accelerated health gains from improved water supply* (Sobsey, 2002). See this report, and sections 5.1 and 5.2 for additional information on household-based treatment systems.

The CDC Safe Water website also has a set of on-line resources on home water treatment, with an emphasis on chlorination (http://www.cdc.gov/safewater/).

Finally, there are a several recent publications reviewing home water treatment technologies and methodologies available on-line:

Household water storage, handling and point-of-use treatment (Nath, Bloomfield and Jones, 2006).
www.ifh-homehygiene.org/2003/2library/low_res_water_paper.pdf

Household Water Treatment and Safe Storage Options in Developing Countries: A Review of Current Implementation Practices (Lantagne et al, 2006).
www.wilsoncenter.org/topics/pubs/WaterStoriesHousehold.pdf

Implementation, Critical Factors and Challenges to Scale-Up Household Drinking Water Treatment and Safe Storage Systems (Murcott, 2006).
www.hip.watsan.net/page/504

WELL Factsheets on Household Water Treatment (Clasen, 2005) and Household Water Treatment, Storage and Handling (van Wijk, 2005).
www.lboro.ac.uk/well/resources/fact-sheets/fact-sheets.htm

Boiling: While boiling water is highly effective at removing pathogens, due to rising fuel costs (and disappearing forests) this is increasingly out of reach for most people.

Natural solar disinfection (SODIS): When small transparent bottles of water are left out in the sun for a period of time, the combined effect of ultraviolet radiation (UV-A) and heat (pasteurization) inactivates most pathogens, making the water safe to drink. SODIS is growing in popularity because it is ultra-low cost or free (using discarded plastic bottles) and relatively simple to implement. However, because at least 6 hours of exposure to bright sunlight is required to de-activate pathogens, SODIS is not applicable in some climates and during rainy seasons. The technique also requires low-turbidity water to be effective. In some areas user acceptance has been low, due to the time it takes to disinfect water and the fact that drinking water is hot unless the bottles are left aside to cool.

Pasteurization: Pasteurization (heating to temperatures in excess of 70 degrees Celsius) of water on its own (without UV filtration) can also sufficiently reduce the number of active pathogens to make water safe for drinking. While not yet in wide use, a technique from Bangladesh that makes use of waste heat from cooking stoves is showing promise (see the Chulli Household Pasteurization box in section 5.1.4).

Electric UV disinfection: Using an electric system to produce ultraviolet radiation to disinfect water is much faster than relying on the sun. Many household units are available on the marketplace, but are generally too costly for poor families to purchase and operate. However, the popularity of these units (which are widely used in richer urban homes in some countries) is resulting in lower costs and, as electricity becomes more available, they may become a viable alternative for poor people. In addition, work is ongoing to develop less expensive units that use less power (and can be powered by photoelectric cells) and may be appropriate for use in rural areas.

Chlorination: Chlorine, used correctly with low- turbidity water, is a very effective disinfectant**.** Unlike the above technologies, chlorine disinfection has a residual effect – it continues to protect against the re-contamination of water over a period of time. This is the primary advantage of chlorine and the reason it is used widely in municipal systems. Chlorination also has disadvantages: chlorine products can be expensive (even bleaching powder can be too expensive for many households), difficult to market and can have a short shelf life. However new approaches to home chlorination programming are overcoming these problems, and have been shown to be successful at reducing diarrhoea rates (Quick et al, 2002; Lule et al, 2005).

The CDC Safe Water System (www.cdc.gov/safewater/) promotes local chlorine (sodium hypochlorite) production using salt and a targeted community education and mobilization programme, along with promotion of improved containers for household storage (CDC, 2001) (see also the Local Production of Chlorine Disinfectant box in section 5.1.4). CDC, the social marketing NGO PSI, UNICEF, WHO and other organizations support programmes that market ready-made sodium hypochlorite solutions in a growing number of developing countries. Continuous extensive marketing of the product is the key to the success of these programmes, and in some countries high awareness and usage rates have been achieved (Olembo et al, 2004; Stockman et al, 2007).

Coagulation and precipitation: In-home methods have been used in some regions for many years, especially with alum and vegetation extracts. While some studies have shown that good results can be obtained, the method can be difficult to use widely and consistently since it is dependent on a variety of variables, including the chemical characteristics of the water, correct dosages and careful mixing. Unlike the above methods, this method can be effective with turbid water.

Combined coagulation, precipitation and chlorination: Products that combine coagulation and chlorination chemicals in a single packet have been successfully tested in households in developing countries and used widely in emergency situations (see discussion of emergency purification in 5.3). This method can effectively treat poor quality turbid water and provide residual disinfection. It also uses significantly less chlorine than chlorination alone (because it reduces turbidity), which reduces costs. If costs can be further reduced through local manufacturing, it may become a viable alternative for poorer households.

Household chlorination in Guatemala: conventional chlorination vs. combined coagulation/chlorination techniques

In 2000 a study conducted in Guatemala (Rangel et al., 2003) examined the impact of household chlorination on drinking-water quality. The effectiveness of a commercially formulated combined product (Procter and Gamble's PuR, which incorporates precipitation, coagulation, flocculation and chlorination) was compared to conventional chlorination with locally available bleach. Water stored using conventional clay jars was used as a control. The combined product was able to produce water with no detectable faecal coliforms, when used with an improved storage vessel. When used with the conventional clay storage jars, good removal was found in most cases, but some units contained several hundred faecal coliforms per 100 mL sample.

In a follow-up randomized control trial study amongst the same population that focused on diarrhoea morbidity rates (Reller et al, 2003), the combined product reduced incidence by 24 percent over the control population (29 percent in households that also received an improved storage vessel). However, households that received bleach alone achieved similar diarrhoea reduction levels (25 percent).

Since 2003, the PuR sachets (and similar products from other companies – see box in section 5.3.4) are in wider use, including in emergency situations. In 2005, UNICEF entered into a global partnership with Proctor and Gamble to promote water safety in UNICEF programmes worldwide, including through the use of the PuR sachets and other technologies.

Filtration: Many home water filters are available in the marketplace, and are used widely in some countries. However the filters most effective at removing pathogens (factory manufactured ceramic filters, some membrane filters and granular media filters) are often too costly to purchase and operate for poorer households. But there are exceptions. For example, some low-cost artisan-produced ceramic filters have proven to be effective (see section 5.1.3), but quality can vary widely. Effective bucket-type granular filters can be produced locally at low cost, but the maintenance requirements are fairly high and media must be replaced on a regular basis. Slow sand filters can be effective and inexpensive, but the operation and maintenance skills required to keep them functioning well make them difficult to implement at the household level.

Some successes have been reported with the BioSand filter, marketed by the Centre for Affordable Water and Sanitation Technology (www.cawst.org and www.jalmandir.com) and used in several countries, however the filters usually achieve only 90 percent virus inactivation in the field (Lantagne, 2006 and www.jalmandir.com).

Filters that are not effective at removing all pathogens can still be useful in special situations. For example, inexpensive filters are used in guinea worm endemic areas to remove copepods (microscopic host crustaceans, which are much larger than bacteria) to break the cycle of disease, and simple cloth filtration can greatly reduce the transmission of cholera. Simple filtration can also be used to reduce turbidity and improve the efficiency of other treatment processes (e.g., SODIS, chlorination).

Chemical treatment methods

In-home treatment to remove chemical contamination of water is less widespread than for microbiological contamination, but becoming more common in areas with severe contamination problems. As is the case for microbiological treatment, the main constraint is not technical – a variety of technologies exist for removing chemical contaminants. The problem is that few are sufficiently affordable, simple and robust enough to be sustainably applied in household in rural and peri-urban settings. The two most important examples are arsenic and fluoride removal (home treatment systems are also available for other contaminants, such as iron and manganese – see 5.2 for more information).

Nirmal: combined household treatment of arsenic and iron in West Bengal

In West Bengal (and elsewhere) arsenic-contaminated groundwater often has a high dissolved iron content. UNICEF and the Government of West Bengal have developed a low-cost household unit to remove both iron and arsenic. The unit is manufactured in local sanitary marts and marketed under the name “Nirmal”, meaning “clean” in Bengali. It costs about $US10 to purchase and US$1 per year to operate.

The iron removal portion of the filter is based on a successful low-cost domestic iron filter from the Indian state of Tripura. A filter candle is produced by local potters, using a process that combines fired clay and rice husks to produce a porous, easily cleaned, carbon-based “clay husk” filter. Following iron removal, arsenic is removed in an activated alumina sachet. The filter body is constructed of ferro-cement using materials and techniques familiar to local masons.

This choice of a technology that removes both iron and arsenic is highly appropriate. A combined filter is more marketable in the affected areas than an arsenic-only filter because iron, unlike arsenic, is a problem that people can see and taste. In addition, removing iron before removing arsenic makes the arsenic portion of the unit much more efficient, and results in longer use of the activated alumina adsorption media.

Eventually, the media must be changed: the local sanitary mart provides replacement sachets and regenerates the spent activated alumina using strong alkalis and acids. The filter designers have devised a unique system for disposing of the arsenic-rich regenerate solution. It is being used by sanitary marts in the production of latrine squatting plates, effectively preventing any possible re-contamination of the environment.

Fluoride removal in India

The Nalgonda process has been adapted for domestic defluoridation in India. Water is treated in a 50-litre bucket fitted with a tap near the bottom. First, alum and bleaching powder are mixed rapidly with raw water in the bucket. Lime solution is then added and stirred rapidly for a few minutes, followed by slow stirring for 10 minutes. The correct alum and lime dose must be determined before treatment and depend primarily on the fluoride and alkalinity level of the raw water. After stirring, the suspension is allowed to settle for at least two hours, and the supernatant is drawn out through the tap into an appropriate storage container. Filtration is recommended, either through a ceramic candle filter or sand bed, to ensure that residual aluminium flocs are removed.

This system is consistently able to produce water with < 1 mg/L fluoride, with raw waters containing up to 20 mg/L fluoride. The use of bleaching powder protects against contamination with pathogens, and the system is inexpensive and easy to implement with locally available materials. Disadvantages include the need for careful stirring and the regular production of sludge waste, which is discarded in a brick-lined pit.
Source: UNICEF/RGNDWM (2002)

5.3.4 Water treatment in emergencies

The safety of water supplies is often compromised during emergency situations. In some cases, water sources and supplies are contaminated. During floods, for example, contaminated surface water pollutes wells and reservoirs. In other cases, water supplies are interrupted and people are forced to use alternative, unsafe sources. Either water supplies are physically damaged (such as during an earthquake) or the emergency situation forces people to flee their homes, away from established water sources and systems. In both cases, contaminated water and the lack of water can – and often do – lead to the outbreak of water- and hygiene-related diseases such as cholera.

While microbiological contamination is by far the most common risk to water supplies in emergencies (and the subject of this section), the threat of chemical contamination also exists. For example, an oil spill can threaten water supplies. In recognition of this, the 2006 update of the WHO GDWQ includes a new section on chemical water quality in emergencies (WHO, 2006 Section 8.6), which serves as a good resource for this type of emergency (and is included in the additional resources at the end of this section).

Through the Core Commitments for Children (included in the UNICEF Emergency Field Handbook, see additional resources at the end of this section)[6], UNICEF is committed to supporting certain programmatic interventions during emergencies, including water supply and, specifically, the treatment of contaminated water. This discussion focuses on water quality, which is only part of an overall package of WES interventions in emergencies. See the key references at the end of this chapter for further resources on WES in emergencies.

There are three stages of water quality treatment interventions for emergencies: planning and preparedness, emergency water treatment immediately after the emergency event and the re-establishment of treatment systems after the event.

Table 5.8 Water treatment in emergencies

Time period	Possible water treatment interventions
Before event	o preparedness and planning o definition of roles and responsibilities o stockpiling of chemicals, containers and instructional material o vulnerability analysis and improved protection of water systems (e.g., higher headwalls on wells in flood-prone areas, well deepening in drought-prone areas)
Immediately after event	o distribution of purification tablets/sachets o distribution of clean water (water trucking, bottled water distribution) o communication and instruction
Three days to one week after the event until the situation has returned to normal	o repair of existing water treatment facilities in communities/towns/cities o supply of treatment consumables for municipal and camp systems (usually aluminium sulphate for coagulation/flocculation systems, and chlorine) o installation and operation of new water treatment facilities in refugee and displaced people's camps o promotion of alternative home/community water treatment options

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[6] The Core Commitments for Children for water, sanitation and hygiene will be revised in 2008.

Techniques for emergency treatment of household/personal water supplies

All techniques for home water treatment discussed in 5.3.3 can be applied in emergencies, depending on the situation and the stage of the emergency intervention. When possible, it is always better to accelerate or expand ongoing programmes than introduce a totally new treatment technique. In areas with an ongoing SODIS programme, for example, the most effective intervention may be a special intensive campaign using existing promotional material.

When people are displaced due to emergencies, water containers for transporting and storing water are as much a necessity as treatment. In response UNICEF has developed the Basic Family Water Kit which includes buckets, collapsible storage containers, soap, chlorine tablets and/or coagulation/chlorination sachets. Oxfam distributes a similar kit, while WHO has developed a Hygiene in Emergencies kit.

The five most common household/personal treatment techniques used in emergencies are described below.

Chlorine tablets: Chlorination using manufactured tablets is the most common emergency water treatment technique for small volumes of water. A variety of brands, compositions and sizes of tablets are available for use by aid agencies in emergencies. The most common formulation is sodium dichloroisocyanurate (NaDCC) as the chlorine donor in an effervescent formulation for rapid dissolving. Several factors should be considered by planners before purchasing and distributing tablets:

- the tablets procured should be sized so that only one is needed to purify water in standard locally available containers (such as a 20 l jerry can)
- tablets should not be distributed without instructions, including both written instructions in the local language and additional communication material (such as pictographs or radio messages) to reach illiterate people and reinforce the written instructions
- if possible, tablets should be visibly distinct (larger, a distinct colour) from common pills in that country to avoid situations where people take chlorine tablets orally, thinking they are medicine.

Bleach/chlorine powder: Powdered forms of chlorine are also commonly used, both for treating containers of water and for disinfecting family wells and cisterns. The advantage of powdered chlorine is that it is available almost everywhere. The main disadvantage is that it must be measured correctly and mistakes are therefore more likely than with tablets. Different brands of bleaching powder can have different chlorine concentrations, making it difficult to design standard instructional messages. In addition, some bleaching powder contains soap or other additives making it inappropriate for water treatment. Relatively clear water is necessary for the effective use of either chlorine powder or tablets, and in some cases it is necessary to filter water (through cloth, for example) to reduce turbidity before using chlorine.

Combined coagulation, precipitation and chlorination: As discussed in 5.3.3, this method has the important advantage of being effective in purifying poor quality, turbid water, which is common in emergency situations. Some products use a time-release form of chlorine to increase residual disinfection. The same criteria for effectively using chlorine tablets apply to these products (i.e., sizing as per local containers, provision of instructional material). And because this method always requires the extra step of removing the precipitate from the treated water (filtration through a cloth, or by decantation) additional instructions are required.

Microfiltration: Membrane microfiltration products are widely used in recreation (camping, hiking) and increasingly in emergency situations. The technology has two main advantages: it requires no consumables and can remove some pesticides and heavy metals in addition to microbiological pathogens. Due to its relatively high cost (compared to chlorine tablets), microfiltration is still used mainly by emergency workers themselves and not commonly distributed on a large scale. Costs are falling however, and some companies are beginning to manufacture products designed for distribution in emergency situations in developing countries.

Boiling: While boiling is often not viable option due to the lack of fuel and/or receptacles, there are emergency situations in which boiling is appropriate. One common example is in urban areas where piped water supplies have been compromised and no alternative treatment alternative exists. In such situations, a boil water advisory is issued by the relevant authorities over appropriate media channels. The new section 7.6 in the WHO DWQG "Identifying local actions in response to microbial water quality problems and emergencies" discussed criteria, protocols and methodologies concerning boil water advisories in detail (see additional references at the end of this section).

Emergency water treatment products*

Product	**Supplier**
Chlorine tablets	Aquatab, manufactured by Medentech: www.medentech.com Oasis, by HydraChem: www.hydrachem.co.uk/oasis.html
Coagulation/ chlorination sachets	Chlor-Floc, by WaterMaker: www.watermakerusa.com PuR by Proctor and Gamble: available through UNICEF www.supply.unicef.dk/catalogue/
Microfiltration	Nerox by Plastec/Scan-Water: www.scan-water.com/products/nerox/

*This list does not constitute an endorsement of the companies or products**.**

First steps for managing cholera and shigella outbreaks

In emergency situations, large numbers of people may be crowded together in areas that previously had little water and sanitation infrastructure. This leads to a serious risk of an epidemic of diarrhoeal disease. Cholera and shigella are particularly dangerous: these two diseases swept through refugee camps in Goma, Democratic Republic of the Congo in 1994, causing at least 48,000 cases and 23,800 deaths.

The WHO leaflet, “First steps for managing an outbreak of acute diarrhoea” provides specific information on cholera and shigella, including detailed symptoms, strategies for protecting communities from further infection and treatment options for patients. It and other resources on cholera are available online at: www.who.int/csr/disease/cholera/en

A special technique for responding to cholera emergencies is the use of lime juice as a disinfectant. Adding lime juice to water lowers pH levels and can effectively inactivate *Vibrio cholerae.* If pH levels are lowered below 4.5 for at least 3 hours, virtually all the cholera bacteria will be eliminated. To achieve this pH reduction, lime juice should be added to water at a concentration of at least 1 percent. A study in Guinea Bissau showed that adding lime juice to foods such as porridge can also effectively control cholera transmissions (Rodrigues et al., 2000).

As discussed in 5.1, cloth filtration can also be used to help reduce the transmission of cholera.

Techniques for the treatment of water in camps

It is better to use a safe and protected source of water for refugee and displaced people camp systems than to install and operate a water treatment system. If there is a choice, camps should be located near a safe source – such as a deep tubewell – or a new protected source should be constructed. However, in many cases this is not possible: camps need to be set up quickly and unprotected surface sources are often the only viable option. In such cases, treatment to improve the microbiological quality of water is always necessary.

The design of water treatment systems for camps varies, based on many factors, including water source quality, camp size, locally available resources (human and material) and expected lifespan of the camp. But all systems have two things in common: they should be fast and easy to set up and should have low maintenance and operation requirements. Camps must sometimes be set up in two or three days, and are often located in remote locations – treatment systems must be designed accordingly.

Treatment systems in camps usually involve the reduction of suspended solids through sedimentation, coagulation/flocculation or some multi-stage filtration process. In most cases, pre-treated water is then chlorinated. In some instances, treatment for chemical contamination is required, but this is a relatively rare occurrence in camps.

Sedimentation: In emergency situations, sedimentation alone for the removal of suspended solids is usually only used as a temporary measure until a more permanent system can be set up. While sedimentation can effectively remove most suspended solids, it requires either large holding tanks to allow water to sit over relatively long periods of time and/or specially designed horizontal flow sedimentation tanks – both of which are typically not an option in camp settings. Sedimentation is more commonly used as part of a larger system: either as a pre-treatment measure to remove coarse solids or to remove flocs after coagulation/flocculation.

Coagulation/flocculation: This method is the most commonly used for the removal of suspended solids in emergency situations because it can be set up very quickly, and because of the wide availability of aluminium sulphate (alum) in developing countries. In many emergency situations, a batch method is used because it is easier to manage than a continuous flow method.

Filtration: Filtration is used as pre-treatment of water supplies to remove larger particulate matter (roughing filters) and to remove flocs after coagulation/flocculation. Slow sand filtration systems are sometimes used instead of coagulation and flocculation in emergency situations, especially in long-term camps and in areas where a regular supply of alum is unavailable.

Chlorination: Chlorination is recommended in most camp situations. Even when the source is safe, the large population density in camps significantly increases the risk of re-contamination and the residual protection that chlorine provides is a necessity. As is the case for coagulation/flocculation, chlorination is often carried out on a batch basis. In camps that rely on hand-dug wells, pot chlorination units can be used to improve water safety.

All water treatment systems require skilled technicians for operation and maintenance and special health and safety equipment for chemical handling, especially for chlorine. In most countries, there are technicians available who are familiar with the treatment processes used in camps.

In most cases, water treatment systems in camps are set up using pre-manufactured kits that are assembled on site. In developing countries, the kits developed by Oxfam and by ICRC are the most commonly used. The kits are manufactured by several different companies and other agencies – including UNICEF – use these or similar kits on a regular basis. Turn-key water purification units that require no assembly are also used extensively in emergency situations. These units are usually trailer mounted and require a power source. See the key references for more detailed supply procurement information and listings.

Standards for water quality in emergencies

The Sphere Humanitarian Charter and Minimum Standards in Disaster Response is a joint effort by a group of humanitarian NGOs (with support and inputs from many agencies, including UNICEF) to improve the quality and accountability of emergency interventions. Standards have been defined for water and sanitation, food, shelter and health. The standard for water quality from the 2004 edition of the Sphere Handbook is reproduced below. The full water and sanitation and other sector standards are available at the Sphere website: www.sphereproject.org

Water quality standard: Water is palatable, and of sufficient quality to be drunk and used for personal and domestic hygiene without causing significant risk to health.

Water quality indicators
(see Sphere handbooks for guidance notes on each of these indicators)

- a sanitary survey indicates a low risk of faecal contamination
- there are no faecal coliforms per 100ml at the point of delivery*
- people drink water from a protected or treated source in preference to other readily available water sources
- steps are taken to minimize post-delivery contamination
- for piped water supplies, or for all water supplies at times of risk or presence of diarrhoea epidemic, water is treated with a disinfectant so that there is a free chlorine residual at the tap of 0.5 mg per litre and turbidity is below 5 NTU
- no negative health effect is detected due to short-term use of water contaminated by chemical (including carry-over of treatment chemicals) or radiological sources, and assessment shows no significant probability of such an effect.

*The 2000 version of the Standards allowed 10 faecal coliforms per 100 ml, changed to 0 in the 2004 edition.

For water quality standards in emergencies UNICEF is guided by national water quality standards, the Sphere standards and the Core Commitments for Children (CCCs) in Emergencies (see reference below). While the CCCs do not specify water quality standards per se, they do indicate that water should be safe and that purification technologies should be employed in emergencies.

Additional resources on water treatment in emergencies

House, S. and B. Reed (2004). Emergency Water Sources: Guidelines for selection and treatment. Third edition. Loughborough: WEDC.
www.lboro.ac.uk/departments/cv/wedc/publications/ews.htm

Oxfam manuals and guidelines on water quality in emergencies, including:

Coagulation and disinfection manual; Water filtration manual; Water treatment guidelines; and Water quality analysis in emergency situations. All available at: www.oxfam.org.uk/resources/papers/emergency.html

Sphere Project (2004). Sphere Humanitarian Charter and Minimum Standards in Disaster Response. Geneva: Sphere Project. www.sphereproject.org

UNICEF (2005). Emergency Field Handbook: A guide for UNICEF staff. New York: UNICEF. (includes the Core Commitments for Children in Emergencies) http://www.unicef.org/publications/files/UNICEF_EFH_2005.pdf

UNICEF supply catalogue. www.supply.unicef.dk/Catalogue/

WHO (2005b). WHO Technical notes for emergencies. Geneva: WHO. http://www.who.int/water_sanitation_health/hygiene/envsan/technotes/en/ (written by WEDC, see especially titles on well disinfection, point-of-use treatment, chlorine residual calculations and safe water tankering)

WHO (2006). Guidelines for Drinking-Water Quality. Third edition incorporating first addendum. Vol. 1, Recommendations. Geneva: WHO. www.who.int/water_sanitation_health/dwq/guidelines/en (see new sections 7.6 “Identifying local actions in response to microbial water quality problems and emergencies” and 8.6 “Identifying local actions in response to chemical water quality problems and emergencies”)

Wisner, B. and J. Adams, eds. (2002). Environmental health in emergencies and disasters: A practical guide. Geneva: WHO. www.who.int/water_sanitation_health/hygiene/emergencies

5.4 Key resources

CDC (2001). Safe Water Systems Manual. Atlanta: Centers for Disease Control. www.cdc.gov/safewater

IRC (2002). Small community water supplies. Technical paper no. 40. The Hague: IRC International Water and Sanitation Centre.

LeChevallier, M.W. & Au, K.-K (2004). Water treatment and pathogen control: Process efficiency in achieving safe drinking water. Geneva, World Health Organization. www.who.int/water_sanitation_health/dwq/9241562552/en/

Sobsey, M. (2002). Managing water in the home: accelerated health gains from improved water supply. WHO WHO/SDE/WSH/02.07 www.who.int/water_sanitation_health/dwq/wsh0207/en

UNICEF (1999). Water, Environment and Sanitation Guidelines: Water Handbook. New York: UNICEF. www.unicef.org/wes/Wat_e.pdf

(see also online resource listings for household water treatment in section 5.3.3 and on water treatment in emergencies in section 5.3.4).

Chapter 6
Raising Awareness and Building Capacity

Water quality is often a much lower national priority than water coverage. This is especially the case in countries where coverage levels are low, but it is sometimes common in high-coverage countries as well. The focus on coverage has been echoed and reinforced to a large extent by the international community. Programmes of support continue to emphasize coverage over quality, and global coverage figures do not yet take into account the water quality aspect (although this is changing – the UNICEF/WHO Joint Monitoring Programme for Water Supply and Sanitation is currently developing methodologies for the inclusion of water quality data in coverage figures: see JMP, 2008).

This situation is a largely a reflection of the public's low level of awareness of water quality issues. People usually do not demand improved quality, they demand increased coverage and improved service levels – and governments respond accordingly.

Low priority results in poor capacity. In many countries, water monitoring and surveillance systems are weak and sectoral professionals with water quality expertise are relatively rare. Consequently, even widespread water quality problems go unnoticed until the public health system begins to register large numbers of water-related disease cases and deaths. Programming for water quality tends to be reactive – responding to serious problems as they occur rather than focusing on safety and prevention.

The situation is beginning to change. Awareness in communities is increasing in some countries as sources become polluted due to population pressure, intensive agriculture and industrialization. In other countries, especially where coverage is high, additional resources are now being allocated to water quality. In an increasing number of countries, UNICEF programming in the area of water is shifting away from water supply and towards water quality. In addition, the arsenic situation in Asia and elsewhere has highlighted the importance of water quality and resulted in higher awareness among decision-makers in governments and the international sectoral community.
However, because awareness levels continue to be low in most countries, action is necessary to avoid the emergence of more serious water quality problems. UNICEF can play an important role in highlighting the importance of water quality at the national and community levels, contribute to the creation of an enabling policy environment for water quality programming and help to build capacity to strengthen national surveillance and protection systems.

6.1 Advocating for water quality

At the country level, UNICEF is often the most respected external support agency in the water and sanitation sector, due to its long-term programmes of support and continuous presence. UNICEF country offices have an extensive range of contacts at all levels of governments and with civil society organizations and other sectoral stakeholders. Given the increasing importance of water quality, this unique position should be used for raising awareness and promoting action on water quality issues.

Advocacy with governments and other partners is an increasingly important part of UNICEF programmes, in WES and in other sectors. Even though UNICEF often has a prominent role in the water and sanitation sector, its financial resources are typically only a small fraction of those of governments and of development banks and some bilateral agencies. Leveraging the resources of other stakeholders and influencing sectoral allocations is becoming a key role for UNICEF country offices.

Table 6.1 WES budget comparisons: UNICEF and governments

Average Annual UNICEF WES Budget (2001)	US$ 1.9 million
Average Annual Government WES Budget (2001)	US $ 45.3 million

Source: 2001 Regional Analysis

A common concern in UNICEF country offices is that WES professionals work full time (or more!) on implementation, planning, fundraising and other activities and do not have time to focus on advocacy. Prioritizing advocacy within WES sections and country offices, and including advocacy as a specific activity in workplans is the first step towards improving water quality advocacy efforts.

The most effective advocacy is evidence-based, and thus advocacy begins with information gathering (see Table 6.2). In the area of water quality, surveys are often the first step. A rapid assessment (3.1.1) or new data from improved national monitoring systems (S 3.1.2) can form the evidence basis for a water quality advocacy programme. The UNICEF situation analysis exercise is an opportunity for launching a special water quality survey in partnership with government. The act of gathering data can itself be a form of advocacy if carried out in coordination with government and other partners, or as part of multi-agency assessment and coordination frameworks, such as the United Nations Common Country Assessment process, the Poverty Reduction Strategy Paper and Sector-Wide Approaches processes.

Table 6.2 Information sources for water quality advocacy

In-country	*Globally/Regionally*
o data from water quality monitoring systems o data from health monitoring and disease reporting systems on water-related diseases o water and sanitation coverage data o MICS/DHS data on diarrhoea incidence and on faeces disposal practices o sanitary inspection reports o rapid assessment and other water quality surveys o applicable mission reports o KAPs in focus areas related to water quality o evaluation and progress reports on water quality-related programmes	o global/regional data on water quality o WHO Guidelines on Water Quality (and other standard water quality reference texts referred to in this handbook) o progress and evaluation reports on applicable water quality projects from other UNICEF country offices o media articles on water quality impact in other countries o best practices / guidelines on programme design for specific water quality issues (e.g., United Nations Synthesis Report on Arsenic in Drinking Water)

Advocacy for new approaches to water quality programming is more effective when results from field work can be demonstrated. Pilot projects are thus an important part of advocacy. Implementation of the pilot project is only the first step. Assessment, documentation and presentation of results are also important steps – there is no point in implementing a pilot project if results are not disseminated and used to inform policies and practices.

A key component of evidence-based advocacy in the area of water quality is information from other countries. Because of the large number and wide geographic spread of UNICEF WES programmes worldwide, UNICEF country offices are in a unique position to disseminate lessons learned from other countries. The spread of the H_2S system for bacteriological water quality monitoring (see 3.2.1) from India to other countries is one example of this sort of information dissemination. Another example is transfer of knowledge in the area of arsenic mitigation (see box).

Evidence, advocacy, action: arsenic in Vietnam

As the extent of the arsenic contamination problem in Bangladesh and India became clearer in the 1990s, UNICEF and its partners began to investigate the possibility of the presence of arsenic in other regions with similar hydrology and geochemistry. In Vietnam, UNICEF sponsored arsenic testing in Hanoi and other areas in the Red River delta region that confirmed the arsenic in groundwater at levels higher than the national standard. Based on this evidence, and using lessons learned from other countries, UNICEF launched an information sharing and advocacy programme with key government ministries and agencies. The programme used a variety of methods, including publishing an information brochure, raising the subject during regular sectoral coordination meetings and sponsoring visits of government officials to other arsenic-affected countries.

UNICEF also supported two national arsenic conferences in Vietnam, which led to the development and ratification of a national action plan and the formation of a national arsenic coordination committee. Arsenic-related activities are now incorporated into sectoral ministry plans of action, and a coordinated and comprehensive mitigation programme is in place to address the problem (with continued support from UNICEF and partners).

Effective advocacy requires planning. Planning includes the definition of specific advocacy goals (e.g., policy change, increased budgets, staffing), the identification of targets (e.g., high level government officials, sectoral managers, professional associations), the types of information to be presented and the means of dissemination (e.g., print materials for different audiences, effective use of the media, sponsoring national seminars, developing presentations for use at high-level meetings).

UNICEF can also play a role in helping to ensure that data from water quality monitoring and surveillance systems are used as the basis for improvements in water supply system management and programming. UNICEF can help, through advocacy and support to planning processes, that resources are available to support follow-up efforts. If new policies need to be formulated, for example, UNICEF can support the development process. If advocacy leads to new methodologies or implementation systems, UNICEF or its partners can contribute to necessary institutional capacity building.

6.2 Institutional capacity building

Effective and sustainable water safety is best achieved through a preventive management approach that monitors and protects water resources throughout the entire water chain, from catchment and source to end user. This requires the involvement and collaboration of multiple agencies, each working within its own geographic or thematic jurisdiction. A municipal water company, for example, cannot control upstream water pollution without the involvement of other agencies; nor can a ministry of health on its own define and control manufacturing standards of products such as handpumps.

Capacity building for water quality starts with the identification of institutional stakeholders, and an assessment of their current ability to meet roles and responsibilities. This process can be part of the development of a water safety plan (see box in 4.4). Inputs and support to institutions may involve training and professional development, but should focus on the development of sustainable systems within institutions and practical collaboration mechanisms between institutions.

Table 6.3 Institutional stakeholders in water quality

Surveillance, policy development and oversight

- Public health authorities (ministries of health, health boards)
- Water management authorities and bodies (ministries of water, water boards, public health engineering agencies, sectoral coordination groups)
- Environmental management authorities (ministries of the environment, river basin and catchment authorities, land-use policy development authorities)
- Local government authorities (decentralized governing bodies, ministries of local government, community water and health committees)
- Testing and reference laboratories (government and private)
- Rural development agencies (ministries of rural development, extension agencies)
- Disaster management and coordination agencies
- Certification agencies (product certification, laboratory certification)
- Consumer advocacy groups

Water supply and service providers

- Water supply agencies and companies (e.g., municipal water system companies and boards, community water system management agencies and committees, rural and peri-urban water supply programmes, borehole drilling companies, private well diggers)
- Water vendors (direct sales to consumers)
- Manufacturers and manufacturing associations (e.g., of pipes and fittings, hand pumps, drilling rigs, laboratory equipment)
- Civil society service providers (e.g., NGOs, faith-based organizations)

In some cases, institutional capacity building will only be successful if linked to sector reform. In some countries, for example, the bulk of water supply activities are carried out by the private sector but state water supply agencies have yet to make the transition from being service providers themselves to a role of monitoring and supervision. In other countries, decentralization of water supply activities is underway but central government agencies do not yet have the institutional structure to facilitate the trend. In such cases, directing capacity building efforts towards the strengthening of new institutional systems in support of sectoral reform will have a significant impact.

Capacity building is an ongoing process and is sustainable only when national and local institutions are available for providing training and institutional development services for water agencies. The resources of external support agencies like UNICEF can be more effective when working with and strengthening these institutions (e.g., universities and colleges, research institutes, professional societies, private training centres).

Sectoral training programmes do not always include water quality, and even when they do it is often only a minor component. An important part of designing or influencing national water safety programmes is ensuring that water quality is fully embedded in standard sectoral curricula and that separate water quality-specific courses are available for students and sector professionals. Training course subject areas include risk assessment and management, water quality guidelines and standards, health-based planning for water safety, sanitation and hygiene promotion, monitoring and surveillance, groundwater and surface water quality, research skills and techniques, water treatment (including appropriate low-cost remediation technologies), treatment of effluents and water policy development.

Training resources for water quality are available from the academic community and through a variety of sectoral agencies and resources, including the United Nations (see box).

Water quality capacity building resources from UN agencies

UNICEF (www.unicef.org/wes)

- o publishes this handbook, the WES technical guidelines series (manuals on water, sanitation and hygiene)
- o makes use of its extensive network of country programmes to promote information sharing, notably through the India Country Office Information Learning Exchange programme (which includes water quality components)

UNEP GEMS - Global Environment Monitoring System (www.gemswater.org)

- o sponsors training programmes oriented toward assisting developing countries, including courses on initiating and managing water quality monitoring programmes and on surface and groundwater quality (including services for the evaluation and auditing of national water quality monitoring programmes)

UNESCO (www.unesco.org/water)

- o maintains a list of online water quality resources on its website

WHO (http://www.who.int/water_sanitation_health/en/)

- o publishes the DWQG and other key water quality references and makes them available through its website and Water, Sanitation and Health Electronic Library CD ROM
- o publishes training materials for the drinking-water quality guidelines

6.3 Raising awareness and creating demand in communities

People have a right to know about the quality status of their water supplies: whether or not their drinking water is contaminated and what effect that has on their health and the health of their families. People also have a right to know about what solutions are available to improve water quality. As a rights-based organization, UNICEF has a responsibility to ensure that the right to knowledge is respected in the area of water quality.

Safe water is a basic human right

Two core human rights treaties have explicitly recognized the right to water: the Convention on the Rights of the Child and the Convention on the Elimination of All Forms of Discrimination Against Women. The latter also recognizes the importance of sanitation. In both cases, the right to water was affirmed as a prerequisite for the realization of child and human rights to health and adequate living conditions. In 2002, the United Nations formally declared access to domestic water supply service a human right in and of itself, through the Committee on Economic, Social and Cultural Rights.

Convention on the Elimination of All Forms of Discrimination Against Women, 1979, Article 14 states that women have the right to “adequate living conditions, particularly in relation to housing, sanitation, electricity and water supply, transport and communication.”

Convention on the Rights of the Child, 1989, Article 24 notes that states should take steps to ensure the realization of a child’s right to health, including “to combat disease and malnutrition ... through the provision of adequate nutritious foods and clean drinking water, taking into consideration the dangers and risks of environmental pollution.”

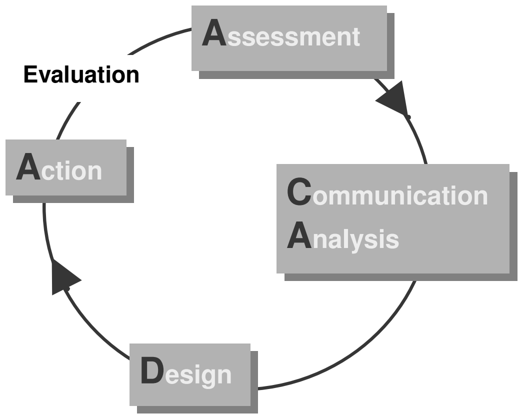
The United Nations Committee on Economic, Social and Cultural Rights, General Comment 15, 2002 affirms that “the human right to water entitles everyone to sufficient, safe, acceptable, physically accessible and affordable water for personal and domestic uses” and that “the human right to water is indispensable for leading a life in human dignity” and that it is “a prerequisite for the realization of other human rights.”

A right to know goes beyond gaining awareness about the problem and possible solutions to the problem. People should also be informed of the responsibilities of duty-bearers in governments, water service providers and the community to ensure domestic water safety. When families and communities are aware of the problem, the solution and the responsibilities they and others have to keep water safe, they can more effectively take action. Knowledgeable communities are also more likely to demand improved service from providers such as water companies or contractors and to challenge politicians and government officials when there are water quality problems in the community. This can sometimes lead to resistance to awareness-raising programmes of this nature.

Awareness-raising for water quality begins with hygiene and sanitation promotion. In developing countries the most serious water quality problem is faecal contamination, and the most effective way of protecting water sources and interrupting the faecal-oral cycle is through hygiene and sanitation. The challenge is not only to inform people about the links between sanitation and health, faecal contamination pathways and remedial measures, but to promote behavioural change and safe hygiene practices. See 4.2 and the UNICEF sanitation and hygiene promotion manuals for more information on hygiene and sanitation promotion.

In addition to hygiene and sanitation promotion, awareness-raising programmes are used as a starting point for community-based water quality surveillance programmes (see 3.1.3), to promote service upgrades to improve water safety and, in areas with specific water quality problems such as fluoride or iron, to sensitize communities about the problem and present solutions.

Figure 6.1 The ACADA communication planning model

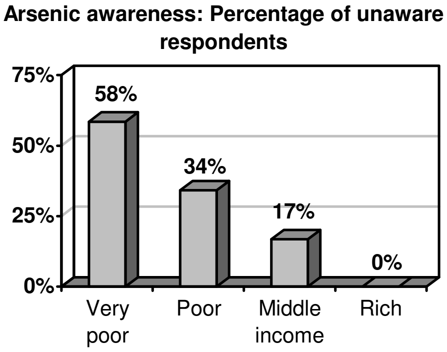


In all cases, awareness-raising and demand-creation campaigns should be carefully designed and planned. They should be based on the best available information and new research on the issue and on the target communities themselves. UNICEF communication programmes use the ACADA communication planning model, an extension of the Triple-A approach (assessment, analysis, action).

The ACADA process begins with a situation assessment using existing and new information sources, including knowledge, attitudes and practices (KAP) studies, special surveys, monitoring and evaluation reports. The situation assessment must ensure that marginalized groups within the community – including women, children and the poor – are taken into account through the collection of disaggregated data. In the case of water quality, the assessment includes best available knowledge of the extent of the water quality problem and its effect on communities. When the assessment is completed a detailed communication analysis is formulated – which clearly defines the problem, analyzes actual practices and desirable behavioural changes, and develops clear communication objectives and strategies. The communication analysis is the basis for the design of the communication campaign itself: the development of messages and choices of media and methodologies. The campaign material is developed, field tested, modified as necessary and launched. See the UNICEF *Manual on Communication for Water Supply and Environmental Sanitation Programmes* for detailed instruction on the ACADA process and communication programming.

For water quality communication, messages will include advice and instruction on what steps the community should take to mitigate water quality problems. In the case of emerging or poorly understood problems, technical advice from specialists and agreement among national stakeholders will be necessary before messages can be formulated. In the development of the UNICEF-supported Bangladesh arsenic communication campaign, for example, a special consultation process was used to develop a set of agreed technical parameters before messages on arsenic mitigation were finalized.

Figure 6.2 Community awareness-raising: the importance of reaching the poor



The results of a UNICEF 2002 survey in rural Bangladesh showed that a much larger percentage of poor people were unaware of arsenic contamination than middle income and rich people.

Communication programmes must ensure that methods, means and messages chosen in the campaign reach poor people.

Source: UNICEF Bangladesh Country Office

A primary goal of water quality communication programmes is demand creation – not only for improved services from government and other service providers as discussed above, but for new services and products purchased by community members themselves. This may be a new or improved community-financed water system, a safer water source, a more accessible water testing facility or service, improved storage and handling containers or home water treatment systems. Successful communication programmes promoting such products or services must ensure that they are available and affordable, and that there is a range of appropriate options from which to choose based on income, willingness to pay and personal preference.

Reaching out to women in particular should be a central part of community awareness-raising programmes. In many communities, household water is managed exclusively by women. Women and girls are generally the ones who obtain water for the home, transport it, store it and then use it for various household purposes. Women are also the primary guardians of household hygiene. It is therefore essential to direct communication messages at women. But effective-awareness raising programmes go beyond simply targeting women with messages, they also enlist women as allies and support women as advocates for water safety within their households and communities.

6.4 Community capacity building

Awareness-raising in communities is the first step in a process of change. Informed and motivated individuals will begin to make the changes necessary to improve the water quality status of their homes and community, but additional knowledge and tools are necessary to improve the community's capacity to act as their own water quality custodians. While improved government surveillance systems and better practices among water service providers are significant steps, empowered communities are the key to significant and sustainable change.

Training is only part of community capacity building – the strengthening of local management bodies and processes is also an important step. Programmes and agencies working with communities on water quality must first determine the role of existing governance structures, including both formal and traditional bodies. In addition, existing sectoral management systems, such as water supply maintenance committees or community health committees, should be inventoried and assessed. In most cases, an existing structure can be used for water quality management and the creation of a new system can be avoided. (In some countries, each new development programme sets up management structures at the community level – which can become a burden on community members who are busy with their own lives.)

Water quality projects – and WES programmes in general – should promote equality of participation in any new or existing management structure. Marginalized members of the community should be given a voice on these bodies, and women – as household water managers – should have a central role. When these structures are inequitable, the project should encourage change.

Once the management structure has been determined, the extent of local authority over water resources and ownership of water systems should be clarified. Only in some countries do communities have clear title to government-provided water systems; in others, water systems remain the property of central government or their ownership is unclear. The productive use of local water resources by individuals (such as farmers) and the effects of this use on domestic water sources is an important consideration. Although it may be governed by national legislation, it must often be dealt with at the local level as well. Only when these issues are clarified can communities effectively take responsibility for the safety of their own water supplies.

All communities have capacity, knowledge and skills. External support programmes should neither impose new systems or methodologies on communities, nor should they make unilateral decisions about what type of capacity building is required. In all cases, participatory approaches should be used to determine the structure and content of capacity building for water quality. Communities, knowing their own capacity, will be best able to choose – with the assistance of support agencies – what new skills are required to supplement existing resources. Training programmes can be designed accordingly. The use of participatory approaches will ensure that the community has ownership of the process and will be motivated to participate in training programmes and apply new skills. On the other hand, participatory approaches often take longer than top-down pre-designed programmes and UNICEF and other agencies must be flexible enough to allow for this.

Community capacity building for water quality may be an independent initiative, or it may be part of a larger water and sanitation development programme. In any case, training for water quality covers a wide range of subject areas (see Table 6.4), applicable on a case by case basis depending on need, the preference of communities and the structure of the national water supply programme.

Table 6.4 Areas for community training related to water quality

- *sanitation and hygiene*: links between water, sanitation, hygiene and health, environmental sanitation, latrine construction, hygiene promotion
- *source protection*: sanitary inspection and remedial action, contamination pathways, importance of sanitation, physical protection of sources, basic siting rules, micro-watershed management
- *water storage and handling*: importance of hygiene, water storage techniques, protection of rainwater cisterns
- *treatment systems*: available technologies/technology ladders, construction and maintenance of community treatment systems, purchase and management of household treatment systems
- *water surveillance and testing*: H_2S and other inexpensive indicative tests, sampling, availability of outside resources for testing water, structure and functioning of national monitoring programmes
- *rights and legislation*: national water laws, community and individual rights and obligations, water resource protection
- *management*: team building, participatory decision making, community mapping, conflict resolution, negotiating, accounting and book-keeping, reporting, referral systems

Community capacity building is an ongoing process. Programmes of support in the area of water quality must be designed to ensure that in-country resources for supporting communities are available on a continuous basis. UNICEF programmes should therefore not only direct resources towards communities themselves, but should strengthen appropriate institutions such as NGOs and rural training institutes as service providers for capacity building.

6.5 Key resources

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(see especially sections 7.6 and 8.6)

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