Deficiencies in drinking water distribution systems in developing countries

Ellen J. Lee and Kellogg J. Schwab

ABSTRACT

Rapidly growing populations and migration to urban areas in developing countries has resulted in a vital need for the establishment of centralized water systems to disseminate potable water to residents. Protected source water and modern, well-maintained drinking water treatment plants can provide water adequate for human consumption. However, ageing, stressed or poorly maintained distribution systems can cause the quality of piped drinking water to deteriorate below acceptable levels and pose serious health risks. This review will outline distribution system deficiencies in developing countries caused by: the failure to disinfect water or maintain a proper disinfection residual; low pipeline water pressure; intermittent service; excessive network leakages; corrosion of parts; inadequate sewage disposal; and inequitable pricing and usage of water. Through improved research, monitoring and surveillance, increased understanding of distribution system deficiencies may focus limited resources on key areas in an effort to improve public health and decrease global disease burden.

Key words | developing countries, diarrhoeal disease, distribution system, potable water

Ellen J. Lee
Kellogg J. Schwab (corresponding author),
Johns Hopkins Bloomberg School of Public Health,
615 N. Wolfe St Room E6620,
Baltimore,
MD 21205-2103,
USA
Phone (410) 614-5753
Fax: (410) 955-9334
E-mail: *kschwab@jhsph.edu*

INTRODUCTION

The declining availability of water supplies is one of the most important environmental issues facing various countries at the present time. It has been estimated that nearly two-thirds of nations worldwide will experience water stress by the year 2025 (United Nations Environment Programme 2002). Climate change, affluence and population growth have resulted in vast requirements of water for use in domestic, industrial and agricultural settings.

There exists a growing demand for centralized systems of water delivery in urban locales due to the continuing trend of population migration to larger cities. In these densely populated areas, the government (or a privately contracted company) has often installed the infrastructure necessary to deliver treated water. This type of potable piped water is necessary to ensure that all residents have convenient and continual access to a clean drinking water supply.

Historically in developed countries, the establishment of a distribution system to disseminate potable water has proven critical for public health improvements (Nelson 2001). However, in developing countries, many existing systems are operating intermittently and at a fraction of their capacity (WHO 2003). In addition, many more problems with distribution systems exist, and also occur more frequently, than in developed countries. Therefore, although presence of a public water distribution network is often an indicator of improved water supply in a developing country, it should not be assumed that the resulting water quality is always adequate for human consumption.

In many urban areas, interrupted service, whereby water is provided to residents for a restricted number of hours per day, encourages stagnancy of water and growth of microorganisms. Negative hydraulic pressure can draw pathogens from fecally contaminated material surrounding water pipes into the water supply, through leakages in the network. Similarly, improper disinfection or failure to maintain a sufficient disinfection residual, as well as natural ageing and corrosion of infrastructure, can create conditions favourable to bacterial growth. These flaws in the distribution system often work in combination with each other and can seriously compromise both quantity and quality of water reaching the consumer. The decreased microbiological quality of the water may cause public health outbreaks of diarrhoeal disease, a significant disease burden in developing countries today (Gadgil 1998). Clearly, these indirect consequences of poor water supply services are counter-productive to the purpose of distribution networks.

The impact that distribution networks have on reducing water quality has been inadequately addressed due to the limited information available on the magnitude of the public health problem. Existing statistics are often optimistic rather than realistic estimates of the actual conditions of distribution networks. Little research is being conducted towards determining whether distribution system inadequacies are a result of sporadic breakdowns or are continually occurring. Moreover, very few epidemiological studies have been published on disease outbreaks in relation to distribution network deficiencies in developing countries. Hence, there is a vital need for further research on drinking water distribution systems in developing countries.

This review will examine the impact that distribution systems have on water quality after the water has left the treatment plant. It will attempt to establish, using microbiological, engineering and epidemiological case examples from various developing countries, that failure in the distribution system can dramatically reduce the quality of water arriving to the consumer resulting in water unsafe for human consumption. The review will also examine the negative impacts that inequitable use of water has on both water quality and quantity, as well as briefly address risk assessment issues. Finally, the numerous political, social and economic causes underlying distribution system failure will be addressed and suggestions will be made in an attempt to ameliorate the current situation. It is hoped that, by identifying and increasing the awareness of the existing problem, solutions will be undertaken to improve public health and markedly reduce the global disease burden.

BACKGROUND

Over the last half-century, there has been a growing trend of population settlement in urban areas. Currently, the greatest migration rates from rural into urban areas occur in developing countries. The United Nations has predicted that, by the year 2030, 56% of people in developing countries will reside in urban areas (United Nations Population Division 2002).

As urban populations continue to expand in these regions, the demand for delivery of clean drinking water will also increase. In most larger cities, governments or privately contracted companies have constructed the necessary infrastructure (distribution networks) to provide a potable water source in a timely and convenient fashion to all residents. Venezuela is reported to serve more than 80% of its urban population with piped water (World Bank 1996b) and Eastern Africa has improved access to piped water sources by 30% in the last 30 years, with more than half of these new sources occurring in urban areas (Thompson *et al.* 2000). Despite these numbers, for the majority of developing countries, access to a treated water supply is generally quite low. In Jakarta, Indonesia, it was determined that only 22% of residents had direct access to piped water (Alberini *et al.* 1996). Regionally, the World Health Organization (WHO) and UNICEF (2000) estimate that, in the largest cities, those with a household or yard connection range from only 43% in Africa, to 77% in Asia, Latin America and the Caribbean, leaving a large proportion of remaining residents without sufficient access to a clean water supply.

Access to a treated, piped water source has proved to be crucial in the improvement of public health and decreased transmission of infectious diseases related to water (Nelson 2001). However, even in developed countries, waterborne diseases do not disappear once water treatment systems have been established. For instance, outbreaks related to failures in the distribution system continue to occur in the United States; approximately 18% of all reported outbreaks are caused by contaminants entering the distribution network after treatment (Craun & Calderon 2001). Hence, presence of a potable water supply system does not automatically ensure that resulting water quality is adequate.

However, unlike developed countries where treatment failures are relatively rare, in many developing countries, treatment failure has become the norm. Many systems operate at a fraction of their capacity (WHO 2003) and resulting water quality is poor. In Jakarta, Indonesia, it was even observed that the public water supply had the highest levels of contamination out of all available sources (Alberini *et al.* 1996). Indeed, a search of the literature indicates that developing countries experience more rapid deterioration of infrastructure, greater distribution system failure, and greater magnitude of distribution system-related problems than developed countries (WHO & UNICEF 2000).

There are numerous political, social and economic issues which underlie the direct causes of poor operations and maintenance of an urban water supply system. These problems result in a substandard water supply, leading to decreases in the *quantity* of water reaching the consumer, as well as deterioration in the *quality* of water reaching the consumer (WHO & UNICEF 2000). While the main focus of this review concerns the impacts on water quality and its effects on public health, it must be emphasized that water *quantity* is highly compromised. Wastage of water through unmetered or illegal household connections, and leakages in pipes and other valves can lead to massive volumes of water loss. This is by no means an insignificant problem, as this 'unaccounted-for water' in large cities of developing countries is estimated to be greater than 40% of the water volume initially entering the treatment plant (WHO & UNICEF 2000).

An urban water supply may become contaminated prior to consumption, from untreated water (either intentionally untreated or through treatment failure) or from cross-contamination in the distribution system after treatment occurs (Ford 1999; Craun & Calderon 2001). Either or both of these mechanisms can result in poor microbial quality of the water supply and may result in diarrhoeal disease and other gastrointestinal illnesses when ingested.

There is evidence suggesting that distribution networks contribute to decreased water quality. For example, in La Plata, Argentina, intestinal parasites were detected in tap water sampled from four regional zones, but no parasites were detected from samples taken in the immediate vicinity of the plant (Basualdo *et al.* 2000). Similarly, in Mexico City, bacteriological contamination increased by 26% from the point of treatment to the consumer's tap (Gaytan *et al.* 1997). Finally, in a Trinidadan community, 80% of household tap water samples tested positive for total coliforms, while no samples from the treated reservoir tested positive (Agard *et al.* 2002).

Areas in Asia and Africa demonstrate similar conditions to the above examples from the Americas. In Dushanbe, Tajikistan, fecal coliform concentrations taken at community taps were triple those leaving the plant (Mermin *et al.* 1999). In Phnom Penh, Cambodia, treated drinking water showed an absence of pathogens, but 25–44% of samples from household taps were contaminated (Dany *et al.* 2000). Moreover, in Johannesburg, South Africa, 14–16% of water samples obtained from the distribution system contained greater coliform counts than samples obtained directly following chlorination, though water quality reaching the consumer was still of high quality (Geldenhuys 1995).

A few epidemiological studies have also established associations between declining water quality from distribution systems and increased risk of gastrointestinal illness. In Dushanbe, Tajikistan, fecal contamination of water occurred after treatment via the distribution system, leading to an outbreak of typhoid fever in the community (Mermin *et al.* 1999). In Nukus, Uzbekistan, low pressure within the distribution system preceded an outbreak of diarrhoea (Semenza *et al.* 1998). Finally, in Cherepovets, Russia, a decline in residual chlorine concentration in the distribution system was associated with an increased population relative risk of 1.42 for gastrointestinal illness (Egorov *et al.* 2002).

Therefore, there exists sufficient microbiological and epidemiological evidence to implicate distribution systems as vehicles of transmission for pathogens. It is not known, however, whether poor quality water results from sporadic breakdowns of distribution systems or from continual, endemic problems in developing nations. The following section will discuss in more detail, what the exact failures in distribution systems are, the specific manner in which they act to decrease water quality, and the resulting impact of these deficiencies on public health in developing countries.

DISTRIBUTION SYSTEM INADEQUACIES

A number of failures in the distribution system, namely loss of adequate disinfectant residual, low water pressure, intermittent service and ageing of infrastructure can result in the declining quality of the water supply (WHO & UNICEF 2000). Pathogen intrusion may occur under these circumstances if poor sanitary conditions exist because of improper wastewater collection and leakages in the network. Consequently, these various deficiencies can result in the cross-contamination of a clean water supply which, in some cases, has led to outbreaks of waterborne and water-related diseases. As demonstrated above, it must be stated that it is often not a *single* flaw, but the *combination* of a number of failures in the system that result in poor water quality.

INADEQUATE DISINFECTION RESIDUAL

The use of a disinfectant in the treatment of a water supply has proved to be crucial to ensuring public health (Gadgil 1998; Ford 1999). There are numerous reasons why water supplies are not disinfected, including the intentional absence of disinfection due to consumer resistance to the taste of disinfected water (Diergaardt & Lemmer 1995), or avoidance of disinfectant by-product formation in the water (van DijkLooijaard & van Genderen 2000). Owing to its effectiveness and relatively low cost, chlorine is the most commonly used disinfectant globally (Baxter 1995). However, its odour, taste and reactivity (defined as the potential for disinfection by-product formation) may negatively influence the choice of chlorine as a disinfectant (Besner *et al.* 2002).

Failure to disinfect the water supply may also occur inadvertently, for example when the supply of treatment chemicals dwindles and cannot be replaced, or from mechanical or human failure during the treatment process (Diergaardt & Lemmer 1995). The failure to disinfect water has clear public health consequences: resulting disease outbreaks have been well documented in both the developing and the developed world (Cárdenas *et al.* 1993; Rab *et al.* 1997; Craun *et al.* 2002).

Despite the importance of disinfection, approximately 20–40% of urban water systems in the developing world do not disinfect their water supplies (WHO & UNICEF 2000). Even following a cholera outbreak in Peru in 1991, increased disinfection rates in Latin America and the Caribbean still resulted in only 59% of the population receiving disinfected water (Pan American Health Organization (PAHO) 1997; PAHO & WHO 2001). Population coverage for disinfected water supplies varies widely between countries, ranging from the lowest at 10% in Guyana (PAHO 1997) to 98% in Venezuela (PAHO & WHO 2001).

Not only is treatment necessary at the water treatment plant, but the *maintenance* of a detectable concentration of the disinfectant (called a residual) in the water distribution systems is also crucial. There are many purposes for maintaining a disinfectant residual; the primary goal is preservation of water quality during transit by preventing regrowth of pathogens, as well as inactivation of pathogens that may later be introduced into the system (Trussell 1998). Both chlorine and chloramines are used widely for this purpose; the latter have a greater ability to persist in the distribution system (Egorov *et al.* 2002).

In addition, the lack of residual in the system is a warning sign that organics, including potential pollutants, have entered the system and has been used as an indicator of contamination (Trussell 1998; Haas 1998). This is usually supported by increasing bacterial counts as residual concentrations decrease. In Trinidad, it was observed that, as the chlorine residual decreased from 4.6 ppm at the plant to 0.2 ppm at the household, there was a statistically significant increase in total and thermotolerant coliforms (Agard *et al.* 2002).

Presence of a disinfectant residual is especially important in developing countries because of poor sanitary conditions and the high risk of recontamination during distribution. This is especially true if the water must travel great distances to reach the end consumer, since generally, residual chlorine levels decline as the distances from the plant increase (Egorov *et al.* 2002). For example, it was observed in Dushanbe, Tajikistan, that a longer length of pipe increased the chances of contamination, especially in the event of low pressure (Mermin *et al.* 1999). In Pietermaritzburg, South Africa, coliforms were found to be associated with low chlorine residual; as distance from the water plant increased, the level of free chlorine decreased with resulting coliform increase (Bailey & Thompson 1995). In addition to distance travelled, other factors that affect the rate of depletion of a residual are: water flow velocity, residence time, age and material of pipes, and water pressure (Egorov *et al.* 2002).

However, a disinfectant residual can guard against only a small amount of reintroduced pathogens, and can easily be overcome by high concentrations of contaminants (Gadgil 1998). The greater the risk of contamination in the pipelines, the higher the residual concentration that must be maintained. The World Health Organization recommends maintenance of a disinfectant residual of 0.2 to 0.5 $\mathrm{mg\,l^{-1}}$ in a distribution system under normal operating conditions (WHO 1997); in general, developing countries maintain higher concentrations of residual than the estimated 0.2 $\mathrm{mg\,l^{-1}}$ maintained by developed countries' water supplies (Geldreich 1996). For instance, in Pietermaritzburg, South Africa, a free chlorine residual of 0.4 $\mathrm{mg\,l^{-1}}$ was necessary to control bacterial growth (Bailey & Thompson 1995). In Johannesburg, South Africa, it was determined that a residual chlorine concentration of 0.3 $\mathrm{mg\,l^{-1}}$ was necessary to reach the furthest points in the distribution system and therefore a free chlorine concentration of at least 0.8 $\mathrm{mg\,l^{-1}}$ was administered at the plant (Geldenhuys 1995). In Hyderabad City, India, the city aims for a residual concentration of 1–2 $\mathrm{mg\,l^{-1}}$ at the tap, and as a result an average of 4 $\mathrm{mg\,l^{-1}}$ of chlorine is added at the treatment plant (Mohanty *et al.* 2003).

There is evidence that problems exist regarding proper disinfection and maintenance of an adequate residual in developing countries; a summary of these studies is shown in Table 1.

Similarly, clear health benefits have resulted when the disinfection of water supplies occurs. In Israel, new regulations have rendered chlorination of community water supplies mandatory and have resulted in a dramatic decrease in the number of waterborne disease outbreaks (Tulchinsky *et al.* 2000).

INADEQUATE PRESSURE

In addition to maintaining a sufficient disinfection residual, the next most important means of protecting quality of the water supply is the maintenance of positive pressure throughout the entire network (Geldreich 1996). It is thought that inadequate pressure and resulting reverse flow or back-siphoning of water is a common cause of distribution system contamination worldwide (Trussell 1998). Insufficient pressure is often inextricably linked to intermittent supply of water, which will be discussed in the following section.

When scarcity of water occurs in a municipality, a commonly employed tactic is to reduce pressure in the pipelines, reducing the supply to each household (del Carmen Gordo Muñoz 1998). A drop or differential in pipeline pressure can result in the reversal of flow, with water flow in the direction of lower pressure. As a result, backflow occurs, which is defined as the flow of undesirable water back into the potable drinking water supply (Herrick 1997).

There are two types of backflow that may occur. The first is back-siphonage, which occurs when the pressure drops sufficiently to cause a vacuum effect in the pipe, which can then draw in contaminants through leaks in the pipes or through cross-connections (Geldreich 1996; Mermin *et al.* 1999; Kelkar *et al.* 2001). A cross-connection refers to 'any connection between a potable drinking water supply and a non-potable, undesirable, polluted or contaminated source' (Herrick 1997). The other type of backflow is called back-pressure, which occurs when 'a pressure is created in the system that is greater than the supply pressure' (Herrick 1997) as will be discussed in the case of individual pumps and storage tanks installed into the system by users.

Insufficient or negative pressure has been known to result from a number of events such as insufficient water supply, power losses, hydrant flushing, rapid closing/opening of valves, the addition of residential booster pumps, transmission main breaks, and pumps ceasing or starting to function (Gadgil 1998; Besner *et al.* 2002). For example, in Dushanbe, Tajikistan, where a recent typhoid epidemic was observed, half of the pumps were not operational, preventing the proper pressure from being achieved (Mermin *et al.* 1999).

Hydraulic pressure, or water pressure in the pipeline, may start off high but drop off rapidly, with those in the end zones experiencing very little pressure or water supply. Thus, those living closest to the treatment plant are at an advantage for receiving sufficient volumes of water than those who are located further away. In Bangladesh, it was observed that system pressure dropped at short distances away from overhead tanks and pumphouses, with some areas even experiencing zero pressure (Chowdhury *et al.* 1999, 2002).

Table 1 | Studies demonstrating inadequate disinfection residuals

Study	Location	Summary of findings
Agard *et al.* 2002	San Fernando, Trinidad	Increase in total and thermotolerant coliforms observed as residual concentrations decreased from 4.6 ppm at plant to 0.2 ppm at household
Bailey & Thompson 1995	Pietermaritzburg, South Africa	As distance from treatment plant increased, concentration of free chlorine decreased with resulting coliform increase
Cárdenas *et al.* 1993	Riohacha, Colombia	Subjects drinking unchlorinated water were at increased risk of contracting cholera and diarrhoea, with prevalence odds ratios estimated at 5.7 and 3.3, respectively
Dany *et al.* 2000	Phnom Penh, Cambodia	Required chlorine dosage applied at plant not achieved, due to shortages of chemical. Resulting free chlorine concentrations lower than the recommended 0.2 $\mathrm{mg\,l^{-1}}$
Diergaardt & Lemmer 1995	Namibia	Failure to chlorinate water in Namibia due mainly to consumer resistance to the taste of treated water, but also to inadequate chemical supply and proper equipment
Egorov *et al.* 2002	Cherepovets, Russia	Residents regularly exposed to drinking water without residual. Increased population relative risk of 1.42 for gastrointestinal illness associated with decline in residual chlorine concentration
Gadgil 1998	India	Impassable roads during monsoon season interrupted supply of chlorine, resulting in cholera outbreaks
Geldenhuys 1995	Johannesburg, South Africa	14–16% of distribution system samples contained greater coliform counts than directly chlorinated samples
Geldreich 1996	Trujillo, Peru	Drip chlorinators not used since liquid chlorine not available on a continuous basis
Geldreich 1996	Lima, Peru	Residual concentrations often not detected at all, despite established goal of 0.5 $\mathrm{mg\,l^{-1}}$
Kelkar *et al.* 2002	Panaji City, India	Chlorine concentrations of 0.2 $\mathrm{mg\,l^{-1}}$ detected in only 79% of water samples
PAHO & WHO 2001	Caribbean & Latin America	Urban population coverage of disinfected supplies ranges from 20% in Haiti to 100% in a number of Latin American countries
Rab *et al.* 1997	Islamabad, Pakistan	Hepatitis E outbreak occurred when consumers drank untreated water during major reparation of a treatment plant
Semenza *et al.* 1998	Nukus, Uzbekistan	Increased risk of diarrhoea in households not possessing adequate chlorine residual in piped water

Intermittent pressure is a problem in developing countries. For instance, in Phnom Penh, water pressure was found to be inadequate at the end of the network, which forced users to install pumps for water storage in tanks (Dany *et al.* 2000). In Lima, Peru, loss of water pressure was a daily occurrence 'due to pump stoppage to reduce the high cost of electrical power in the water treatment budget' (Geldreich 1996). Insufficient pressure has also caused disease outbreaks in the developing world. For instance, in Nukus, Uzbekistan, an outbreak of diarrhoea resulted from intermittent pressure within the distribution system two days prior to the outbreak (Semenza *et al.* 1998). It is clear that insufficient pressure in the distribution system can cause epidemics of disease in the population; evidence of this can be viewed in Table 2.

INTERMITTENT WATER SUPPLY

In arid and tropical areas, sources of water are scarce but the demand for domestic connections continues to increase in urban areas. In Colombo, Sri Lanka, this demand for domestic connections has increased by more than 10% annually since 1990 (Bradley *et al.* 2002). Some areas have even experienced depletion of groundwater sources because enormous withdrawals have exceeded the rate of aquifer recharge, as in the reported case of Mexico City (Gaytan *et al.* 1997).

Owing to the scarcity of water as a resource and the fact that treatment plants were designed and built for populations much smaller than they currently supply (Ford 1999), these water supply systems are not able to provide a continual supply of water. Thus, intermittent water service has become the norm, rather than the exception in many developing countries (Kumar 1998). In Latin America and the Caribbean, it is estimated that 60% of the population is served by household connections having intermittent service (PAHO & WHO 2001). In Africa and Asia, it is estimated that more than one-third and one-half of urban water supplies, respectively, operate intermittently (WHO & UNICEF 2000). Intermittency of water is affected by water availability and can also vary according to season. For example, in Phnom Penh, Cambodia, it was observed that continuous operation of the water supply was interrupted during the wet season, due to frequent filter backwashing and the need for basin cleaning (Dany *et al.* 2000), while in Jakarta, Indonesia, frequent interruptions in service occurred particularly in the summer (Alberini *et al.* 1996). In the city of Makkah, water supply increases during the Ramadan period by approximately 18%; nevertheless, current *supply* provided by the water authority is still only half of the actual *demand* for water (Al-Ghamdi & Gutub 2002).

Since treatment plants often encounter water shortages, consumers are provided with service for a restricted time period each day. Numerous examples of this intermittent supply are listed in Table 3.

A sporadic water supply means that, for the majority of the time that water is not provided to households, pressure in the system is drastically reduced and stagnant water remaining in the pipelines draws surrounding contaminants into the potable supply (Gadgil 1998; del Carmen Gordo Muñoz 1998; Ford 1999; Mermin *et al.* 1999). If wastewater drains or open gutters are located next to these pipes, the risk of contamination of drinking water with sewage is substantial (Moe *et al.* 1991; Mermin *et al.* 1999) thus increasing the risk to public health. In addition, surges in pressure from intermittent supply can cause uneven strain on pipes and connections, making them more prone to leaks (Al-Ghamdi & Gutub 2002; Chowdhury *et al.* 2002).

There are data showing that a continual water supply is safer than an intermittent supply. In Panaji City, India, all samples were negative for total coliforms in the continuous mode compared with 88% negative samples in the intermittent mode (Kelkar *et al.* 2002). Moreover, in a sample of four different Indian zones, nearly all (90–100%) samples were negative for fecal coliforms during continuous service, while only 24–73% were negative during intermittent supply (Kelkar *et al.* 2001).

Interrupted service has also been linked to a number of disease outbreaks in the developing world. In Jakarta, Indonesia, poor reliability of the water supply was most strongly associated with diarrhoeal illness, though overall diarrhoea rates were relatively low (Alberini *et al.* 1996). In Dushanbe, Tajikistan, low and intermittent water supply was a causal factor for a typhoid outbreak (Mermin *et al.* 1999) similar to the case of Nukus, Uzbekistan, where intermittent pressure was responsible for causing an outbreak of diarrhoea (Semenza *et al.* 1998).

Table 2 | Studies demonstrating inadequate network pressure

Study	Location	Summary of findings
Cárdenas *et al.* 1993	Riohacha, Colombia	Cross-contamination of water supply caused by negative pressure and back-siphonage
Chowdhury *et al.* 1999, 2002	Bangladesh	Inadequate system pressure at short distances from overhead tanks and pumphouses, with some areas experiencing zero pressure
Dany *et al.* 2000	Phnom Penh, Cambodia	At time of field visit, pumps not functioning well. Water pressure deemed inadequate at end of network
Geldreich 1996	Lima, Peru	Loss of water pressure a pre-planned, daily occurrence aimed at reducing high cost of electrical power in water treatment budget
Mermin *et al.* 1999	Dushanbe, Tajikistan	Typhoid epidemic resulted from contamination of water supply from inadequate pressure. Half of pumps non-operational, preventing proper pressure from being achieved
Moe *et al.* 1991	Cebu, Philippines	Fluctuations in pressure resulted in contaminated water where pipes lay in open gutters
Semenza *et al.* 1998	Nukus, Uzbekistan	Low pressure within distribution system preceded an outbreak of diarrhoea
Thompson *et al.* 2000	Iganga, Uganda	Frequent power cuts led to the inoperability of water pumps, resulting in unreliable water supply

An intermittent supply influences the behaviour of those receiving the service, which may further exacerbate water supply problems. First, an intermittent supply has been associated with increased water use and wastage (Kumar 1998; Bradley *et al.* 2002) compared with a continual supply. Wastage occurs because taps are left on owing to inconsistency or lack of predictability of when the next water supply will arrive, and thus each household attempts to draw a maximum quantity during supply hours (Kumar 1998). In addition, because of the unpredictability of service, many users construct their own pumps and water storage tanks either underground or aboveground. A marked increase in this trend is evident in East Africa, where 90% of piped households store water, whereas this figure was only 3% in 1967 (Thompson *et al.* 2000).

The construction of individual pumps and tanks further reduces the pressure and supply of water available to other consumers (Kumar 1998), complicating the hydraulics of the system (Massato & Thornton 1999) and exacerbating the problem enormously. Further health risks may also exist from the storage of water, as domestic tanks are often infrequently cleaned and/or improperly used (Geldreich 1996; WHO 1997; Jensen *et al.* 2002). Thus, it is clear that intermittent pressure and intermittent supply are complex but important contributors to distribution system failure and decreased health status.

LEAKAGES

The problem of unaccounted-for water, also called non-revenue water, is substantial in many developing countries. Unaccounted-for water is defined as the difference in the quantity of water delivered to the system and the quantity of water sold to customers (World Bank 1996a). This water loss comprises two components: commercial losses and physical losses (such as leaks) from the system; the latter constitutes the majority of non-revenue water (WHO & UNICEF 2000; Chowdhury *et al.* 2002).

Table 3 | Studies demonstrating intermittent water supply

Study	Location	Summary of findings
Agard *et al.* 2002	San Fernando, Trinidad	41% of households reported water shortages
Alberini *et al.* 1996	Jakarta, Indonesia	41% of households experienced frequent interruptions in service. Poor reliability of water supply most strongly associated with diarrhoea
Al-Ghamdi & Gutub 2002	Makkah, Saudi Arabia	Water pumped into one regional zone for certain number of days then rotated to another zone, to combat extra demands for water during Ramadan
Dany *et al.* 2000	Phnom Penh, Cambodia	During wet season, continuous service interrupted due to frequent filter backwashing and need for basin cleaning
Kelkar *et al.* 2001	India	Contamination of distribution systems due to intermittent water supply in conjunction with joint repair, leaky pipes and back-siphonage. 90–100% of samples found negative for fecal coliforms during continuous service, while only 24–73% found negative during intermittent supply
Kelkar *et al.* 2002	Panaji City, India	Usual water supply restricted to 3 hours in morning and 2 hours in evening. Water samples from continuous mode negative for total coliforms while only 88% negative during intermittent mode
Mermin *et al.* 1999	Dushanbe, Tajikistan	Half of residents reported daily outages lasting a median of 6 hours
Mohanty *et al.* 2003	Hyderabad City, India	Treatment plants capable of providing water supply for only 2 hours per day
PAHO & WHO 2001	Caribbean & Latin America	Percentage of population experiencing intermittent water service range from 0% in Chile to nearly 100% in Peru
Thompson *et al.* 2000	Iganga, Uganda	Some households reported being without piped water for up to 3 days

There is evidence that the crude number of leaks is extremely elevated in developing countries (Table 4). Pipe breaks in Minsk, Belarus, and Bogotá, Colombia, have been estimated at approximately 70 breaks per 100 km per year and 187 breaks per 100 km per year, respectively, compared with a US average of 17 breaks per 100 km per year (World Bank 1996a). The Water and Sewer Company in São Paulo, Brazil, has estimated an astonishing 35,000 leak situations per month (Massato & Thornton 1999). Furthermore in Hyderabad City, India, approximately 181 leaks are reported each day, and these refer only to leaks that are visible to the consumer (Mohanty *et al.* 2003).

Leakage rates for a water supply system are also calculated; these rates are expressed in the form of a ratio of lost water to the amount of water coming into the network. However, these estimates do not account for important distribution system properties including number of connections supplied, pipeline length, consumption rates and mean pressure (Al-Ghamdi & Gutub 2002), which may vary considerably from city to city. In addition, the condition of the infrastructure, volume of water supplied and supply continuity are important determining factors for leakage rates (World Bank 2003). Therefore, this ratio (often expressed as a percentage) is a simple way to estimate overall losses from a system, but is a crude indicator and cannot be used to compare distribution systems from region to region (Al-Ghamdi & Gutub 2002). Leakage rates have been determined for Mexico City at 37% (Conger 1999) with some rates reaching as high as 56% in Makkah, Saudi Arabia (Al-Ghamdi & Gutub 2002).

Further rates of unaccounted-for water (of which leakage rates are the greatest component) have been published for various regions by the World Bank (1996a) and in a review by Chowdhury *et al.* (2002), listed in Table 4. The average rate of unaccounted-for water has been estimated to be between 37% and 41% in the developing world (World Bank 1996a; WHO & UNICEF 2000); regional rates range broadly from 17% in Abidjan, Côte d'Ivoire, to 62% in Bursa, Turkey (World Bank 1996a), with most areas falling in the 30–50% range (Chowdhury *et al.* 2002). These rates of unaccounted-for water in developing countries are nearly twice the rate considered acceptable (20% or less) in developed countries (World Bank 1996a). For example, the rate of unaccounted-for water in North America is estimated to be 15% (WHO & UNICEF 2000); however, this figure was derived from only two cities, Toronto and New York, and is clearly not representative of North America as a whole.

The leakages rates estimated for a distribution system are a good indication of its state of structural integrity (Mohanty *et al.* 2003). As expected, the physical and chemical properties of the water supplied (including corrosivity and hydraulics) affect the deterioration and corrosion rates of infrastructure (Geldreich 1996). In addition, rates of deterioration are influenced by technology chosen, design engineering and spatial planning of the distribution system, which are often inferior in developing countries (Chowdhury *et al.* 2002). Furthermore, governments often contract projects to the lowest bidder, who may use low-grade materials and carry out poor workmanship (WHO 2003), including the installation of pipes at shallow depths which renders them vulnerable to frequent ground movements (Al-Ghamdi & Gutub 2002; Chowdhury *et al.* 2002). For instance, in Hyderabad, India, it was observed that pipelines laid only 1 metre below the surface cracked under high traffic loads (Mohanty *et al.* 2003).

If leaks occur in the pipeline and fecal contamination exists in the environment because of inadequate sewage collection or leaking wastewater pipes, a route exists for contaminants to be introduced into the water supply. This is a significant problem, since the greater the amount of leaks in the pipeline, the more opportunities for pressure loss and therefore the greater probability of contamination through the introduction of pathogens (Mohanty *et al.* 2003). Leaks in distribution systems have been found to result in poor quality water. For instance, in Cebu, Philippines, leaky pipes and fluctuations in pressure resulted in contaminated waters where pipes lay in open gutters (Moe *et al.* 1991). In addition, water sampled in Mexico City had high total and fecal coliform levels, thought to result from broken or poorly maintained pipes (Gaytan *et al.* 1997). An additional route of entry for pathogens exists during the reparation of leaks; inadequate disinfection following main break repair has resulted in contamination of the water supply (Kelkar *et al.* 2001; Besner *et al.* 2002).

Unfortunately, the replacement of distribution system infrastructure is a very slow process. Some visual leaks were reported in Bangladesh to have been flowing for several years before being repaired (Chowdhury *et al.* 2002). While it may only require 20 years for significant deterioration in a pipe to occur, in some cities it has been estimated to take up to 90 years to replace the system (Ford 2003). It is clear that the problems of leaking and deteriorating pipelines are important means for pathogen intrusion in the water supply.

CORROSION AND AGEING INFRASTRUCTURE

All distribution systems deteriorate over time; corrosion is an essential factor in the natural ageing process. Corrosion is defined as the partial solubilization of distribution system materials (del Carmen Gordo Muñoz 1998), and is a means of introducing organic and inorganic matter into the water supply. All materials, no matter what their composition, will deteriorate and corrode over time (Agard *et al.* 2002).

There is evidence that distribution systems are corroding in many regions in the world due, in part, to ageing processes. Even in developed countries, it is not uncommon to find pipes in service that are at least a century old (Haas 1998). In Hyderabad5, India, the oldest parts of the city's distribution system are approximately 100 years old; others are 60–70 years old and badly corroded (Mohanty *et al.* 2003). Chowdhury and colleagues (2002) also found that, in one Bangladeshi zone, approximately 20% of the piping from early last century was corroded and leaking and over 50% of sluice valves and fittings were badly rusted.

Table 4 | Studies demonstrating unaccounted-for water and leakages

Study	Location	Summary of findings
Al-Ghamdi & Gutub 2002	Makkah, Saudi Arabia	Leakage rates estimated at 56%
Cárdenas *et al.* 1993	Riohacha, Colombia	Cross-contamination of water supply suggested to originate from cracks in pipelines
Chowdhury *et al.* 2002	Bangladesh and Asia	Average rate of unaccounted-for water (UFW) estimated to range between 22 and 56% in Bangladesh. Other Asian cities range from 25% in Calcutta, India, to 58% in Manila, Philippines
Conger 1999	Mexico City, Mexico	Leakage rates estimated to be 37%
Gaytan *et al.* 1997	Mexico City, Mexico	High total and fecal coliform levels found in samples, probably resulting from broken or poorly maintained pipes
Massato & Thornton 1999	São Paulo, Brazil	Occurrence of 35,000 leak situations per month
Moe *et al.* 1991	Cebu, Philippines	Leaky pipes resulted in contaminated water where pipes lay in open gutters
Mohanty *et al.* 2003	Hyderabad City, India	181 leaks reported each day
World Bank 1996a	Various cities	Average rate of UFW in developing countries estimated to range from 17% in Abidjan, Côte d'Ivoire, to 62% in Bursa, Turkey
World Bank 1996a	Minsk, Belarus	Pipe breaks estimated at 70 breaks per 100 km per year
World Bank 1996a	Bogotá, Colombia	Pipe breaks estimated at 187 breaks per 100 km per year
World Bank 2003	Middle East and North Africa	Average rate of UFW ranges from 15% in Dubai, UAE, to 64% in Damascus, Syria

Characteristics of the distribution network, namely pipe material and composition, affect the extent of corrosion (Besner *et al.* 2002). Inferior-grade materials used in developing countries may enhance the rate of corrosion. In Bangladesh, a survey of four medium-sized cities found pipes to be of poor quality, mainly composed of asbestos-cement and cast iron. These pipes and additional fittings were also found to have been installed with poor workmanship (Chowdhury *et al.* 1999). Generally, cement-based materials undergo rapid deterioration in structural integrity, often within 15–25 years of operation (Wagner 1994). Similarly, in Latvia, the distribution network was declared to be ageing and composed of cast iron pipes (Juhna & Klavins 2001), which, although commonly used as a building material in distribution systems worldwide, offers 'insufficient protection against internal corrosion' (Wagner 1994). It has been suggested that pipes made out of PVC, galvanized iron and mild steel are superior alternatives to the above materials used in water supply infrastructure (Chowdhury *et al.* 1999).

High concentrations of metal precipitates solubilized in the water seriously decreases the chemical quality of the water ingested by the consumer (Wagner 1994). This can be a significant public health concern, depending on the material composition of the pipes. For example, lead pipes and solders, commonly used in distribution systems in the last century, degrade over time, causing lead to leach into the water and be ingested by the consumer. Furthermore, it has been shown that concentrations of lead in drinking water may be significant after periods of stagnation (van Dijk-Looijaard & van Genderen 2000), as is common in intermittent supply systems. While lead pipes are no longer being installed in new networks (Wagner 1994), there are still many such pipes in existence which can only be replaced at high cost (del Carmen Gordo Muñoz 1998). Cement-based materials such as concrete and asbestos-cement may leach calcium-containing products and asbestos fibres into the water, while metal-based materials such as iron will oxidize to form precipitates in the water (Wagner 1994). In addition, elevated levels of copper, zinc and cadmium may dissolve in the water (Wagner 1994) and could be a public health concern in many countries where distribution systems are ageing.

Furthermore, corrosion decreases the bacterial quality of the water supply by creating conditions suitable for the growth of microorganisms. Even the more inert materials such as plastics or rubber-based materials can provide organic nutrients for bacteria and therefore enhance microbial growth (Agard *et al.* 2002). During corrosion, tiny pitted cavities or tubercules develop within the walls of the distribution system, wearing away the smooth surface and creating sites for bacteria to attach and grow (Besner *et al.* 2002). These tubercules provide microenvironments for the growth of biofilms, which are thin layers of anaerobic and aerobic microorganisms adhering to the inner surface of the pipe wall (Geldreich 1996). Biofilm formation can decrease water quality by rapidly depleting the chlorine residual present, and can possibly 'hide' pathogens by protecting them from disinfection exposure (Geldreich 1996).

Not only does corrosion enhance biofilm formation, but in turn the growth of biofilms enhances corrosion of pipes because of the increased surface perforation (Egorov *et al.* 2002). There has been an association observed between corroding systems and deteriorating water quality. In Phnom Penh, 44% of water samples connected to ageing pipes revealed coliform contamination, while only 25% of water samples connected to newly constructed pipes were contaminated (Dany *et al.* 2000). In addition, higher coliform concentrations have been demonstrated to occur with certain materials that corrode easily (for instance, iron) than with PVC or galvanized copper piping (LeChevallier *et al.* 1996).

Corrosion further decreases the microbial quality of the water by increasing the turbidity of the water. Turbidity, defined as the interference of light passage through water by insoluble particles, is used as an indicator to determine water quality and often, filtration effectiveness (Hammer & Hammer 2001; US Environmental Protection Agency 2003). Due to the increased amount of precipitates in the water from corrosion, the amount of particulate matter (and thus turbidity) increases (Juhna & Klavins 2001). As a result, microbes may attach and aggregate onto these particles and be protected from disinfection (Besner *et al.* 2002), rendering a disinfection residual less effective.

There is evidence to suggest that high turbidity may be a significant problem in developing countries; at one plant in Tajikistan, algae growing in the sedimentation basins contributed to increased turbidity leaving the plant (Mermin *et al.* 1999). Meanwhile, an increase in water turbidity of 0.8 nephelometric turbidity units in Cherepovets, Russia, was associated with a 47% increased risk for diarrhoeal illness (Egorov *et al.* 2003). However, while turbidity is a useful analytical tool for water quality at the treatment plant, it is not an informative indicator of actual numbers of organisms that are present, nor can it be used as an indicator within the distribution system, which is a function of time, flow rates and corrosion (del Carmen Gordo Muñoz 1998; Egorov *et al.* 2002).

In addition to turbidity, other physical and chemical parameters of the water can determine the rate of corrosion and the quality of the water supplied. These properties include: the disinfectant residual concentration, temperature, pH, mineral content, and nutrient levels as determined by dissolved oxygen and assimilable organic carbon (Wagner 1994; del Carmen Gordo Muñoz 1998; Juhna & Klavins 2001; Agard *et al.* 2002; Egorov *et al.* 2002). However, each distribution system is unique because of the varying structural materials used and varying properties of the supply water. Therefore, a particular water characteristic may be an important determinant of corrosion and water quality in one system, but unimportant in another (McNeill & Edwards 2001).

Generally, disinfection residual in the water supply decreases the viable microorganisms present. However, corrosion rapidly reduces the concentration of free disinfectant (Trussell 1998); in fact, the type and extent of corrosion seriously affects the ability of a disinfectant to inactivate pathogens (LeChevallier *et al.* 1996). Disinfection has even been determined to 'provide selection pressures on pathogens that promote a wide range of survival strategies' (Ford 1999). Clearly, the ability of a disinfectant to inactivate pathogens is crucial to ensuring high microbial quality of water, and therefore, the extent of corrosion can seriously hinder the effectiveness of a disinfectant residual.

Water temperature is also a crucial determinant of microbiological water quality. Bacterial growth rates, decay of disinfection residual, corrosion rates and even distribution hydraulics are all affected by water temperature (LeChevallier *et al.* 1996). It has been observed, for instance, that when water temperatures rise above 15°C, the growth of colonizing bacteria in the distribution system increases markedly (LeChevallier *et al.* 1991; LeChevallier *et al.* 1996; Geldreich 1996). In Pietermaritzburg, South Africa, higher coliform counts were found to be associated with higher water temperatures in the distribution system (Bailey & Thompson 1995). Thus, when water temperatures are high year-round, as in the case of tropical climates in developing countries, there is more rapid growth of microorganisms than would be found in temperate climates. In addition, higher temperatures of water increase corrosion rates in certain infrastructure materials (Wagner 1994).

Mineral content of waters and pH also determine the extent of corrosion and growth of bacteria in the distribution network. Water sources may vary widely; some are 'soft' (low mineral content) and usually accompanied by low pH, while some are 'hard' (high alkalinity and dissolved neutral salts) (Wagner 1994). It was determined that, in Mexico City, owing to the 'softness' of the water supplied, pipes were susceptible to corrosion (Gaytan *et al.* 1997). For iron pipes, however, generally as pH decreases the rate of corrosion decreases (McNeill & Edwards 2001). This is compatible with the requirement for rapid disinfection of water, which requires a lower pH range of 6.0 to 6.5 (Dany *et al.* 2000; Besner *et al.* 2002). However, this low pH requirement may increase the leaching rates of certain materials into the water, such as lead (Wagner 1994). Therefore, depending on a number of characteristics of the distribution system, pH can be a strong determining factor in the bacterial and chemical quality of water.

Finally, additional parameters that may influence water quality and corrosion rates are nutrient levels in the water, often measured by dissolved oxygen and assimilable organic carbon concentrations. Generally for iron-based materials, increasing dissolved oxygen levels result in higher corrosion rates because of oxygen's role in reduction–oxidation reactions (McNeill & Edwards 2001). Assimilable organic carbon (AOC) is a means of detecting the level of nutrients necessary for bacteria to thrive; these include carbon, nitrogen and phosphate (Geldreich 1996), as well as humic and fulvic acids (del Carmen Gordo Muñoz 1998). While the ageing of infrastructure and stagnancy of water in the pipelines increases organic content of water, it has been proposed that an adequate disinfection residual can control the growth of bacteria arising from these high AOC concentrations (del Carmen Gordo Muñoz 1998).

Most developing countries have severe limitations on resources which restrict the continued operational capability of their water supplies. The breakdown of equipment is a frequent occurrence in many regions. For example, in Phnom Penh, Dany *et al.*(2000) noted that 'at the time of the field visit … the pumps were not functioning well'. In Iganga, Uganda, while four pumps had been operational in the 1960 s, only one pump was functional by 1980. Furthermore, frequent power cuts led to the inoperability of water pumps, resulting in an unreliable water supply (Thompson *et al.* 2000). Some regions, such as Lima, Peru, even plan for pump stoppage each day, 'to reduce the expense of electrical power in the budget' (Geldreich 1996). These resource limitations in turn result in poor quality of water supplied to users.

IMPROPER WASTE COLLECTION AND POOR SANITATION

Inadequate waste collection and its potential for contamination of the water supply is a significant problem in developing countries. It has been suggested by Gadgil (1998) that:

> good drinking water quality is a necessary, but by no means sufficient, condition for elimination of diarrhoeal diseases as a public health issue … good sanitation practices and adequate methods to dispose of human and animal excrement are thus first necessities.

It is becoming clear that simply improving the quality of the water supply is not sufficient to eliminate all of the associated water-related diseases in developing countries (Gadgil 1998). Rather, a *combined* intervention of water supply and sanitation improvements, including waste collection and emphasis on personal hygiene such as bathing, handwashing and other hygienic behaviour (Luby *et al.* 2001; Roberts *et al.* 2001; Cairncross 2003) is necessary to significantly reduce the global diarrhoeal disease burden (Younes & Bartram 2001; Mohanty *et al.* 2003).

INEQUITABLE PRICING AND USAGE OF WATER

Commercial losses from the water supply system, or the use of water without being monetarily charged, is a serious problem in developing countries and contributes significantly to unaccounted-for water. The World Bank even suggests that, in certain regions, commercial losses pose a greater problem than physical leakages in the system (Yepes 1995). For example, it is estimated that in San José, Costa Rica, and Bogotá, Colombia, commercial losses comprise 54% and 65% of unaccounted-for water, respectively (World Bank 1996a).

Meters are used to document water usage, but may not capture all users of the service owing to meter malfunctions or non-metered, illegal tap-ins to water supply lines (Chowdhury *et al.* 1999). A number of countries experience either or both of these problems. It was observed in Panaji City, India, that only 65% of the meters were in working condition (Kelkar *et al.* 2002) while in Colombo, Sri Lanka, the overall estimate of illegal connections was estimated to be as high as 19% in some areas, with 85% of these illegal connections being unmetered (Bradley *et al.* 2002). Unfortunately, the cost of meter replacement is a substantial expenditure for many water supply organizations (WHO & UNICEF 2000), which may be an important reason for poor meter installation and replacement.

In many regions, a fixed price for water supply is charged to all customers (Geldreich 1996), resulting in a disproportionate percentage of income paid for the service by the poor (Bowonder & Chettri 1984; PAHO & WHO 2001). Since impoverished residents are less able to afford this service, this may encourage the use of illegal connections. This is a major emerging problem in many urban cities of the world where, increasingly, unauthorized connections and bypass lines are being constructed (Chowdhury *et al.* 2002) especially in squatter settlements (Bradley *et al.* 2002). Additionally, consumers may also be reluctant to pay for an intermittent, poor-quality service which therefore compounds the problem (WHO 1997). As a result, the true number of users and necessary volume of water is not accounted for by the water supplier. Thus, the volume of water output is underestimated, further decreasing water supply and increasing shortages, exacerbating problems with low pressure and intermittent service which then affect water quality.

In addition, since non-metered or illegal users are not held financially accountable for the service that they obtain, there is no incentive to conserve water. In Bangladesh, non-metered connections were found to be among the primary contributors of water wastage (Chowdhury *et al.* 1999). Also, in Dushanbe, Tajikistan, where water was provided without charge in the community, vast wastage of water occurred, half of it resulting from leaving taps open in the home. Since residents were not charged monetarily for their water consumption, leaving the faucet running was not considered wasteful (Mermin *et al.* 1999). It is apparent that, until users are held financially accountable for the resource used, continued wastage of water will have a severe impact on the quantity and quality of the water supplied.

RISK ASSESSMENT

At this point in time, limited data are available for risk assessment regarding the number of people, globally, who are exposed to pathogens resulting from distribution system failure. However, as may be speculated from this review, this appears to be a relatively common occurrence in many urban areas of the developing world. Thus, millions of people may be at risk of contracting illness from what should be considered a safe water supply. In addition, as for most diseases, variations in humans and differing health status allow certain groups to be more susceptible. It is thought that 'the risk for those in developing countries, where there is often poor water treatment and management as well as inadequate medical support, is very much greater' (Gleeson & Gray 1997).

Uncertainties in the scientific domain are extremely large due to the scarcity of information available, the multi-aetiological nature of diarrhoeal disease, numerous possible exposure pathways, and limited analytical techniques and indicators utilized. It is clear that there is yet much to be explored in the realm of risk assessment.

RECOMMENDATIONS

In developing countries, the rate of unaccounted-for water is much higher than rates found in developed countries. It has been shown that as operations and maintenance of a distribution system decrease, unaccounted-for water levels increase rapidly (World Bank 1996a). While the World Health Organization (2003) has suggested that wastage of water should be minimized to no more than 10% once all contributing factors have been accounted for, it has been proposed that a more realistic goal is closer to 20% in developing countries (Kumar 1998).

In order to achieve lower rates of unaccounted-for water and to increase quality of water supplied, a number of problem-specific, point-source strategies have been recommended, including: chlorination at multiple points within the system (Egorov *et al.* 2002), leak detection and prompt repair (Kumar 1998; Chowdhury *et al.* 2002), rehabilitation of old pipes, and routine checks on valves (Massato & Thornton 1999). Recent programmes to reduce water loss in São Paulo have incorporated the above strategies and have proved to be tremendously successful (Massato & Thornton 1999). To combat pressure problems and intermittent service, strict enforcement of a minimum pressure is required, with the potable water supply always maintained at higher pressure than the non-potable system. Dead-end connections and cross-connections should be eliminated to protect against backflow and cross-contamination (Trussell 1998). Intermittent service can be improved by increasing the volume of water reaching residents, minimizing water loss by proper management of the distribution system (Semenza *et al.* 1998).

To counter problems with corrosion, possible solutions include increasing the pH of the water and the addition of phosphates or silicates (del Carmen Gordo Muñoz 1998; Besner *et al.* 2002) which decreases the solubility of metals and reduces surface corrosion. Specific programmes may also be undertaken to flush out sediment and organic matter in low-flow areas to prevent biofilm formation (Trussell 1998; Besner *et al.* 2002). In addition, using more inert structural materials in construction can decrease the rate of deterioration (Trussell 1998).

In order to appropriately account for water use and control wastage, accurate valuation of water must occur (Ford 1999) with equitable pricing of services (PAHO & WHO 2001). Careful monitoring and billing of water usage, maintenance and replacement of faulty meters, and location of unauthorized users must occur (Yepes 1995; Bradley *et al.* 2002). It has further been suggested that penalties should be enforced if regulations are not followed (Dany *et al.* 2000). If users are forced to pay out of their own pockets for a service, they will be reluctant for the resource to go to waste. In Latvia, a successful campaign to decrease water usage involved the installation of household water meters, one factor which drastically decreased consumption of water to 100 l per person per day (Juhna & Klavins 2001).

The fundamental causes of distribution system failures are related to problems in political, social and economic commitment, leading to poor operation and maintenance of the water supply system. Collapsed water systems have been linked to absence of political support, inadequate or improper use of funds, poor management and poor cost-recovery. In addition, major problems including lack of sector coordination, poor communication, insufficient community involvement, inadequate human resources or insufficiently trained personnel have also been implicated (WHO & UNICEF 2000; WHO 2003). Since the continued operation and maintenance of a supply system ensures its sustainability (Davis & Brikké 1995), it is clear that these fundamental problems must first be addressed before any significant changes to the operations of water supply systems will occur.

Overall, solutions to ensure high quality potable water involve a sustainable approach. As Younes and Bartram (2001) have stated, drinking water supply cannot be considered independently of other water-related issues. For example, water treatment is crucial but polluted water sources 'are more costly to treat than less polluted sources, and increasing reliance on degraded water resources is likely to increase the costs of supply' (Younes & Bartram

2001), thus decreasing sustainability. In addition, Haas (1998) has emphasized the danger of relying solely on mechanical integrity to protect public health. A solution, therefore, would be a multi-barrier approach to water supply and resource management. That is, a number of steps comprising: watershed protection to ensure cleaner sources, adequate treatment of water, proper sanitation practices with sewage collection and treatment, maintenance of the distribution system, and minimizing the wastage of water (Geldreich 1996; World Resources Institute *et al.* 1996; Mermin *et al.* 1999; Ford 2003).

The financial benefits reaped from decreasing unaccounted-for water are tremendous. During the 1980 s in urban areas in Thailand, every 10% reduction of unaccounted-for water saved an additional US$8 million per year (World Resources Institute *et al.* 1996). For Latin America as a whole, water losses add up to an estimated US$1 to $1.5 billion per year (World Resources Institute *et al.* 1996), and thus the majority of this cost would be recovered if campaigns were undertaken to reduce loss. Furthermore, in Bangladesh, the volume of water recovered from various losses was estimated to serve thousands, to tens of thousands of additional customers in a single city (Chowdhury *et al.* 2002). Thus, it is clear that if water losses are minimized, there would be a substantial increase in the population receiving access to water, not to mention huge financial benefits reaped which could be diverted to other projects.

In summary, there are a number of system-specific solutions to distribution system flaws; however, it is clear that these are only temporary solutions. Until political and financial support for the water supply sector increases, poor management and cost-recovery will result in an unsustainable water supply. A multi-barrier approach to sector operations and management must occur, to ensure improved quantity as well as quality of water supplied to consumers.

CONCLUSION

As is evident from the available microbiological, engineering and epidemiological studies, a water distribution system does not simply transport water from the treatment plant to the consumer. Distribution system deficiencies, encompassing: inadequate disinfection residual, low pressure, intermittent service, leaks and corrosion often interact with each other and result in decreased quantity as well as quality of water arriving at the consumer. A poorly maintained distribution system can act as a vehicle of transmission for pathogens, and may even contribute significantly to gastrointestinal disease in the community. In addition, equipment malfunction or treatment failure may result from scarce resources available, or as a result of poor operations and maintenance. Clearly, the health consequences of these supply services are counter-productive to the primary purpose of distribution networks.

The problems relating to unaccounted-for water and distribution system deficiencies remain overlooked and unacknowledged by some governments in developing countries. The usual response is to expand and build new infrastructure in an attempt to increase water supply, requiring expensive investment capital (World Resources Institute *et al.* 1996; Younes & Bartram 2001; World Bank 2001). This is partially due to political visibility: provision of a novel water supply is a ‘vote-winning exercise’ while continued operation and maintenance has an inferior profile (WHO 2003).

Currently, the scientific basis is tenuous for the quantitative risk assessment process for diarrhoeal disease resulting from distribution system failure. The uncertainties inherent regarding incidence of distribution system problems, underreporting of disease, estimation of a minimum-infectious dose, and limitations of sampling and detection, render the estimation of dose-response difficult. Uncertainties in population impact, behaviour and susceptibility add to the difficulty in characterizing risk.

A number of suggestions to improve the operation, maintenance and sustainability of a water supply system have been described by the World Bank (2001). These recommendations include: routine and preventive maintenance such as leak detection and repair, maintaining a minimum pressure in the system, adequate pricing through setting tariffs, careful billing of users, and monitoring and evaluation of services provided.

It is evident that the topic of distribution systems as significant contributors to water-related diseases is slowly gaining recognition globally. Despite the growing interest, there is a limited amount of information regarding this topic. Data on the frequency of diarrhoeal disease resulting from distribution system inadequacies, let alone as a result of particular distribution problems, are not available. Should data exist, they are often for a single zone or city of a developing nation and may be published in the local language. The WHO (2003) has specifically requested more data to be obtained on: the number of failed water systems, exact parts of systems that have failed (such as pumping stations, treatment plants and distribution networks) and specific reasons why systems have failed. Furthermore, financial data have been requested in order to calculate economic losses from poor operation and maintenance (WHO 2003).

An increased scientific body of literature will thus allow policy makers and governmental bodies to effectively manage risk in their respective countries. It is hoped that, through the implementation of appropriate solutions, the disease burden from diarrhoea will be reduced globally.

ACKNOWLEDGEMENTS

This report was partially funded by a cooperative research agreement with Procter & Gamble and funds provided by the Johns Hopkins Center for Livable Future.

REFERENCES

Agard, L., Alexander, C., Green, S., Jackson, M., Patel, S. & Adesiyun, A. 2002 Microbial quality of water supply to an urban community in Trinidad. *J. Food Prot.* **65**(8), 1297–1303.

Alberini, A., Eskeland, G. S., Krupnick, A. & McGranahan, G. 1996 *Determinants of Diarrheal Disease in Jakarta*. World Bank, Washington, DC, Policy Research Working Paper 1568.

Al-Ghamdi, A. S. & Gutub, S. A. 2002 Estimation of leakage in the water distribution network of the Holy City of Makkah. *J. Wat. Suppl.: Res. & Technol.- AQUA* **51**(6), 343–349.

Bailey, I. W. & Thompson, P. 1995 Monitoring water quality after disinfection. *Wat. Suppl.* **13**(2), 35–48.

Basualdo, J., Pezzani, B., De Luca, M., Cordoba, A. & Apezteguia, M. 2000 Screening the municipal water system of La Plata, Argentina, for human intestinal parasites. *Int. J. Hyg. Environ. Health* **203**(2), 177–182.

Baxter, G. 1995 Chlorine disinfection: the industry standard. *Wat. Suppl.* **13**(2), 183–193.

Besner, M. C., Gauthier, V., Servais, P. & Camper, A. 2002 Explaining the occurrence of coliforms in distribution systems. *J. Am. Wat. Wks Assoc.* **94**(8), 95–109.

Bowonder, B. & Chettri, R. 1984 Urban water supply in India: environmental issues. *Urban Ecol.* **8**(4), 295–311.

Bradley, R. M., Weeraratne, S. & Mediwake, T. M. M. 2002 Water use projections in developing countries. *J. Am. Wat. Wks Assoc.* **94**(8), 52–63.

Cairncross, S. 2003 Editorial: Water supply and sanitation: some misconceptions. *Trop. Med. Int. Health* **8**(3), 193–195.

Cárdenas, V., Saad, C., Varona, M. & Linero, M. 1993 Waterborne cholera in Riohacha, Colombia, 1992. *Bull. PAHO* **27**(4), 313–330.

Chowdhury, M. A. I., Ahmed, M. F. & Gaffar, M. A. 1999 Water system leak detection in secondary towns of Bangladesh. *Wat. Suppl.* **17**(3/4), 343–349.

Chowdhury, M. A. I., Ahmed, M. F. & Gaffar, M. A. 2002 Management of nonrevenue water in four cities of Bangladesh. *J. Am. Wat. Wks Assoc.* **94**(8), 64–75.

Conger, L. 1999 Delivering water to Mexico City. *Urban Age Mag., Urban Dev.* **6**(3), 16–17.

Craun, G. F. & Calderon, R. L. 2001 Waterborne disease outbreaks caused by distribution system deficiencies. *J. Am. Wat. Wks Assoc.* **93**(9), 64–75.

Craun, G. F., Nwachuku, N., Calderon, R. L. & Craun, M. F. 2002 Outbreaks in drinking water systems, 1991-1998. *J. Environ. Health* **65**(1), 16–23.

Dany, V., Visvanathan, C. & Thanh, N. C. 2000 Evaluation of water supply systems in Phnom Penh City: a review of the present status and future prospects. *Int. J. Wat. Resour. Dev.* **16**(4), 677–689.

Davis, J. & Brikké, F. 1995 *Making Your Water Supply Work: Operation and Maintenance of Small Water Supply Systems*. IRC International Water and Sanitation Centre, The Hague, The Netherlands.

del Carmen Gordo Muñoz, M. 1998 International report: water quality in distribution. *Wat. Suppl* **16**(1/2), 89–97.

Diergaardt, G. F. & Lemmer, T. N. 1995 Alternative disinfection methods for small water supply schemes with chlorination problems. *Wat. Suppl.* **13**(2), 309–312.

Egorov, A., Ford, T., Tereschenko, A., Drizhd, N., Segedevich, I. & Fourman, V. 2002 Deterioration of drinking water quality in the distribution system and gastrointestinal morbidity in a Russian city. *Int. J. Environ. Health Res.* **12**(3), 221–233.

Egorov, A., Naumova, E. N., Tereschenko, A. A., Kislitsin, V. A. & Ford, T. E. 2003 Daily variations in effluent water turbidity and diarrhoeal illness in a Russian city. *Int. J. Environ. Health Res.* **13**(1), 81–94.

Ford, T. E. 1999 Microbiological safety of drinking water: United States and global perspectives. *Environ. Health Perspect.* **107**(Suppl. 1), 191–206.

Ford, T.E 2003. *Increasing Risks from Waterborne Disease: Both U.S. and International Concerns*. Center for Health and the Global Environment, Harvard Medical School, www.med.harvard.edu/chge/textbook/global/drinking/transcript.htm.

Gadgil, A. 1998 Drinking water in developing countries. *Ann. Rev. Energy Environ.* **23**, 253–286.

Gaytan, M., Castro, T., Bonilla, P., Lugo, A. & Vilaclara, G. 1997 Preliminary study of selected drinking water samples in Mexico City. *Rev. Int. Contamin Ambient* **13**(2), 73–78.

Geldenhuys, J. 1995 Chloramination to preserve microbiological quality: experience at Rand Water. *Wat. Suppl.* **13**(2), 313–316.

Geldreich, E. 1996 *Microbiological Quality of Water Supply in Distribution Systems*. CRC Lewis Publishers, Boca Raton, Florida.

Gleeson, C. & Gray, N. 1997 *The Coliform Index and Waterborne Disease*, 1st edn. E FN Spon Ltd, London, UK.

Haas, C. N. 1998 Benefits of a disinfection residual. *Wat. Suppl.* **16**(3/4), 85–93.

Hammer, M. J. & Hammer, M. J. J. 2001 *Water and Wastewater Technology*, 4th edn. Prentice-Hall, Upper Saddle River, New Jersey.

Herrick, D. 1997 Cross-connections and backflow. *Wat. Well J.* **51**(5), 67–70.

Jensen, P. K., Ensink, J. H., Jayasinghe, G., van der, H. W., Cairncross, S. & Dalsgaard, A. 2002 Domestic transmission routes of pathogens: the problem of in-house contamination of drinking water during storage in developing countries. *Trop. Med. Int. Health.* **7**(7), 604–609.

Juhna, T. & Klavins, M. 2001 Water-quality changes in Latvia and Riga 1980-2000: possibilities and problems. *Ambio* **30**(4-5), 306–314.

Kelkar, P. S., Talkhande, A. V., Joshi, M. W. & Andey, S. P. 2001 Water quality assessment in distribution system under intermittent and continuous modes of water supply. *J. Indian Wat. Wks Assoc.* **33**(1), 39–44.

Kelkar, P. S., Andey, S. P., Pathak, S. K. & Nimbalkar, K. G. 2002 Evaluation of water distribution system for water consumption, flow pattern and pressure survey during intermittent vis-à-vis continuous water supply in Panaji City. *J. Indian Wat. Wks Assoc.* **34**(1), 27–36.

Kumar, A. 1998 Technologies to improve efficiency in distribution system with intermittent supplies. *Wat. Suppl.* **16**(1-2), 577–579.

LeChevallier, M. W., Schulz, W. & Lee, R. G. 1991 Bacterial nutrients in drinking water. *Appl. Environ. Microbiol.* **57**(3), 857–862.

LeChevallier, M. W., Welch, N. J. & Smith, D. B. 1996 Full-scale studies of factors related to coliform regrowth in drinking water. *Appl. Environ. Microbiol.* **62**(7), 2201–2211.

Luby, S. P., Agboatwalla, M., Raza, A., Sobel, J., Mint, E. D., Baier, K., Hoekstra, R. M., Rahbar, M. H., Hassan, R., Qureshi, S. M. & Gangarosa, E. J. 2001 Microbiologic effectiveness of hand washing with soap in an urban squatter settlement,Karachi, Pakistan. *Epidemiol. Infect.* **127**(2), 237–244.

Massato, P. & Thornton, J. 1999 Pressure control – a success story in reducing losses in one of the world's largest water supply organizations. *Wat. Suppl.* **17**(3/4), 253–257.

McNeill, L. S. & Edwards, M. 2001 Iron pipe corrosion in distribution systems. *J. Am. Wat. Wks Assoc.* **93**(7), 88–100.

Mermin, J. H., Villar, R., Carpenter, J., Roberts, L., Samaridden, A., Gasanova, L., Lomakina, S., Bopp, C., Hutwagner, L., Mead, P., Ross, B. & Mintz, E. D. 1999 A massive epidemic of multidrug-resistant typhoid fever in Tajikistan associated with consumption of municipal water. *J. Infect. Dis.* **179**(6), 1416–1422.

Moe, C. L., Sobsey, M. D., Samsa, G. P. & Mesolo, V. 1991 Bacterial indicators of risk of diarrhoeal disease from drinking-water in the Philippines. *Bull. WHO* **69**(3), 305–317.

Mohanty, J. C., Ford, T. E., Harrington, J. J. & Lakshmipathy, V. 2003 A cross-sectional study of enteric disease risks associated with water quality and sanitation in Hyderabad City. *J. Wat. Suppl.: Res. & Technol. - AQUA* **51**(5), 239–251.

Nelson, K. E. 2001 Early history of infectious disease: epidemiology and control of infectious diseases. In *Infectious Disease Epidemiology: Theory and Practice* K. E. (Nelson, C. Masters Williams & Graham N. M. H. eds). Aspen Publishers, Gaithersburg, Maryland.

PAHO 1997 *Water Supply and Sanitation*. Subcommittee on Planning and Programming, Provisional Agenda Item 7. Pan American Health Organization, Washington, DC.

PAHO & WHO 2001 *Regional Report on the Evaluation 2000 in the Region of the Americas*. Pan American Health Organization, Washington, DC.

Rab, M. A., Bile, M. K., Mubarik, M. M., Asghar, H., Sami, Z., Siddiqi, S., Dil, A. S., Barzgar, M. A., Chaudhry, M. A. & Burney, M. I. 1997 Water-borne hepatitis E virus epidemic in Islamabad, Pakistan: a common source outbreak traced to the malfunction of a modern water treatment plant. *Am. J. Trop. Med. Hyg.* **57**(2), 151–157.

Roberts, L., Confalonieri, U. E. & Aron, J. L. 2001 Too little, too much: how the quantity of water affects human health. In *Ecosystem Change and Public Health: A Global Perspective,* (Aron J. L. & Patz J. A. eds). Johns Hopkins University Press, Baltimore, Maryland.

Semenza, J. C., Roberts, L., Henderson, A., Bogan, J. & Rubin, C. H. 1998 Water distribution system and diarrheal disease transmission: a case study in Uzbekistan. *Am. J. Trop. Med. Hyg.* **59**(6), 941–946.

Thompson, J., Porras, I. T., Tumwine, J. K., Mujwahuzi, M. R., Katui-Katua, M., Johnstone, N. & Wood, L. 2000 *Drawers of Water II: Thirty Years of Change in Domestic Water Use and Environmental Health in East Africa*. Russell Press, Nottingham.

Trussell, R. R. 1998 An overview of disinfectant residuals in drinking water distribution systems. *Wat. Suppl.* **16**(3/4), 1–15.

Tulchinsky, T. H., Burla, E., Clayman, M., Sadik, C., Brown, A. & Goldberger, S. 2000 Safety of community drinking-water and outbreaks of waterborne enteric disease: Israel, 1976-97. *Bull. WHO* **78**(12), 1466–1473.

United Nations Environment Programme 2002 *Vital Water Graphics: An Overview of the State of the World's Fresh and Marine Waters*. United Nations, Nairobi.

United Nations Population Division 2002 *World Urbanization Prospects: The 2001 Revision*. United Nations, New York.

US Environmental Protection Agency 2003 *National Primary Drinking Water Standards*. Environmental Protection Agency, Washington, DC.

van Dijk-Looijaard, A. M. & van Genderen, J. 2000 Levels of exposure from drinking water. *Food Chem. Toxicol.* **38**(1 Suppl.), S37–S42.

Wagner, I. 1994 International report: internal corrosion of pipes in public water distribution networks. *Wat. Suppl.* **12**(1/2), IR7-1–IR7-5.

WHO 1997 *Guidelines for Drinking Water Quality, Volume 3: Surveillance and control of community supplies*. World Health Organization, Geneva, Switzerland.

WHO 2003. *Constraints Affecting the Development of the Water Supply and Sanitation Sector*. World Health Organization, http://www.who.int/docstore/water_sanitation_health/wss/constraints.html.

WHO & UNICEF 2000 *Global Water Supply and Sanitation Assessment 2000 Report*. Iseman Creative, Washington, DC.

World Bank 1996a *Indicators: Water and Wastewater Utilities*, 2nd edn. World Bank, Washington, DC.

World Bank 1996b *Venezuela to Improve Water Supply and Sanitation Service in the State of Monagas*. World Bank, http://web.worldbank.org/WBSITE/EXTERNAL/NEWS/0,contentMDK:20016167 ~ menuPK:34466 ~ pagePK:34370 ~ piPK:34424 ~ theSitePK:4607,00.html.

World Bank 2001 *Managing Urban Water Supply and Sanitation: Operation and Maintenance*. Operations Evaluation Department, http://lnweb18.worldbank.org/oed/oeddoclib.nsf/DocUNIDViewForJavaSearch/DA03FC69245CF326852567F5005D805D?opendocument.

World Bank 2003 *Unaccounted for Water*. World Bank, http://lnweb18.worldbank.org/mna/mena.nsf/All/6C586003928975DE85256949006FC441?OpenDocument.

World Resources Institute, United Nations Environment Programme, United Nations Development Programme & World Bank 1996 *World Resources: A Guide to the Global Environment*. Oxford University Press, Oxford.

Yepes, G. 1995 *Reduction of Unaccounted-for Water: the Job Can Be Done!. World Bank Report*. World Bank, Washington, DC.

Younes, M. & Bartram, J. 2001 Waterborne health risks and the WHO perspective. *Int. J. Hyg. Environ. Health* **204**(4), 255–263.