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DRINKING WATER IN DEVELOPING COUNTRIES

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ABSTRACT

Safe drinking water remains inaccessible for about 1.1 billion people in the world, and the hourly toll from biological contamination of drinking water is 400 deaths of children (below age 5). This paper reviews the general guidelines for drinking water quality and the scale of the global problem. It reviews the various water disinfection technologies that may be applicable to achieve the desired quality of drinking water in developing countries. It then summarizes financing problems that deter extending access to safe drinking water to the unserved population and identifies feasible policy positions for enhancing availability of drinking water in these countries.

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1. DRINKING WATER QUALITY

At any given time, about half the population in the developing world is suffering from one or more of the six main diseases associated with water supply and sanitation (1. Diarrhea—caused by a number of microbial and viral pathogens in food and water; 2. *Ascaris*, 3. *Dracunculisis*, 4. Hookworm, and 5. *Schistosomiasis*, all by infestation with various worms leading to disability, morbidity and sometimes death; and 6. Trachoma—caused by a bacterium, leading to blindness). About 400 children below age 5 die per hour in the developing world from waterborne diarrheal diseases (1).

Improved longevity, reduced infant mortality, health, productivity, and material well-being are generally recognized as fruits of development. The developing country populations generally have poor ranking on these indices compared to those of industrial countries. Availability of plentiful and safe water for domestic use and adequate sanitation to dispose of waste have long been known to be fundamental to the development process, with benefits, such as labor productivity, spread across all sectors.

Different developing countries define differently what constitutes safe drinking water. Although the World Health Organization (WHO) is the premier and most prestigious international health organization, it does not directly recommend national enforceable water quality standards. Instead, it recommends guidelines for drinking water quality. The first such guidelines were issued in three volumes in 1984–85. In 1993, WHO started publishing the second edition of these documents, which presents modified guidelines in response to comments on the first edition. The revised guidelines reflect a multi-year effort from a substantial number of experts from nearly 40 different countries. The first volume of the 1993 guidelines contains the actual recommended maximum acceptable values for water contaminants, and the second volume, *Health Criteria, and Other Supporting Information*, discusses the detailed reasoning behind the recommendations, for each substance covered in the first volume. The third volume of the revised guidelines was published this year and recommends processes for setting national feasible targets for drinking water quality and methods to safeguard water sources and supplies for small communities in developing countries.

Potable or drinking water is defined as having acceptable quality in terms of its physical, chemical, and bacteriological parameters so that it can be safely used for drinking and cooking. A daily per capita consumption of 2 liters is the generally accepted value for a person weighing 60 kg (2). This is the value used in estimating ingestion exposure to potentially hazardous chemicals in drinking water. The actual water intake, however, varies considerably from individual to individual, and also according to climate, physical activity, and culture.

Water need increases sharply as ambient temperature exceeds 25°C, primarily to make up for moisture loss through perspiration. Infants and children consume more water per unit weight than adults. Where appropriate, WHO guidelines for maximum permissible concentrations include corrections for the higher specific consumption of drinking water by infants and children. A maximum of 8 liters is the expected annual average base daily consumption for drinking and cooking (3). Depending on circumstances, a much larger amount of water could come in contact with skin or cooking utensils daily and must also have minimal contamination.

In its document, WHO cautions, "It must be emphasized that the guideline values recommended are not mandatory limits. In order to define such limits, it is necessary to consider the guideline values in the context of local or national environmental, social, economic, and cultural conditions." WHO further states, "The main reason for not promoting the adoption of international standards for drinking-water quality is the advantage provided by the use of a risk-benefit approach (qualitative or quantitative) to the establishment of national standards and regulations. This approach should lead to standards and regulations that can be readily implemented and enforced. . . . The standards that individual countries will develop can thus be influenced by national priorities and economic factors." In other words, stringent quality standards that are (technically or economically) impractical and thus remain on paper are useless. Implementable standards (even if representing a compromise between economic cost and health risks) are much more useful.

The actual guidelines present maximum acceptable values for a number of contaminants in drinking water. Specific guidelines are presented for acceptable concentrations of (*a*) bacteria, viruses, and parasites; (*b*) chemicals of health significance including specific inorganic and organic constituents, pesticides, disinfectants, and disinfection byproducts; (*c*) radioactive constituents; and (*d*) substances and parameters in drinking water that may give rise to complaints from consumers.

The final section of the WHO guidelines deals with protection and improvement of water quality including selection of water sources, treatment methods, distribution methods, and emergency measures.

1.1 *Biological Contamination*

1.1.1 SIGNIFICANCE

The most common and deadly pollutants in the drinking water in developing countries are of biological origin. WHO states that the "infectious diseases caused by pathogenic bacteria, viruses and protozoa or by parasites are the most common and widespread health risk associated with drinking water." One study (4) using 1986 data estimates that 10 major waterborne diseases are responsible for over 28 billion disease episodes annually in the developing countries. Of these, diarrheal diseases are the big killers. Esrey et al (5) surveyed 142 studies on 6 of the major waterborne diseases and estimated that in developing countries (excluding China), there were 875 million cases of diarrhea and 4.6 million deaths annually in the mid-1980s. According to the World Bank estimate, more than 3 million children below age 5 die annually from diarrheal diseases contracted through drinking water in the developing world (6). The WHO estimate of the toll is more than 5 million deaths annually (of these, about 4 million children are under age 5) from unsafe drinking water (1). Although the quality of data on mortality and morbidity from unsafe drinking water is mixed (the estimates made by different experts of annual global child deaths vary by almost a factor of 2, from 2 to 4 million), the magnitudes of the mortality and morbidity from waterborne diarrheal diseases unquestionably make them the planet's biggest environmental health threat to populations.

In addition, the primary cause for stunted growth for millions of children in the developing world is poor nutrition resulting in part from frequent bouts of diarrhea. Repeated bouts of diarrhea inhibit the ability of the body to absorb nutrition for a much longer period than the duration of the actual diarrheal episodes. Thus, children who survive the risk of dying from diarrheal diseases are at risk of stunting from malnutrition.

There are large economic costs stemming from waterborne diarrheal diseases. These include billions of hours of lost adult productivity annually, and economic and health costs of about 10 million person-years of time and effort annually mostly by women and girls carrying water from distant, often polluted sources. Sickness of the adult breadwinner has a severe impact on the income and nutritional status of children and other family members in poor households (7).

The major factors that reduce the significance and impact of diarrheal diseases in public health are good sanitation, plentiful availability of good quality water, adequate disposal of human and animal excrement, and public education in hygienic practices. Literature suggests that good drinking water quality is a necessary but by no means sufficient condition for elimination of diarrheal diseases as a public health issue.

In fact, in a given situation with poor sanitation and poor-quality drinking water, the beneficial impact of improving only the sanitation will be larger than that of improving only the quality of drinking water (8). Furthermore, the quantity of water used for personal and domestic hygiene has been shown to be more important than the quality of drinking water in its impact on diarrheal incidence (9). This increased use reflects more frequent bathing and thorough washing of hands, more careful washing of food, and greater general domestic cleanliness. As Dr. Haldan Mahler, former director general of the World Health

Organization (WHO), has said, "The number of water taps per 1000 persons is a better indicator of health than the number of hospital beds." (10).

However, improved access to water does not always ensure its improved or better use. Usage patterns may change more or less slowly with improved access depending on the perceived need to use the water for improved sanitation and hygiene, hence the importance of public education in hygienic practices. One recent anthropological study of diarrheal incidence in rural Bolivia reports that only 30% of the respondents associated dirty water with diarrhea, and that many regarded diarrhea as a normal occurrence in childhood (11). This is not unique. Similar lack of knowledge about probable causation and casual attitudes about occurrence of childhood diarrhea are widely prevalent in developing countries.

The pathogens ingested by drinking contaminated water are listed in Table 1. Since the contamination of water supplies (often with raw sewage) is a likely route of spread of each disease, the persistence of the pathogen in water supplies is relevant to how far downstream from the contamination point such waters can cause morbidities and mortalities. As discussed below, exposure to a single pathogenic organism does not always result in infection and disease; several (sometimes several hundred) must be ingested to cause infection, depending on the pathogen in question. Therefore, these parameters are also noted in the table for each pathogen (2). This simple tabulation reveals a large diversity, with pathogenic organisms showing a range of persistence in water, infectious dose, and health significance. The methods to isolate and enumerate the organisms are complex, expensive, time consuming, and specific to each organism. This makes determining and enumerating contamination from specific organisms in water supplies a daunting task beyond the ability of most municipal water-supply authorities.

Waterborne infectious diseases are transmitted primarily through contamination of the water sources with excreta of humans and animals who are either active cases or carriers of the disease. Use of such water for drinking or cooking, contact with it during washing or bathing, or even inhalation of its fine droplets as aerosols, may then result in infection.

The minimum infectious dose (the smallest number of ingested pathogens necessary to cause disease) for the average healthy adult varies widely for various microorganisms. This dose ranges from just a few organisms for *Salmonella typhi* (to produce typhoid), several hundred organisms for *Shigella flexneri* (to cause dysentery), several million cells of *Salmonella* serotype needed to cause gastroenteritis, to as many as a hundred million cells of *Vibrio cholerae* needed to produce cholera. The minimum infectious dose also varies by the age, health, and nutritional and immunological status of the exposed individual. As WHO notes, "Those at greatest risk of waterborne disease are infants and young children, people who are debilitated or living under unsanitary conditions, the sick,

Table 1 Orally transmitted pathogens in drinking water

Pathogen	Health significance	Persistence in water supplies[a]	Relative infective dose[b]
BACTERIA			
Campylobacter jejuni, C. coli	High	Moderate	Moderate
Pathogenic *Escherichia coli*			
Salmonella typhi	High	Moderate	High[c]
Other *Salmonellae*	High	Long	High
Shigella spp.	High	Short	Moderate
Vibrio cholerae	High	Short	Moderate
Yersinia enterocolitica	High	Long	High (?)
Pseudomonas aeruginosa[d]	Moderate	May multiply	High (?)
Aeromonas spp.	Moderate	May multiply	High (?)
VIRUSES			
Adenoviruses	High	?	Low
Enteroviruses	High	Long	Low
Hepatitis A	High	?	Low
Enterically transmitted non-A, non-B hepatitis virus, hepatitis E	High	?	Low
Norwalk virus	High	?	Low
Rotavirus	High	?	Moderate
Small round viruses	Moderate	?	Low (?)
PROTOZOA			
Entamoeba histolytica	High	Moderate	Low
Giardia intestinalis	High	Moderate	Low
Cryptosporidium parvum	High	Long	Low
HELMINTHES			
Dracunculus medinensis	High	Moderate	Low

Source: World Health Organization (1993).

?—Not known or unclear.

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

[b] Dose required to cause infection in 50% of healthy adult volunteers; may be as little as one infective unit for some viruses.

[c] From experiments with human volunteers.

[d] Main route of infection is by skin contact, but can infect immunosuppressed or cancer patients orally.

and the elderly. For these people, infective doses are significantly lower than for the general adult population" (2). The size of the minimum infectious dose does not directly translate into ease of prevention of the relevant disease (since concentrations of the pathogens in the water are variable, too). However, it does point to the reasonableness of the approach to minimize disease risk by defining a maximum allowable concentration of an indicator organism in drinking water, as discussed below.

1.1.2 INDICATOR ORGANISMS Although methods are now available to enumerate the concentration of various specific bacterial contaminants in water, these methods are commonly complex and time consuming, and hence impractical for routine monitoring of water quality. A more expedient approach is to test for the presence of an indicator bacterial species that would signal fecal contamination. Such an indicator organism must have the following characteristics: It (*a*) must be easily isolated and enumerated, (*b*) must be present in very large numbers in normal fecal matter of humans and other warm-blooded animals (potential carriers of human pathogens), (*c*) must be more resistant to disinfection than the pathogens, (*d*) must not multiply in water, and its persistence in water must be comparable to that of fecal pathogens, and (*e*) must be generally absent from other sources (e.g. vegetable matter, soils, etc) of bacteria coming in contact with water. Thus, the presence of the indicator organism will signal fecal contamination and possible presence of pathogens, and its absence (in pre-treated or post-treatment) water will suggest that the water is probably free of pathogens.

In reality, no organism exactly fits all the above criteria. However, coliform organisms, especially *Escherichia coli*, come very close. Other organisms (e.g. fecal *streptococci, Clostridium perfringens*) also satisfy some of these criteria, although to a lesser extent than general coliforms or *E. coli* (e.g. some of them may have sources other than excreta of warm-blooded animals, others may grow in aquatic environments). *E. coli* is accepted as the indicator organism of choice for fecal contamination of water and for possible presence of fecal pathogens.

Since complete identification of *E. coli* is complex and time consuming, thermotolerant coliform count is often used as a surrogate. Thermotolerant coliform organisms (until recently incorrectly called 'fecal coliforms') are the coliforms that can ferment lactose at 44.0° to 44.5°C, and comprise primarily *E. coli*, and a few strains of other organisms (*Enterobacter, Klebsiella, Citrobacter*). Of these, only *E. coli* is specifically of fecal origin, and found in very large numbers (up to 10^9 organisms per gram) in the excrements of humans, other mammals and birds. Therefore, detection of thermotolerant coliform in raw (or treated) water is considered sufficient to determine its fecal contamination (or inadequacy of water treatment).

Another alternative to counting *E. coli* is to identify and enumerate the total coliform count in the water sample. Total coliforms are broadly characterized by their ability to ferment lactose in culture at 35° to 37°C, and include *E. coli*, *Citrobacter*, *Enterobacter*, and *Klebsiella*. General coliforms can originate not only from feces of warm-blooded animals, but also from vegetable matter and soil. Under certain conditions, coliforms may persist and grow using the available organic carbon from non-metallic components in construction materials. Therefore, presence of small numbers of coliform, particularly in untreated groundwater, may be innocuous and may not indicate presence of fecal contamination.

Although bacterial pathogens are less or comparably resistant to disinfection as the coliform organisms, Enteroviruses and the cysts of some parasites are more resistant. Therefore, the absence of coliforms from disinfected water does not necessarily indicate absence of enteroviruses, and the cysts of *Cryptosporidium*, *Giardia*, amoebae, and other parasites.

1.1.3 TEST METHODS Methods for detection, characterization, and enumeration of various fecal indicator bacteria in water have well-defined national and international standards such as those from the International Standardization Organization (ISO). For the detection of *E. coli*, the two standard methods are the membrane filtration test (defined in ISO 9308-1:1990), and the most probable number, or MPN, test (ISO 9308-2:1990).

In the membrane filtration test, the water sample is filtered through a 0.45-μm cellulose filter supported on a porous or perforated disk by applying negative pressure (or vacuum) to the other side of the disk. This draws the sample through the membrane filter, retaining coliforms and many other bacteria on its surface. The membrane filter is then incubated by placing it, face up, on an appropriate selective medium. Colonies developed on the membrane can be quickly and easily identified (e.g. by their characteristic color), and counted. Subsequent tests can be carried out on the colonies for further species identification and confirmation.

The MPN test is carried out by incubating an appropriate medium in multiple tubes, each inoculated with a water sample (suitably diluted if necessary). Each tube that receives one or more viable organs will show a positive reaction appropriate to that medium. The most probable number of organisms in the water sample is then deduced by counting the number of tubes showing positive and negative reactions, and looking up statistical tables of probability which give confidence limits on the results.

1.1.4 GUIDELINES There is no minimum value for the tolerable level of pathogenic contamination of drinking water. WHO recommends *E. coli* (or as an alternative, thermotolerant coliforms) as the indicator organism of choice for bacterial contamination of drinking water. Thermotolerant coliforms are also recommended as the indicator of choice in assessing the efficiency of water treatment in removing enteric pathogens and fecal bacteria. For water intended for drinking, WHO recommends that *E. coli* or thermotolerant coliforms must not be detectable in any 100-ml sample. In practical terms (as evinced by WHO's examples of performance targets for water treatment plants), this implies that the maximum loading of thermotolerant coliform bacteria in the water intended for drinking must be less than 1 organism per 100 ml. This is consistent with the maximum contaminant level goal (of *E. coli* and thermotolerant coliforms) of zero organisms per 100 ml, and a maximum contaminant level of less than 1 organism per 100 ml, expressed in USEPA's current Final Rules for bacterial quality under National Primary Drinking Water Regulations (3). Both WHO and USEPA recommend regular sampling of treated water supplies, and that not more than 5% of the samples in any 12-month period should test positive for *E. coli* or thermotolerant coliforms.

In providing this guideline, WHO is cognizant of the very large difference between the reality in the rural developing world and the guidelines. WHO adds that in the great majority of rural water supplies in the developing countries, fecal contamination is widespread. Under these conditions, the national surveillance agency should set medium-term targets for the progressive improvement of water supplies, as recommended in WHO's Volume 3 of *Guidelines for Drinking Water Quality* (2).

In fact, the World Bank is even more explicit on this point while commenting on the issue of desirability of residual disinfection imparted to drinking water by residual chlorine on the one hand, and the urgency of getting clean, safe water to households (even without residual protection) on the other. "Contrary to common belief, contamination of water in the home is relatively unimportant. What matters is whether the water coming out of the tap or pump is contaminated. In most developing countries the imperative is to get from "bad" quality (say, more than 1000 fecal coliforms per 100 ml) to "moderate" quality (less than 10 fecal coliforms per 100 ml), not necessarily to meet the stringent quality standards of industrial countries." (6)

Even a single virus particle is sufficient, in principle, to induce disease. However, enumeration of viruses in water samples is significantly more complex, costly, and time consuming than bacterial analysis. Furthermore, information is inadequate regarding the virological, epidemiological, and risk analysis dimensions of viral contamination of water supplies necessary for issuing virological criteria for drinking water. Hence WHO does not directly recommend a minimum viral guideline for drinking water quality. Instead, it recommends various treatment methods for various raw water sources according to their degree of detectable fecal contamination, so as to produce drinking water with negligible virus risk. These methods comprise appropriate combinations of disinfection, filtration, settling, and pre-disinfection or storage.

Similarly, WHO does not set a guideline value for pathogenic protozoa, helminthes, and free-living organisms in drinking water, other than that these agents should not be present in drinking water, because one or very few organisms can induce infection in humans. There are no analytical methods suitable for routine sampling for these pathogens that WHO finds it can recommend. Instead, it notes that the attainment of bacterial criteria and the application of recommended treatment for virological reduction should generally ensure that water has a negligible risk of transmitting parasites.

1.2 *Chemical Contaminants*

Although its guidelines for chemical contaminants are quite comprehensive, WHO cautions that not all chemicals that may be found in drinking water were evaluated in developing the guidelines, only those which were considered by the experts to be important, and known or likely sources of risk. On the other hand, although a large number of chemicals are now covered in the guidelines, WHO also cautions that it is unlikely that all of these chemical contaminants will occur in all water supplies or even in all countries. Therefore, WHO suggests that care should be taken in selecting substances for which national standards will be developed.

WHO based its guidelines for acceptable levels of chemical contaminants on information from human and animal dose-response data, to develop tolerable daily intake values of the contaminants. Appropriate scale factors are used to lower tolerable exposure, accounting for uncertainties owing to interspecies and intraspecies variation, adequacy of data, and the nature and severity of effect. Guideline values for tolerable daily intake (TDI) are based on no observable effect for a lifetime (assumed 70 years) exposure at the TDI concentration of the pollutant. WHO comments that TDIs could be exceeded for short periods of time so long as the individual's long-term average intake does not exceed the guideline value. However, greatly exceeding the TDI for short periods could lead to acute toxic effects.

The derivation of guidelines for potential and known carcinogens took into account the risk grouping made by the International Agency for Research on Cancer (IARC). The guidelines for potential and known carcinogens are set so that there will be no more than a 10^{-5} increased risk of cancer in an average individual drinking such water for 70 years. In other words, the water will produce statistically 1 excess cancer case in a population of 100,000 drinking such water for 70 years.

Among inorganic chemicals and attributes, there are several that have no health-based guideline values because either

1. they pose no significant health risks, or
2. the risk data are inconclusive and insufficient to warrant a guideline, or
3. inordinately small concentrations of the chemical are found in water sources, or

4. objectionable taste or smell develop well before concentrations with health significance are reached.

In this list are the following elements: aluminum, beryllium, iron, dissolved oxygen, silver, sodium, inorganic tin, and uranium; the following compounds or ionic groups: ammonia, asbestos, chloride, compounds producing hardness in water, and sulfate; and the following physical properties of water: pH and total dissolved solids.

Guideline TDI values are set for the following elements: antimony, arsenic, barium, boron, cadmium, chromium, copper, fluorine, lead, manganese, mercury, molybdenum, nickel, selenium, and zinc. Among the compounds and ionic groups, guideline TDI values are set for cyanide, nitrate, and nitrite. Among these, the well-known widespread and significant naturally occurring waterborne toxics are arsenic and fluoride (with guideline maximum concentrations of 10 μg/l, and 1.5 mg/l). Field concentrations in drinking water in severe problem areas reach a few mg/l and tens of mg/l respectively, causing arsenic poisoning (and cancer) and crippling skeletal flurosis, respectively. These two chemicals alone affect on the order of a hundred million persons in developing countries. (For comparison, the fluoride concentrations in municipally fluoridated tap water in the US is about 1 mg/l.)

Among organic contaminants, WHO guidelines address the several toxics that increasingly find their way into drinking water supplies in the developing countries with the spread of modern agribusiness practices (systemic and contact pesticides, acaricides, nematocides, insecticides, pre- and post-emergence herbicides, soil fumigants, weedicides, etc), and chemical, dyestuff and process industries with improper disposal of byproducts, intermediates, solvents, as well as plasticizers and stabilizers in manufacturing synthetic materials. In this list are chlorinated alkanes, chlorinated ethenes, aromatic hydrocarbons, chlorinated benzenes, and 36 specific pesticides. Anecdotal evidence suggests that concentrations of anthropogenic chemical toxics in the drinking water supplies in East Europe and the former Soviet Union are higher (owing to widespread industrial pollution) than those in the rural areas of most developing countries.

1.3 *Other Attributes*

The WHO guidelines also cover attributes affecting acceptability of water by populations for drinking. These attributes, such as color, turbidity, odor, etc, affect acceptability significantly more than health, and are of far lower health significance in the developing countries than the pathogenic microbial contamination of drinking water supply.

The impact of weather events on drinking water quality in developing countries is well documented. In many parts of the developing world, the rainy season washes fecal matter into surface waters, causing an increased level of microbial contamination and outbreaks of diarrheal diseases. Floods and heavy rains cause large runoffs of silt and clay into the catchment areas of municipal water supplies, which overwhelms routine sedimentation and filtration methods. Droughts lead to water scarcity, which leads in turn to a reduction in water use for hygiene and a reduction in drinking water quality, thus raising health risks. If global climate change increases the incidence of extreme weather variability, these impacts will be more severely felt in the coming decades.

2. SCALE OF THE GLOBAL PROBLEM

The international drinking water supply and sanitation decade, declared by the United Nations, ended in 1990 with an additional 1.3 billion people having access to drinking water, but still left about 1.2 billion people without access to safe drinking water (12). Additionally, the decade of advocacy effort successfully put drinking water access and supply on the agenda of many national and international agencies. As mentioned earlier, the quality of detailed national level data on these two topics has been mixed, and one of the basic needs to establish and operate successful water and sanitation program is obtaining reliable data regarding the initial situation and any progress (or its absence). In 1990, WHO and UNICEF pooled resources and experience to form a joint monitoring program (JMP) in water supply and sanitation. The JMP has persuaded and helped many developing countries to design and establish national monitoring operations for drinking water and sanitation. It collects its data from 38 African, 23 Asia-Pacific, 5 West Asian, and 18 Latin American and Caribbean national monitoring centers, and issues regular status reports using 1990 as the baseline year. It is widely considered the best source of global data on water and sanitation access and availability in the developing countries.

Definitions of "access" to safe drinking water differ substantially since they are determined individually by the reporting countries. Walking distance or time from household to water source is the principal criterion, particularly for rural populations. About half of the 84 countries include the quantity of water available in the definition of access. The responses from the JMP survey summarized in Tables 2 and 3 provide a measure of what constitutes access to safe drinking water for most of the developing world (13).

Table 2 Definitions of "Access to Safe Drinking Water Source"

	Number of countries defining access as "water source at a distance of less than..."								
	50 m	100 m	250 m	500 m	1000 m	2000 m	5 min	15 min	30 min
Urban	20	6	3	8	1	—	1	—	1
Rural	10	1	6	17	4	4	—	1	1

Source: World Health Organization (1996b).

Table 3 Definitions of acceptable water quantities for rural areas

Number of countries defining the minimum quantity per person per day as...				
15–20 liters	20 liters	20–30 liters	30–50 liters	>50 liters
1	19	5	10	3

Source: World Health Organization (1996b).

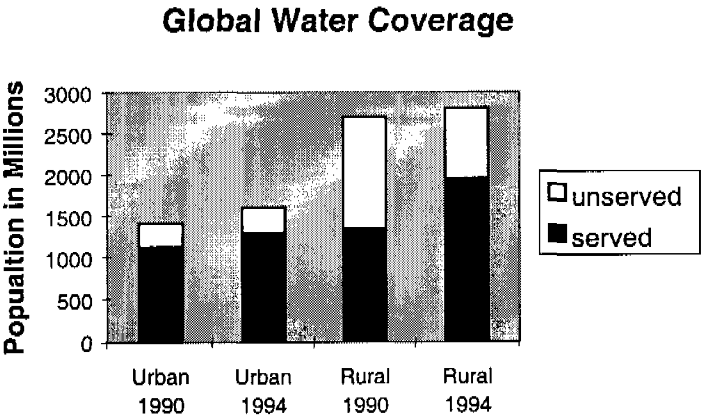
Even with these definitions, about 25% of the developing world's population (1.1 billion people) lacked access to safe drinking water according to these standards in 1994. It should not come as a surprise, then, that UNICEF estimates the effort spent annually in developing countries for fetching water to be 10 million person-years.

For comparison to data summarized in Table 3, populations in industrial countries use from 350 to 850 liters per person per day (3).

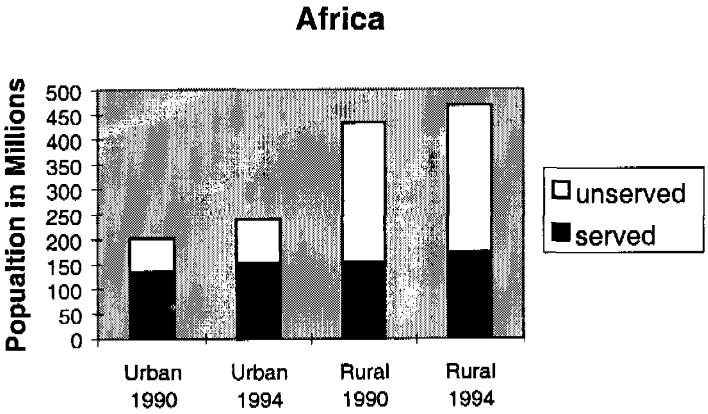
The JMP data and those from earlier years show that the improvements in access to safe water have been impressive in the years 1990–1994 (Figure 1). More than 780 million people gained access to drinking water in that period (an average of about half million per day!). However, the data also show large regional imbalances. Almost all of the gains in improved access have taken place in Asia and the Pacific, where more than 700 million people gained access. In Africa only 38 million gained access, while in Latin America and the Caribbean an additional 30 million people gained access. The greatest progress in water supply access was in the rural areas, where 611 million extra people gained access, raising total rural access rates from 50 to 70%. In urban areas an extra 170 million gained access; however, this was more than offset by the rapid rise in urban population of 205 million, leaving the access rate almost unchanged at 82%. Country-wide data are available from JMP, either through UNICEF or WHO (13).

Note that the investment rate in water supply critically depends on the country's economic health and the revenue generated by the governments, as well as on the political emphasis placed on water supply by the government then in power. Therefore it would be risky to extrapolate the numbers to predict the time when 100% coverage would be achieved for a given region. Also, the population segments that are easy to supply and are politically powerful generally receive water services first, leaving behind the more distant and politically weak ones. Both investments and the political will to make them will be harder to come by for the last of the unserved population segments, slowing the rate of progress toward 100% coverage as countries approach the goal. Lastly, appropriate water supply and management technologies for city slums and distant rural villages are likely to be quite different, and need to be conceptualized differently.

We can expect significant disruptions to local water balance in many places owing to global climate change and resulting weather variability in the coming



Global Water Coverage



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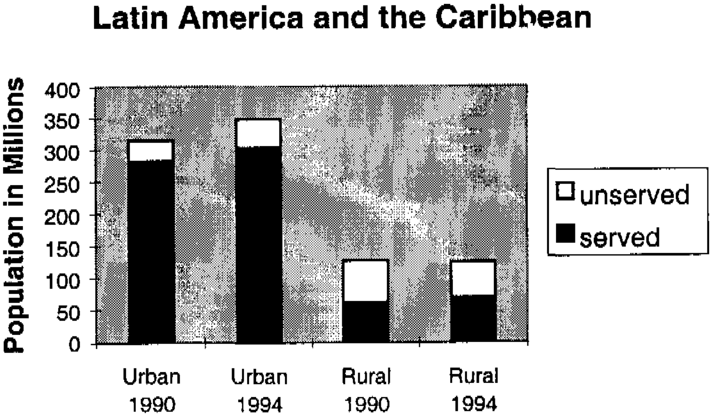

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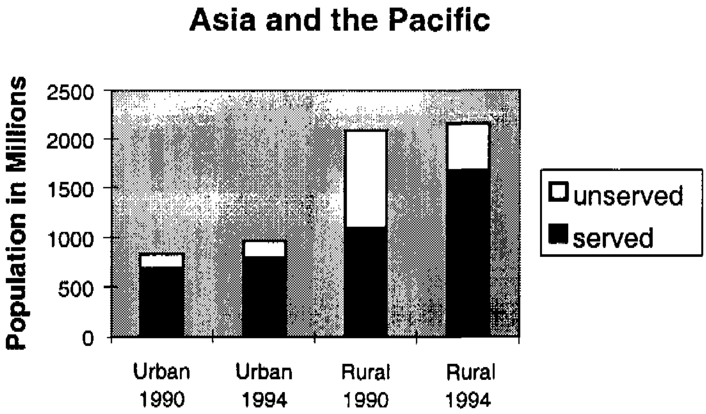

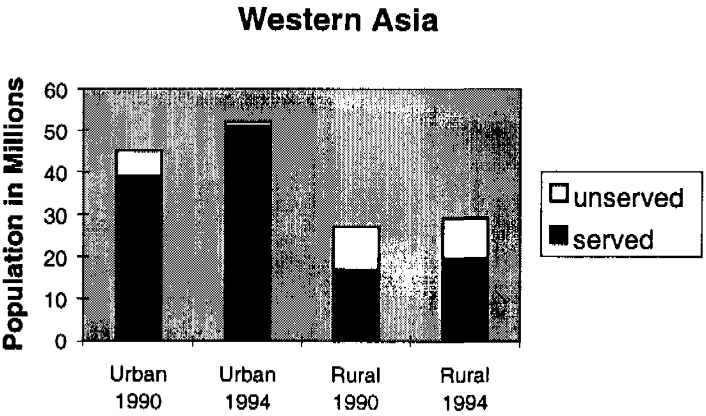

Figure 1 Water coverage in developing countries by region, 1990–1994.

Africa (38 countries): Angola, Benin, Burkina Faso, Burundi, Cape Verde, Central African Republic, Chad, Cote d'Ivoire, Djibouti, Egypt, Equatorial Guinea, Gambia, Ghana, Guinea, Guinea Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Senegal, Sierra Leone, South Africa, Sudan, Swaziland, Togo, Tunisia, Uganda, Zaire, Zambia.

Latin America and the Caribbean (18 countries): Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guyana, Haiti, Honduras, Mexico, Nicaragua, Panama, Peru, Venezuela.

Asia and the Pacific (23 countries): Afghanistan, Bangladesh, Bhutan, China, Micronesia, Fiji, India, Indonesia, Iran, Kiribati, Lao PDR, Maldives, Myanmar, Nepal, Niue, Pakistan, Papua New Guinea, Philippines, Sri Lanka, Tokelau, Tonga, Tuvalu, Vietnam.

Western Asia (5 countries): Iraq, Jordan, Lebanon, Oman, Syria.

decades. This may change the pattern of agricultural runoffs, sedimentation, and erosion, and ground water recharge rates. Already in parts of the developing world the rate of ground water use, especially from intensive agricultural irrigation, far exceeds the rate of ground water recharge. The resulting drop in the ground water table and water scarcity has implications for health and hygiene and drinking water access. In coastal areas, excessive draw on the ground water also implies intrusion of salinity in fresh water aquifers, making well waters too saline for drinking.

In southern Bangladesh and parts of the Indian state of West Bengal, close to a hundred million people obtaining drinking water from shallow tube wells are now exposed to high levels of arsenic. This arsenic is hypothesized to have leached from the local underground geological strata owing to the water table being lowered. The geochemical mechanism of this leaching is not yet understood. However, this recent development (in the last 5 years) has led to widespread arsenic poisoning among the exposed people. WHO experts project that (under the default scenario) arsenic poisoning will account for about 10% of adult deaths in these populations in the coming decades.

3. WATER TREATMENT TECHNOLOGIES

The most important way to obtain safe drinking water for a community is to protect its source from fecal contamination and to sufficiently isolate it from dumping of household garbage, industrial waste, mining and quarrying activities, and agricultural runoffs of fertilizers, herbicides, and pesticides. For the major killers—the fecally transmitted pathogens in drinking water supplies—no disinfection practice is failsafe. Disinfection-resistant pathogen strains exist, and more may emerge in the future. It is therefore recommended to implement multiple barriers to the potential transmission of microbial pathogens in the water supplies. Good sanitation practices and adequate methods to dispose of human and animal excrement are thus first necessities. These establish the first barrier between contaminants such as fecal pathogens and the drinking water source. If surface waters are used as a source, appropriate filtration establishes a second barrier and should be considered wherever feasible. The resulting reduced turbidity generally enhances the effectiveness of all disinfection methods. However, if only one barrier is feasible, it should certainly be disinfection.

The microbiological quality of water should be given priority over the chemical quality of the water whenever a conflict exists between the two, except in cases where unequivocal proven evidence exists that the nature and concentration of chemical contaminants is more harmful to human health than the risk from ingestion of microbial pathogens. This is of particular relevance to the production of trace quantities of potentially harmful disinfection by-products in the water. For this reason, WHO states that "... the risks to health from these by-products are extremely small in comparison with the risks associated with inadequate disinfection, and it is important that disinfection should not be compromised in attempting to control such by-products." Source protection and filtration reduce organic carbon in the water; thus, they also reduce the formation of disinfection by-products if the water is later treated with chlorine.

Recontamination of disinfected (or safe) water owing to poor storage practices or owing to dipping unwashed hands in the stored water can be a problem for a number of disinfection methods that leave no post-treatment residual protection (e.g. boiling, UV treatment, ozonation). A recent innovation successfully introduced into the Bolivian market comprises a 20-liter narrow-mouthed carrying and storage water vessel with a spigot for withdrawing water (14). The same vessel can also be used as the container in which a solution of chlorine bleach is added to disinfect the water in a few hours. The vessel sells for about $6, and the cost of the chlorine solution at the local dealer is about $0.40 per month for a typical local family (R Quick, personal communication).

Storage of surface waters in protected reservoirs or in impoundment lakes leads to considerable improvements in microbiological quality of water through predation, settling of bacteria attached to particulates, starvation, and effect of solar UV in the near-surface layer of water. With residence periods of 3–4 weeks, reduction of fecal indicator bacteria by two orders of magnitude is achieved during summers (less during winters). Whether this reduction is sufficient to make the water safe for drinking would, of course, depend on the initial level of contamination.

With a much higher level of supervisory skills and supply of appropriate chemicals (e.g. ferric chloride or sulfate, aluminum sulfate, or synthetic cationic polyelectrolytes), water can be further treated to make it safer by removing suspended solids and turbidity through flocculation followed by settling or filtration. With such chemical treatment, electrical charges on suspended fine solids in the water can be neutralized and the coagulated particulates removed through settling or filtration.

A major alternative to impounding and/or filtering surface waters is to tap the ground water resource. Ground water is naturally filtered through several meters of soil and rock, and is commonly free of protozoan cysts and larger parasites. It is also commonly free of significant suspended particles (i.e. turbidity), making subsequent disinfection treatment (e.g. chlorine, UV), if desired, more effective. Accessing such ground water requires drilling deep (e.g. 80 m) borewells that tap deep aquifers containing old ground water that has little organic carbon and usually little biological contamination. In the late 1970s, UNICEF-India supported an NGO-led move to develop a hard-rock drilling technology using hydraulic drill rigs that can drill fast and inexpensively to 100 meters. Private entrepreneurs and competition have brought hard-rock drilling costs in India down to an average of $20 per meter, probably the lowest in the world. A handpump fitted on the borewell completes the picture. Over the last decade, UNICEF sponsored the development of a rugged, inexpensive, and low-maintenance handpump, now commonly known as UNICEF India Mark II. Today the cost of a 5-inch-diameter well drilled by a private contractor to 60 meters in hard rock, cased to 10 meters, and fitted with an India Mark II handpump is US$1300. Remarkable advances are being achieved in India with installations of 100,000 deep borewell handpumps annually, with each handpump serving about 200 persons (15). This publicly funded, impressive advance in drinking water access and quality for rural India has caused a massive shift in the last few decades for rural populations from former overwhelming reliance on polluted surface sources to ground water.

A similar aggressive effort, installing shallow tube wells (instead of deep ones) in the Indian state of West Bengal and in Bangladesh, however, has now led to a calamity of the largest-ever case of mass arsenic poisoning (15a).

In urban and peri-urban areas, sources of fecal pollution, such as pit toilets and leaks in city sewers, can contaminate ground water with pathogenic bacteria and viruses. The resulting ground water, while still free of turbidity, protozoan spores, and larger parasites, is contaminated with fecal bacteria and viruses, and requires disinfection.

3.1 *Filtration*

Rapid and slow filters are effective in reducing turbidity of the source water. Turbidity is measured in standardized nephalometric turbidity units (NTUs), determined by measuring the scattering of light as it passes through the water. High turbidity interferes with the effectiveness of disinfection by chlorine, ozonation, and UV. Owing to this, WHO recommends that the mean turbidity of the source water being treated with these disinfection methods should be below 1 NTU, with no single sample having turbidity exceeding 5 NTUs. In addition to substantially removing turbidity, slow sand filters also permit large reductions in bacterial and viral contamination and remove larger biological contaminants (such as cryptosporidium, giardia, amoebae, parasite eggs, etc). Any given design of a filter will have inherent limits on the level of turbidity (in units of NTUs) and total suspended solids (TSS, in units of mg/l) it can treat. If the incoming water exceeds these design parameters, the filter may clog up rapidly and may produce filtrate (i.e. outlet water) with turbidity and TSS exceeding the intended design values. Common design limits on inlet water turbidity and TSS are about 50 NTUs and 50 mg/l, respectively. Water with higher values for turbidity and TSS is preferably pretreated with coagulation and/or flocculation before filtration.

3.1.1 RAPID SAND FILTERS Rapid sand filters reduce larger micro-organisms and suspended solids. Water passes through the filter bed by gravity at a velocity between 2 to 5 to meters per hour. The filter performance is initially poor and then improves for a period. As the filter bed becomes compacted, the performance deteriorates again. This can be rectified by regular monitoring of filtrate quality and backwashing as needed (16). As an example, Visscher & Galvis (17) report on the performance of a rapid sand filter used in rural Colombia at Puerto Mallarino. The filter routinely reduces turbidity by 50% and TSS by 90% from the local river water. The filtrate from the rapid sand filter is used as input to a slow sand filter to produce drinking water for the community.

Rapid sand filters do not by themselves disinfect water adequately (they will not remove fecal pathogens) but can prepare water for treatment by UV, chlorine, or ozone.

3.1.2 SLOW SAND FILTERS Slow sand filters are more effective than rapid filters at removing particulates and microbial contaminants and are also simpler to operate. They do not require backwashing as frequently as rapid sand filters. A layer of active biological community (known as smutzdecke, comprising food chains of ciliated protozoa, free-living bacteria, amoebae, crustacea, and other small organisms), develops in the sand a few centimeters below the top surface and captures organic particulates and microbial contaminants in the inlet water. When the filter clogs up, the top layer can be scraped off, and the filter restarted. The new smutzdecke takes a few days to establish (depending on the temperature and local conditions) before the filter becomes fully operational again.

Water seeps through slow sand filters at rates of 0.1 to 0.2 meters per hour. Thus, the technology is low cost and low maintenance, but requires sufficient land area (18, 19). Other limitations of the slow sand filter technology are that the inlet water should not have a very high concentration of suspended solids, high coliform counts, or large quantities of algae; otherwise, the filter can clog rapidly. Also, low operating temperature, low oxygen content in the inlet water, or low nutrient content can inhibit the operation of the smutzdecke.

A number of documents on selection, operation, care, and maintenance of rapid and slow sand filters for small community water systems in developing countries are available from the IRC International Water and Sanitation Center (20).

3.1.3 CARBON FILTERS FOR HOUSEHOLD USE Many commercial firms offer activated carbon filters for urban household use in the developing countries, to be fitted at the end of the municipal water tap in the kitchen, for removal of various waterborne chemical pollutants. The growth of bacteria in activated point-of-use carbon filters for household use has been well documented. These bacteria colonize the filters and slough off into the water stream in very large numbers when water is turned on. WHO (2) remarks that the ample published reports on this topic have convincingly demonstrated that incorporating bacteriostatic agents (e.g. silver) in the filters has only a limited effect in controlling such growth. For this reason, point-of-use household carbon filters must be periodically replaced, and should be used only with water that is known to be already microbiologically safe. While this is not yet a major problem (in terms of absolute numbers of people at risk), it could become one without appropriate consumer education.

3.2 *Chlorination*

Chlorine in various forms is the most common disinfectant used worldwide. Chlorine dose is measured in units of concentration times contact time. For example, a chlorine dose of 2 mg/l and 30-minute contact time (obtained in a chlorination holding tank) provides 99.9% disinfection of *Giardia* at 20°C, 1 NTU, and pH of 7 (21). Chlorine in water reacts to form HOCl and H^+ and Cl^-. HOCl, or hypochlorous acid, itself partially dissociates as H^+ and OCl^-; the latter is called the hypochlorite ion. Warmer water temperature, and to a much greater extent, lower water pH, decrease the dissociation of the hypochlorous acid, i.e. decrease the ratio [OCl]/[HOCl]. Furthermore, chlorine in the water reacts with and binds to the material in suspended solids, and thus is removed from the reaction to form hypochlorous acid. Hypochlorous acid is a stronger bacterial disinfectant than the hypochlorite ion. Therefore, the required chlorine dose for disinfection increases sharply with increasing turbidity, increasing pH, decreasing water temperature, and increasing concentrations of ammonia, hydrogen sulfide, Fe, and Mn. The chlorine doses needed over the full range of these water properties would differ by a factor larger than 10. With poor quality water (e.g. high turbidity, high pH), disinfection with chlorine may become impractical because the chlorine dose required may be so high that the contact time may extend into tens of hours or the chlorine concentrations may exceed objectionable taste threshold.

Conventional automated chlorine-dosing plants can apply the right amount of chlorine; however, they require highly trained operators, engineers, and repair and maintenance infrastructure available in and appropriate for only large urban populations. In many smaller communities in the developing countries, various solid or liquid chemical forms of chlorine (e.g. bleaching powder [calcium hypochlorite, $Ca(OCl)_2$], or sodium hypochlorite (NaOCl), are used since they are safer to transport and handle than chlorine gas.

An alternate chlorination technology needs mention here, distinct from the automatic dosing plants delivering chlorine gas in some form to municipal water. In this method, a solution of ordinary household common salt (NaCl) is prepared and electrolyzed with no separation attempted between the cathode and the anode. This leads to the formation of a solution of NaOCl in the brine, which can be immediately added to the water to disinfect it. This method has the advantages of not requiring storage of any form of chlorine, relying on inexpensive (and impure) household common salt for chlorine source, and not being sensitive to the maintenance of a supply chain of the chlorine source chemical. The disadvantage is that the NaOCl brine must still be properly metered or dosed into the raw water, which will get disinfected over a period of time ("contact time") before it can be used.

The major advantage of chlorine is its ability to leave a residual disinfection concentration in the water supply. Residual free chlorine is the available chlorine left in the water after a specified contact period, which can further disinfect any newly introduced biological contamination. A residual free chlorine of 0.25 mg/l is considered adequate for warm climates (20°C water supply) for water with total organic carbon content of less than 0.25 mg/l. The residual chlorine suppresses regrowth of nuisance bacteria and guards against small amounts of recontamination of the water by reintroduced pathogens. A large infusion of pathogens and organic matter, however, can overwhelm the protection provided by residual chlorine. An occasional occurrence in developing-country city supplies is the intake of raw sewage–contaminated urban ground water into leaky underground drinking water mains during periods when insufficient water supply forces reduction in (or absence of) positive pressure in the water mains (or when residential booster pumps cause negative pressure in the water supply mains). Residual chlorine concentrations under such circumstances are often inadequate to disinfect the admitted contaminated ground water, leading to outbreaks of waterborne disease with pathogens piped right into people's homes. In general, however, the residual disinfection is a valuable guard.

The primary disadvantage of chlorine is the necessity to maintain an appropriate supply chain of source chemical to the water treatment location. Both liquid and powder bleach degrade over time with half lives of the order of weeks to months (depending on storage conditions). Cholera outbreaks have been reported in India when impassable roads blocked the chlorine supply chain during heavy monsoons. An equally serious disadvantage is the need for a skilled and trained operator and a repair and maintenance infrastructure. For large systems (cities of 100,000 or more), chlorine disinfection costs are low, approaching about \$.02 per m^3 of water. With small-scale systems, however, the costs rapidly increase, as does the impracticality of having skilled technical operators.

The various methods of disinfection by chlorination lead to the production of disinfection by-products (DBPs) in the water containing dissolved organic carbon compounds. In almost all cases in the developing world, the health risks from pathogenic microbial contamination of drinking water are thousands of times larger than the health risks from the ingestion of the DBPs. DBP risks and disinfection methods for developing country communities are reviewed by Ellis (22). In recent years, a potentially new health risk from DBPs is being investigated in the US and European countries beyond the traditionally understood one—the risk of endocrine disruption potential of DBPs. At present, this is an active and important research topic, but compelling conclusions are not in hand to warrant a change in recommended disinfection practices in developing countries.

3.3 *Mixed Oxidant Gases Systems (MOGGOD)*

MOGGOD stands for mixed oxidant gases generated on demand. This is the most recent arrival on the technical scene for drinking water disinfection. There are several different designs and manufacturers of MOGGOD systems. The basic concept is to electrically produce the mixed oxidant gases on demand using an electrochemical cell that uses industrial high-purity salt (NaCl) brine as the chlorine source. The separation in the brine electrochemical cell is based either on a membrane or a density gradient in the salt solution. The oxidant gases in the disinfecting liquid produced from electrolysis are a mix of chlorine dioxide, ozone, and hypochlorite. This liquid is then either metered into the source water or sold bottled to be added to household water storage tanks (23).

The main advantages of MOGGOD are that the source of the disinfectant is inert and relatively inexpensive (industrial high-purity NaCl), the mixed oxidants are a more effective disinfectant than chlorine alone, and a residual protection is produced in the water (24). One US manufacturer states that a mixed oxidant dose of 4 mg/l with a contact time of 60 minutes provides greater than 99.9999% disinfection against E. coli, and 99.99% disinfection of giardia cysts (25). Most of the experience with MOGGOD systems has been in Latin America. These systems are built and sold on demand, so prices are not stable (26). The operating cost of water disinfection by MOGGOD systems is stated to be attractive for large systems, comparable to that from chlorine or bleach (sodium or calcium hypochlorites), although the first costs are much higher than those for disinfection with bleach.

The disadvantage of the MOGGOD system is that it requires dozens of hours of skilled maintenance per year of the electrochemical system, dosing valves, flow meters, and venturi ducts, including handling of caustic chemicals. Systems based on a membrane require cleaning and replacing the membrane every few months to a year (depending on the level of impurities in the salt), and so appear inappropriate for typical developing country applications.

3.4 *Pasteurization*

Boiling is the oldest method to obtain water free of biological contaminants. In many developing countries and several cities of the former Soviet Union, residents routinely boil their drinking water because the safety of the water supply cannot be trusted or is known to be compromised. World Bank (6) reports that 1% of Jakarta's GDP is spent by the residents of the city boiling their drinking water. Anecdotal reports suggest that about half the population of China boil their drinking water, mostly over biomass-fueled stoves. As has been well documented, biomass is generally the most air-polluting, and if purchased, expensive (owing to low efficiency of cookstoves) of cooking fuels, but it is the only one accessible to the poorest of the populations in the developing world (27).

In fact, one does not have to boil the water to disinfect it. Holding it at a high enough temperature (e.g. 6 minutes at 70°C) is sufficient to pasteurize the water and render it safe. Figures providing the minimum holding time for various temperatures to kill various pathogens are available in the literature (28). However, given the absence of easy thermometry for household use, boiling the water is the safe and common choice. At 100°C, enteric pathogens are killed in less than a minute. WHO recommends bringing water to a vigorous roiling boil for a minute for disinfecting it at sea level, and adding a minute of extra boiling time for each 100 meters in altitude, to account for the progressively lower boiling point of water at higher altitudes (2).

With an average cookstove efficiency of 12%, fuelwood can boil water about three times its own weight. For a family of 5 with a drinking water need of 35 liters (35 kg of water) daily, this will consume about 12 kg of wood, several times more than the few kilograms the family would use for cooking its daily food. Gathering fuelwood for daily cooking is already a heavy burden on hundreds of millions of women and girls in the developing world (29). In fact, it is economically unrealistic and environmentally unsustainable to recommend boiling daily drinking water to the poor of the developing world. Boiling can be recommended only in an emergency situation, and is practiced routinely only by the fraction of the population that can afford it.

Presumably, with improved information dissemination about the linkage between unsafe drinking water and diarrheal disease, those who risk their health to unsafe drinking water today will start boiling water as soon as they can begin to afford it. This poses a potentially very large increase in the biomass extracted for household use. Even if the biomass is harvested sustainably, non-CO_2 combustion products from biomass burning can be significant in terms of their greenhouse potential (1 kg of fuelwood burnt in a biomass cookstove releases about 440 grams of carbon as CO_2, and about 650 grams carbon-equivalent of non-CO_2 greenhouse gas emissions, estimated from emissions data from 27, 30, and 31). Provision of safe drinking water to these populations would be an effective way to circumvent the potential impending depletion of biomass resources for boiling drinking water, and the associated large contribution to greenhouse gas emissions.

3.5 *UV Disinfection*

Ultraviolet light in the wavelength range 240 to 280 nm has been known to be germicidal for almost a century. The germicidal effect occurs because the UV light causes severe damage to the DNA of the micro-organisms. Specifically, the UV exposure covalently bonds together certain adjacent bases in the DNA, thus disabling it from replication. The germicidal effect is most potent at a wavelength of 260 nm. A good review of the biology of UV damage is given by Harm (32). Wolfe (33) reviews UV disinfection of potable water.

Since a low-pressure mercury arc (same as that used inside ordinary household fluorescent lamps) puts out 95% of its energy at 254 nm, it can provide an extremely effective germicidal effect. UV dose is measured in microwatt-seconds of UV energy (at or close to 260 nm) per sq. cm of water surface. UV dosages for various degrees of inactivation of selected microorganism are found in the literature (33). The dose to inactivate 90% of E. coli is 3000 μWs/cm^2. Other pathogenic bacteria and viruses have doses of similar magnitude (rotavirus at 8000 μWs/cm^2 is the highest among these). On the other hand, UV doses of very much larger magnitudes are needed to inactivate the cysts of protozoa, such as *Giardia* and *Cryptosporidium*. UV is not a treatment of choice for removal of cysts. Appropriate filtration or sedimentation can remove these larger pathogens and also reduce turbidity (which improves UV transmittance and reduces shielding of microbial pathogens by particulate matter) before UV treatment.

For successful UV disinfection, the raw water must have adequate UV transmittance. Transmittance of UV light in water is measured with an extinction coefficient (units of cm^{-1}). UV extinction coefficient for distilled water is about 0.01/cm, for municipal tap waters about 0.1/cm is common, and that for the average waste water discharge from US municipal treatment plants 0.3/cm. The design of the UV disinfection device must take into account UV extinction and ensure adequate UV dose to even the water streamlines farthest away from the UV source. Certain dissolved salts (e.g. those of Fe), and humic acids in the water can reduce UV transmittance and thus UV treatment effectiveness.

The energy efficiency of UV treatment is very high. Compared to boiling over a biomass cookstove of 12% efficiency, UV disinfection can require 20,000 times less primary energy (assuming a design delivering 38,000 μWs/cm^2 UV energy dose to the water). In contrast to many of the chemical disinfectants, UV disinfection imparts no taste or odor to the water, and presents no risks from overdosing or formation of carcinogenic disinfection by-products. The very high sensitivity of DNA to UV light allows very short treatment time for the water. In contrast to chlorine (which requires contact times of 30–60 minutes), UV disinfects water in a few seconds. Because it does not have diseconomies of scaling down, the cost of disinfection per cubic meter remains about $.02 even for small systems, while for chlorine treatment units the costs are comparably low for large-scale systems but rise by an order of magnitude as the scale gets smaller.

Since UV does not impart residual disinfection to the water, it is appropriate only for point-of-use disinfection systems and under circumstances where the disinfected water will be protected from recontamination. Furthermore, since enzyme mechanisms exist within several bacterial species that try to repair the damaged DNA (although in a slow and error-prone manner), UV disinfection by itself, at the minimum UV dose required by current standards, is not suitable for disinfection of drinking water intended for long-term storage.

Most UV system designs comprise a linear UV lamp, enclosed within a cylindrical coaxial UV-transparent sleeve (made of quartz or teflon), submerged in water in the UV-exposure chamber. Water flows axially on the outside of the sleeve and receives the UV dose (Figure 2). Chemical fouling and biological film (particularly when the lamp is off and the water stagnant during hours of disuse) builds up on the sleeve surface over time. This fouling seriously impairs the UV transmittance of the sleeve and necessitates its periodic cleaning with chemical and mechanical methods. This makes maintenance complex and expensive and puts it beyond the means of most rural communities. Another limitation of most UV systems is that they are designed to be operated with a

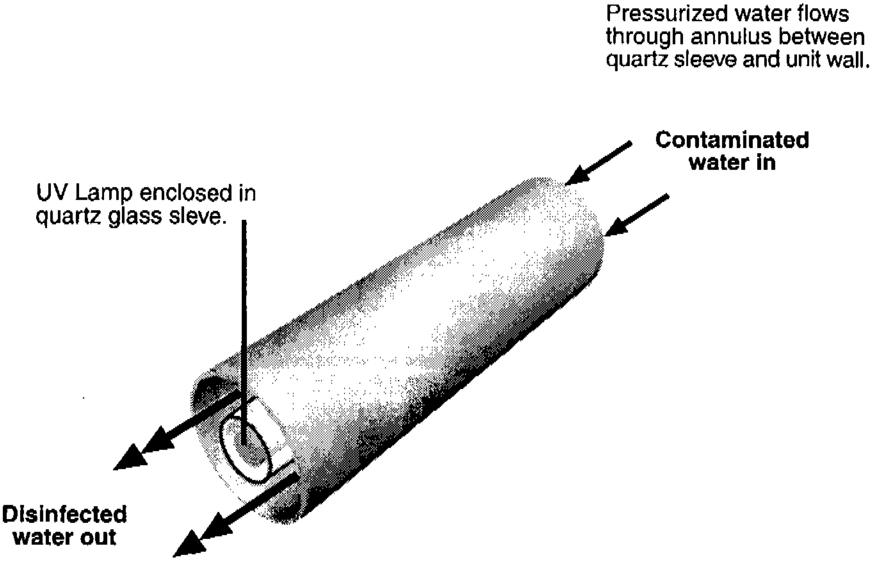

Figure 2 Conventional coaxial UV treatment unit.

pressurized raw water source (e.g. from a municipal tap). They are not useful for communities collecting water from handpumps and/or surface water sources (e.g. wells, rivers, or lakes).

Recently, UV systems with an air gap between the UV lamp and the water surface were developed by the author and his colleagues, and have been licensed for commercial production (34). In this design, the linear UV lamp is positioned horizontally below a semi-cylindrical reflector, above the free surface of water flowing in a shallow tray (Figure 3). This design innovation circumvents the problem of chemical- and bio-fouling of the solid surface between the UV source and the water. Also, since the flow resistance is small, water with pressure equal to only a few centimeters of water column can flow through the device. One particular implementation of this design consumes 40 watts of electricity, disinfects 1 ton water per hour by delivering it a UV dose of more than 100,000 μWs/cm^2, and accepts atmospheric-pressure raw water (e.g. poured from a hand-carried pot). Data from several independent laboratory tests and limited data acquired from field performance of such a UV system are very encouraging (35).

UV systems obviously need electricity to operate. The typical (grid-based) electricity cost of about $US0.05 per ton of water treated increases to about $0.025 per ton of water if one uses PV panels for the electricity. Including amortized cost of capital, consumables, and grid-electricity, the disinfection of 10 liters of water daily for a person costs about $0.10 annually.

3.6 *Ozone*

Ozone (O_3) is a potent oxidant since it readily decomposes into oxygen and a nascent oxygen atom. Ozone is currently the next most widely used drinking water disinfectant after chlorine (there are some 1100 water treatment plants using ozone worldwide), although its use is almost exclusively limited to the

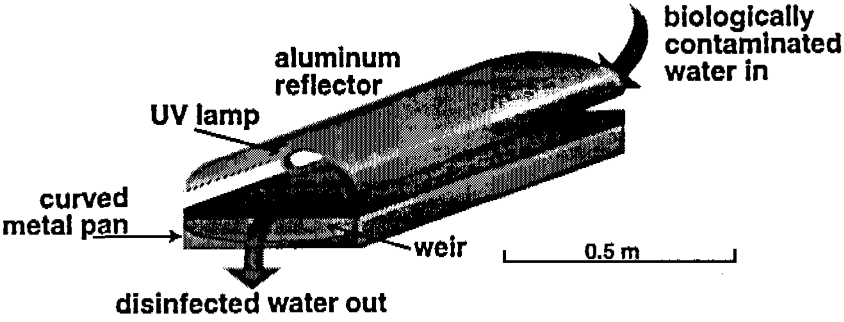

Figure 3 Simplified schematic of new gravity flow UV treatment unit.

industrial countries with high-integrity piped water networks. Ozone is produced electrically by passing oxygen from ambient air between electrodes with a high voltage (tens of thousands of volts) applied across them. Care is needed in operating and maintaining the generators, and in destroying excess ozone so it is not released into ambient air. An accessible review of primarily ozone technology for water disinfection is available from the Electric Power Research Institute (36).

Ozone does not provide residual protection against recontamination in the distribution system. Therefore, its common use is to pre-treat the water source before chlorination in a municipal system, so that a smaller chlorine dose is required (37). Although ozonation can effectively disinfect water, it is not suited for most developing country applications owing to its high cost, need for operational and maintenance infrastructure, and lack of residual protection in the distribution system.

3.7 *Comparisons*

Several methods of drinking water disinfection described above (excluding ozonation owing to its inappropriateness in the developing world context) were compared for cost and suitability by Burch & Thomas (38). Some of their results are summarized in Table 4. The three village community level systems were assumed to include a roughing filter to reduce turbidity from surface waters before treatment. The two home-use methods assumed no such pre-treatment.

Table 4 Comparison of disinfection methods for small water systems

	Roughing filter + chlorine dosing plant	Roughing filter + grid-powered MOGGOD	Roughing filter + slow-sand filter	Roughing filter + grid-powered UV	Roughing filter + PV-powered UV	Batch-scale chlorine for home	Boiling at home with purchased fuel
Operating cost, US cents per m^3	7	58	3	3	15	9	2083
Effectiveness							
Residual	High	High	Nil	Nil	Nil	High	Nil
Against bacteria & viruses	High	High	High	High	High	High	High
Against protozoa and worms	High	High	High	High	High	Med.	High
Ease of Use							
Supply chain independence	Low	Medium	High	High	High	Low	High
Independence from need for skilled labor	Low	Nil	High	Medium	Medium	High	High
Independence from need for unskilled labor	Low	Medium	Low	High	High	Medium	Low

Source: Burch & Thomas (1998).

The batch-scale chlorine at home assumes essentially no labor and no capital costs. In this approach, the conventional life-cycle cost analysis is used with a discount rate of 20%, and inflation rate of 10% on all future costs. Costs of components that must be imported have been multiplied by 1.3 to reflect shipping and customs costs. Labor costs were assumed at $0.50/hour for skilled labor, and $0.05 for unskilled labor.

In an independent and earlier study, the South Africa's Council for Scientific and Industrial Research (CSIR) compared UV, MOGGOD, and on-site hypochlorite generation in terms of their technical strengths and weaknesses, economics, and reliance on skilled labor. This study (39) concludes that each of these technologies has features that can be important for the overall water supply solution to small and medium communities. Although none of the three is a perfect solution, none poses insurmountable demands for maintenance and operational skill, and they all have a high disinfection effectiveness. The report concludes that a complete comparison will require field testing of all the three treatment technologies to see how they fare under actual field conditions.

Parotta and Bekdosh (40) recently reviewed UV disinfection of small groundwater supplies for US communities of less than 3000 persons. They present cost comparisons of UV disinfection with ozonation and chlorination for a range of system sizes (from 9–7000 m^3/day). They conclude that UV disinfection is effective and affordable relative to conventional disinfectants assuming US labor costs and infrastructure.

4. ECONOMICS AND POLICY

The major underlying constraint to increasing coverage of access to safe drinking water is the shortage of investment capital for extending the service, and the negligible or partial recovery of operating costs of providing service. The specifics vary according to the level of service, choices of technologies, management systems, and cost recovery practices.

The total of the global annual investment in the water and sanitation sector in the developing countries was estimated to be about US$10 billion in the 1990s. On average, 65% of this funding was raised from in-country resources, the rest from bilateral and multi-lateral external funding. There is strong regional variation in the fraction of funding from in-country resources, from a high of 90% in the Middle East to a low of about 25% in Africa (12). UNICEF estimated in 1990 that to reach 100% coverage by the year 2000, the annual investment rate in water and sanitation will have to rise from US$10 billion to US$36 billion. Since this was unlikely, UNICEF suggested that a focus on greater cost efficiency and effectiveness is essential to make substantial progress. This also implied that a stronger focus on low-cost technologies is critical for a significant acceleration in the rate of increase of coverage. In UNICEF's assessment, the average per capita investments (in 1990 US dollars) for various water supply technology options were as follows:

1. High-cost technologies with pumping stations appropriate for urban distribution systems providing piped safe water to individual households: $200
2. Intermediate-cost technology applicable to peri-urban areas providing piped water supply with minimal treatment delivering safe water at public standposts: $100
3. Low-cost technologies targeted to rural areas, including handpump-equipped boreholes or hand-dug wells, rainwater harvesting systems, and simple pipe-borne gravity-fed systems with public standposts: $30

These costs are also broadly consistent with the World Bank's assessment (41). UNICEF experts note that as of 1990, only about 4% of the $3 billion annual external funding went to support low-cost technology projects (12).

However, a sharp and significant debate has emerged in the last few years about how to proceed to increase coverage of access to safe drinking water. The old world-view about drinking water coverage is best reflected in the 1990 New Delhi declaration at the Global Consultation on Safe Water and Sanitation for the 1990s, which approved the concise slogan: "Some for All rather than More for Some." This position also was later approved by the UN General Assembly. [Both the relevant texts are reproduced in *Water International* (42)]. The operational approach based on this old world-view is summarized by its critics as follows:

1. Estimate the cost of extending the service (at some chosen level) to the population that does not have coverage (do not pay much attention to their willingness to pay, nor to the level of service they think they really need),
2. Undertake exhortations to obtain the funds from government or external assistance.
3. Spend the funds to implement the service extension through public sector machinery (do not pay much attention to recovering costs)
4. Proceed to step 1.

As Briscoe & Garn (43) comment, what is needed according to the advocates of the old view is [only] more financial outlays to increase the global spending from US$10 billion toward US$50 billion needed by this formula to obtain full coverage. Since a five-fold increase in investments is not immediately feasible, a somewhat lower (e.g. two-fold increase, in Agenda 21) is selected as a target. This view assumes that the local government has the primary responsibility for financing, managing, and operating the services. The government should define what level of services are needed, subsidize them (especially for the poor), and develop and operate public organizations for the delivery of the services.

However, this system does not work very well. What gets implemented is an extremely cost-inefficient (and consumer-unresponsive) water distribution system that uses up the available public resources to deliver inexpensive piped water service to the lucky few, leaving the majority of the populace to fend for itself by purchasing water from water vendors.

Furthermore, the lucky few who get the piped water connections always happen to be the economically and politically more powerful social segments. There are very large economies of scale in water delivery (it is far cheaper to pipe water into cities than to transport it in with trucks and tankers). The upshot, as observed by Briscoe (44) and many others, is a perverse, de facto tariff system in most developing world cities. In almost all poor countries, there is an element of subsidy in urban water supply that goes mainly, albeit unintentionally, to the rich.

Commonly, the technical performance of the public water systems is poor (e.g. there is much "stolen" or unaccounted-for water: 58% in Manila, 40% in most Latin American cities), leading to huge foregone revenue to the water utility. Organizational performance is poor. The number of employees per 1000 connections is small in a well-run water utility in a developing country (e.g. 4 in Santiago, Chile and 3 in Hong Kong), but between 10 to 20 in most Latin American utilities and occasionally even higher in Asia (e.g. 33 in Mumbai, India) (43, 44a). Lastly, financial performance is also poor. Hundreds of millions of dollars of annual government subsidies are needed to keep the water utilities solvent.

The justification for the high level of government subsidy for water services is claimed to be the low ability of the poor to pay for services. In practice, it is the rich, not the poor, who almost always benefit disproportionately from subsidized water services in the developing countries.

Briscoe & Garn (43) summarize the World Bank analyses of 40 years of water utility performance in the developing countries: Heavily subsidized services lead to relatively slow service expansion, poor-quality service (owing to cost- and performance-unaccountability to those being served), and inefficient resource use; the subsidized services are provided to the lucky ones who happen to be also otherwise privileged, while the unlucky ones, who happen to also be poor, pay a huge human, social, and financial price to get the service. In

Onitsha, Nigeria, for instance, the revenues collected by the water vendors are about 10 times the revenues collected by the formal water utility.

In contrast, the new world-view is more ambitious and more sophisticated about the extension of service in terms of both the quality of service to be extended and how to finance the extension. The guiding principles for the new view, which emerged at the 1992 pre-UNCED International Conference on Water and Sanitation, in Dublin, were as follows:

1. Water has an economic value in all its competing uses and should be recognized as an economic good, and

2. Water development and management should be based on a participatory approach, involving users, planners, and policy makers at all levels, with decisions taken at the lowest appropriate level.

There is an attendant third principle for financing of water resource management with efficiency and equity. This principle is that private financing should be used for financing private goods, and public financing should be used for financing only public goods.

Applying these principles requires rethinking of institutional arrangements, managing the water resources by making decisions at appropriate levels (households, community blocks, townships, urban regions, watersheds, river basins), separating regulation and provision, expanding the role of the private sector in services to public utilities and operation of water companies, increasing community involvement in deciding on (and paying for) the feeder infrastructure while public financing pays for the main trunk infrastructure.

A remarkable consensus has been building around the new world-view of water financing. The Dublin conference had delegates from more than 100 countries; many of them had attended many previous "old view" conferences. However, the majority of them recognized the impossibility of continuing in the old way to deliver services, and the conference accepted the new principles stated above.

To compare its operational process with that of the old view, the new view focuses on (43).

1. Managing water resources better, taking into account economic efficiency and environmental sustainability,

2. providing, at full cost, the level of "private" services that people want and are willing to pay for (e.g. yard taps versus fully piped bathrooms),

3. mobilizing and using scarce public funds for only those services that provide wider community services, and
4. developing flexible, responsive, financially sustainable institutions for providing these services, with a larger role for community organizations and the private sector.

In closure, it is worthwhile to specifically answer the question that the "old view" proponents would raise about how the "new view" proposes to provide drinking water to the absolute indigent in the rural hinterlands. A significant body of research demonstrates that many rural people can and will pay for improved water supplies. Assessing the willingness to pay for water and sanitation services, and determining the tariffs for various levels of water services where alternate (though lower quality) water options exist continues to be an active area of applied research (45, 46, 47, 48). These and other studies show that willingness to pay varies according to household socio-economic characteristics (e.g. level of education, employment in the formal sector, income), and the characteristics of the new and existing water supplies (e.g. reliability, ease of access, quality). Field surveys of actual and hypothetical water-use practices can provide determination of willingness to pay and the level of tariffs at which costs of service can be recovered without significant numbers of households reverting to older, pre-existing water resources (49). Using such surveys, tariffs can be set for household services (e.g. yard taps) allowing cost recovery and simultaneous provision of free public standpipes that would protect the poor without financially harming the water utility.

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