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Global challenges in water, sanitation and health

Christine L. Moe and Richard D. Rheingans

ABSTRACT

The year 2005 marks the beginning of the "International Decade for Action: Water for Life" and renewed effort to achieve the Millennium Development Goals (MDGs) to reduce by half the proportion of the world's population without sustainable access to safe drinking water and sanitation by 2015. Currently, UNICEF and WHO estimate that 1.1 billion people lack access to improved water supplies and 2.6 billion people lack adequate sanitation. Providing safe water and basic sanitation to meet the MDGs will require substantial economic resources, sustainable technological solutions and courageous political will. We review five major challenges to providing safe water and sanitation on a global basis: (1) contamination of water in distribution systems, (2) growing water scarcity and the potential for water reuse and conservation, (3) implementing innovative low-cost sanitation systems, (4) providing sustainable water supplies and sanitation for megacities, and (5) reducing global and regional disparities in access to water and sanitation and developing financially sustainable water and sanitation services.

Key words | drinking water, ecological sanitation, megacities, millenium development goals, water distribution systems, water reuse, water scarcity

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INTRODUCTION AND BACKGROUND

It is currently estimated that 1.1 billion people in the world lack access to improved water supplies and 2.6 billion people lack adequate sanitation (UNICEF *et al.* 2004). The global health burden associated with these conditions is staggering, with an estimated 4000–6000 children dying each day from diseases associated with lack of access to safe drinking water, inadequate sanitation and poor hygiene (WSSCC 2004). The UN Millennium Development Goals (MDG) aim to reduce by half the proportion of people without sustainable access to safe drinking water and basic sanitation by the year 2015. Although, some parts of the world are making encouraging progress in meeting these goals, serious disparities remain. Lack of access to improved drinking water is still a serious problem in large portions of Asia where an estimated 675 million people are without improved drinking water sources (UNICEF *et al.* 2004). In Sub-Saharan Africa, only 36% of the population has access to basic sanitation (UNICEF *et al.* 2004). To meet the MDG for sanitation alone implies that sanitation must be provided for approximately 2.1 billion people from 2002 to 2015 when adjusting for population growth. In order to provide toilets for 2.1 billion people over 13 years requires a minimum of 44,300 installations per day for the next 13 years (assuming one toilet for every 10 people). If one assumes that the cost per installation is $100 USD for basic dry sanitation, then the investment required just to install the most basic level of sanitation over the next 13 years is $4.4 million USD per day (UN Millennium Project 2005).

Meeting the MDGs for water and sanitation in the next decade will require substantial economic resources, sustainable technological solutions and courageous political will. We must not only provide "improved" water and "basic" sanitation to those who currently lack these fundamental services, but also to ensure that these services provide:

- safe drinking water,
- adequate quantities of water for health, hygiene, agriculture and development

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- sustainable sanitation approaches to protect health and the environment.

As we move forward to meet this challenge, it is critical that we learn from past mistakes and identify creative new approaches to provide sustainable water and sanitation. This paper will review five major challenges in water and sanitation (water quality in distribution systems, water scarcity, provision of safe, ecological sanitation, sustainable water and sanitation approaches for megacities, and disparities in water and sanitation access) and make recommendations for research and policy.

ISSUES

Water quality in distribution systems

Historically, the provision of piped water directly to the household has been associated with improved hygiene and reduction in disease. However, as standards of living have risen and water infrastructures have aged, there has been growing recognition that water distribution systems are vulnerable to intrusion and contamination and may contribute to endemic and epidemic waterborne disease. Analyses of the data from the waterborne disease outbreak passive surveillance system in the United States indicate that the total number of reported waterborne disease outbreaks has decreased since 1980. This may be due to improved water treatment practices and the Surface Water Treatment Rule which reduced the risk from waterborne protozoa. However, the proportion of waterborne disease outbreaks associated with problems in the distribution systems is increasing (Figure 1). Craun and Calderon (2001) examined causes of reported waterborne outbreaks from 1971 to 1998 and noted that, in community water systems, 30% of 294 outbreaks were associated with distribution system deficiencies, causing an average of 194 illnesses per outbreak. Distribution system contamination was the single most important cause of outbreaks in community water systems over that time period (Craun & Calderon 2001). Contamination from cross-connections and backsiphonage caused 51% of the outbreaks associated with distribution systems. Contamination of water mains and household plumbing problems caused 39% of the outbreaks, and contamination of storage facilities caused the remaining 10% of outbreaks. From 1999 to 2002, there were 18 reported outbreaks in community water systems, and 9 (50%) of these were related to problems in the water distribution system (Lee *et al.* 2002; Blackburn *et al.* 2004) (Figure 1).

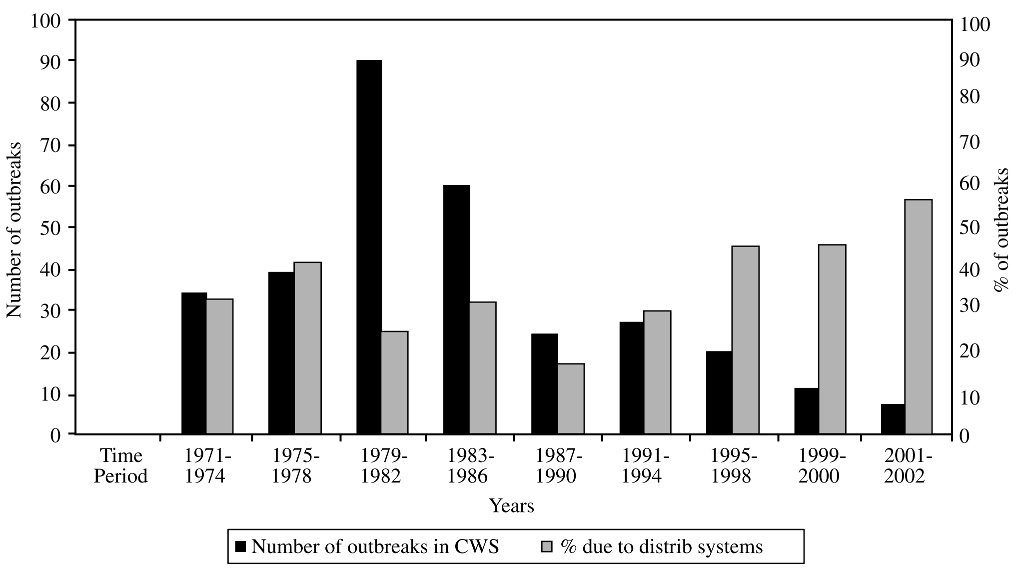

Figure 1 | Reported waterborne disease outbreaks in the United States in community water systems associated with distribution system deficiencies, 1971 – 2002 (Data extracted from Craun and Calderon 2001 and MMWR summary reports on waterborne disease surveillance, Nov 2002 and Oct 2004) (Craun *et al.* 2001; Blackburn *et al.* 2004; Lee *et al.* 2002). Adapted from *Journal AWWA* **93** (9) (September 2001), by permission copyright © 2001, American Water Works Association.

Microbial contamination in parts of the distribution system may also play a role in risks of endemic illness. Studies by Payment *et al.* (1991, 1997) suggest that the distribution system may have contributed to gastrointestinal illness rates observed in study households which drank tapwater compared to study households which drank tapwater, with additional treatment, or bottled water. A recent study conducted in Wales and northwest England between 2001 and 2002 found a very strong association ($p < 0.001$) between self-reported diarrhoea and reported low water pressure at the home tap based on a postal survey of 423 subjects (Hunter *et al.* 2005). Although there has been concern about possible health risks from pressure loss and pathogen intrusion in water distribution systems (LeChevallier *et al.* 2003), this is the first study to provide solid evidence of that risk.

Biofilms in distribution systems may provide a favorable environment for some bacterial pathogens – especially opportunistic pathogens which cause disease primarily in people with weak or immature immune systems. These pathogens can enter the distribution system from faecal contamination and then replicate and colonize parts of the distribution system. Non-enteric pathogens, such as *Legionella*, *Pseudomonas aeruginosa* and *Mycobacterium avium-intracellulari*, can also colonize parts of the distribution system and plumbing systems in buildings and may play a role in waterborne disease. Biofilm in the distribution system may also protect viral and protozoan pathogens from disinfection and allow them to survive longer. Storey and Ashbolt recently demonstrated the accumulation and persistence of model enteric virions in potable water biofilms (Storey *et al.* 2003).

Aging distribution systems may be particularly vulnerable to contamination problems. A recent report by the American Water Works Association (AWWA 2001) and a white paper by the American Water Works Service Company, Inc. (AWWSC 2002) point out that the majority of water distribution system pipes in the United States are reaching the end of their expected lifespan in the next 30 years. Analysis of main breaks at one large mid-western water utility which kept careful records of their management of the distribution system documented a sharp increase in the annual number of main breaks from 1970 (approximately 250 breaks/year) until 1989 (approximately 2200 breaks/year) (AWWSC 2002). There is increasing recognition that the water industry is beginning a new era where it must make substantial investments in pipe repair and pipe replacement. A USEPA report on water infrastructure needs (2002) predicted that transmission and distribution pipe replacement rates need to be around 0.3% per year in 2005 and will rise to 2.0% per year by 2040 in order to adequately maintain the water infrastructure. Cost estimates for drinking water infrastructure replacement range from $4.2 to $6.3 billion per year (AWWSC 2002). Recent investment in water infrastructure in the United States has not been adequate to meet current water demands. It will be an even greater challenge for public and private water utilities to generate the necessary excess revenue to implement these critical pipe replacement programs.

Problems with water quality in the distribution system are especially serious in middle income and developing countries where there are inadequate resources to maintain the distribution system infrastructure and disinfectant residual. Rapid urbanization in developing countries is often accompanied by overwhelming demands on existing water systems and illegal connections to distribution systems in poor neighborhoods. Many systems have cracks and high leakage. In 1991, an international survey of water loss as a percentage of water supplied reported that in industrialized countries water loss ranged from 8% to 24%. However, in middle income or newly industrialized countries, water loss ranged from 15% to 24%, and in developing countries, water loss was estimated at between 25% and 45% (WHO 2001). Frequent power outages contribute to low or negative pressure in the pipes which allows contaminated water or wastewater surrounding the pipes to be drawn in through any cracks. Many of the largest documented waterborne outbreaks in the last two decades have been associated with cross-contamination in the distribution system (e.g. typhoid in Dushanbe, Tajikistan, 1997, cholera in Cape Verde, 1994–1997, Guinea Bissau, 1996 and Trajillo, Peru, 1990) (Renkevich *et al.* 1998).

Water scarcity

Freshwater is a finite global resource. Water is also a basic requirement for the human body. The available quantity of freshwater is linked to human health in several ways: water for ingestion, water for hygiene and water for food production.

Adequate water for ingestion and food preparation is necessary for human health. Estimates of minimum daily water intake range from 1.8 to 5 liters per capita per day (Gleick 1996). However, water consumption increases in warm climates, with physical activity and during pregnancy and lactation. A recent WHO review recommended a minimum of 7.5 liters per capita per day to meet the requirements of most people under most conditions (Howard *et al.* 2003).

Water is necessary for hygiene. The amount of water use varies with distance from the water source and climate. Where people must walk farther than 1 kilometer or spend more than 30 minutes for total water collection time, per capita water use drops to between 5 and 10 liters per day. At this level of service, adequate hygiene is not possible. When there is a household water connection, per capita water use for basic needs rises to between 60 and 100 liters per day or more if used for gardening (Gleick 1996; Howard *et al.* 2003). In 1977, Bradley observed that many "waterborne" diseases are actually "water-washed" diseases due to inadequate quantities of water available for washing hands, food, laundry, and cooking utensils (Bradley 1977). The appropriate intervention to prevent these diseases, such as shigellosis, trachoma and scabies, is to provide more water quantity rather than improve microbiological water quality. This includes providing household connections or closer public standpipes and setting up hand washing stations, and communal bathing and laundry facilities. The classic review of the impact of water, sanitation and hygiene interventions by Esrey *et al.* (1991) observed that water quantity and hygiene interventions were associated with a 20 to 33% median reduction in diarrhoeal disease morbidity (Esrey *et al.* 1991). A more recent review and meta-analysis of the impact of water supply and hygiene interventions concluded that water supply interventions in developing countries were associated with a 24% reduction in diarrheal disease and hygiene interventions were associated with 42% reduction in diarrhea morbidity (Fewtrell *et al.* 2004).

Water is necessary for food production. By far, the greatest global demand on freshwater resources is for agriculture. The International Water Management Institute estimates that over 70% of the world's developed water supplies are used for irrigation (Seckler *et al.* 1998). Recent estimates show that 300 to 3000 liters of water are required to produce one kilogram of grain and that food production for a balanced diet requires 1300 cubic meters of water per person per year (SIWI *et al.* 2004). However, water requirements for food production vary regionally by type of diet and need for irrigation. Gleick estimated the average daily water input to produce a typical diet in California, with high meat consumption and heavy water irrigation needs, to be 5908 liters; in Egypt, with lower meat consumption but considerable water irrigation, to be 3242 liters and in Tunisia, with lower meat consumption and less irrigation, to be 2964 liters (Gleick 1996). This example illustrates the large range in water consumption used for food production. Water for food production is also one area where there is the greatest potential for increased efficiency to maximize the "nutrition per drop" (SIWI *et al.* 2004).

Global water use has risen dramatically in the past 50 years due to population growth and the demands of irrigated agriculture (Figure 2). There is growing recognition that increasing water scarcity threatens agricultural production, human health and political stability in many parts of the world. Current water use rates are not sustainable. There is serious aquifer depletion in China, India, Pakistan, the western United States, North Africa, and the Middle East. Several major rivers in the western United States and in Asia are now completely used during the dry months of year (Postel 2000). For example, in the US, increasing withdrawals from the Colorado River for agricultural and urban uses in seven states and Mexico have resulted in no runoff reaching the river's delta in the Sea of Cortez during most years (Gleick 2003). Now, there is added concern that some western regions in the Colorado River basin may currently be in the grip of a 500-year drought (USGS 2004).

Figure 3 indicates the geographic regions and populations most affected by inadequate freshwater quantity. The magnitude of the water scarcity crisis will have grave consequences on the health and well-being of a large proportion of the world's population. Many water scarce areas in Africa and the Near East have some of the highest population growth rates in the world. The International Water Management Institute (IWMI) projects that 1.8 billion people will live in areas facing physical water

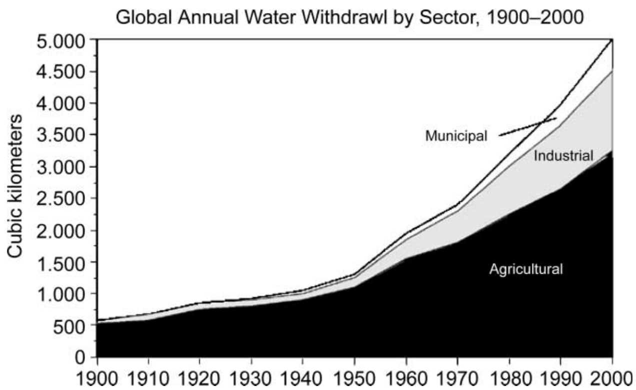

Figure 2 | Global Annual Water Withdrawal by Sector, 1900–2000. From: Hinrichsen *et al.* 1997. (Hinrichsen *et al.* 1997) (Primary Source: Abramovitz 1996).

scarcity by 2025 (Seckler *et al.* 1998). Another estimated 894 million people will live in areas of economic water scarcity by 2025. A study by Hinrichsen et al. predicted that the number of "water-scarce" (defined as areas where annual water supplies are less than 1000 cubic meters per person) and "water-stressed" (defined as areas where annual water supplies drop below 1700 cubic meters per person) countries will grow in the next 50 years from 31 countries with about half a billion people in 1995 to 54 countries with 4 billion people by 2050 (Hinrichsen *et al.* 1997). This will be about 40% of the projected global population in 2050.

A study by the IWMI examined water supply and demand in 118 countries from 1990 to 2025 and classified countries into categories of water scarcity based on estimated percent increase in water withdrawals from 1990 to 2025 and the projected water withdrawals in 2025 as a percent of the "Annual Water Resources" of a country. (Seckler *et al.* 1998). The countries in the most critical category are those with "physical water scarcity", those that will not have enough water in 2025 to maintain 1990 levels of per capita food production from irrigated agriculture as well as meet water needs for industry, household and environment. This category includes 17 countries, mainly in the Middle East and North Africa,

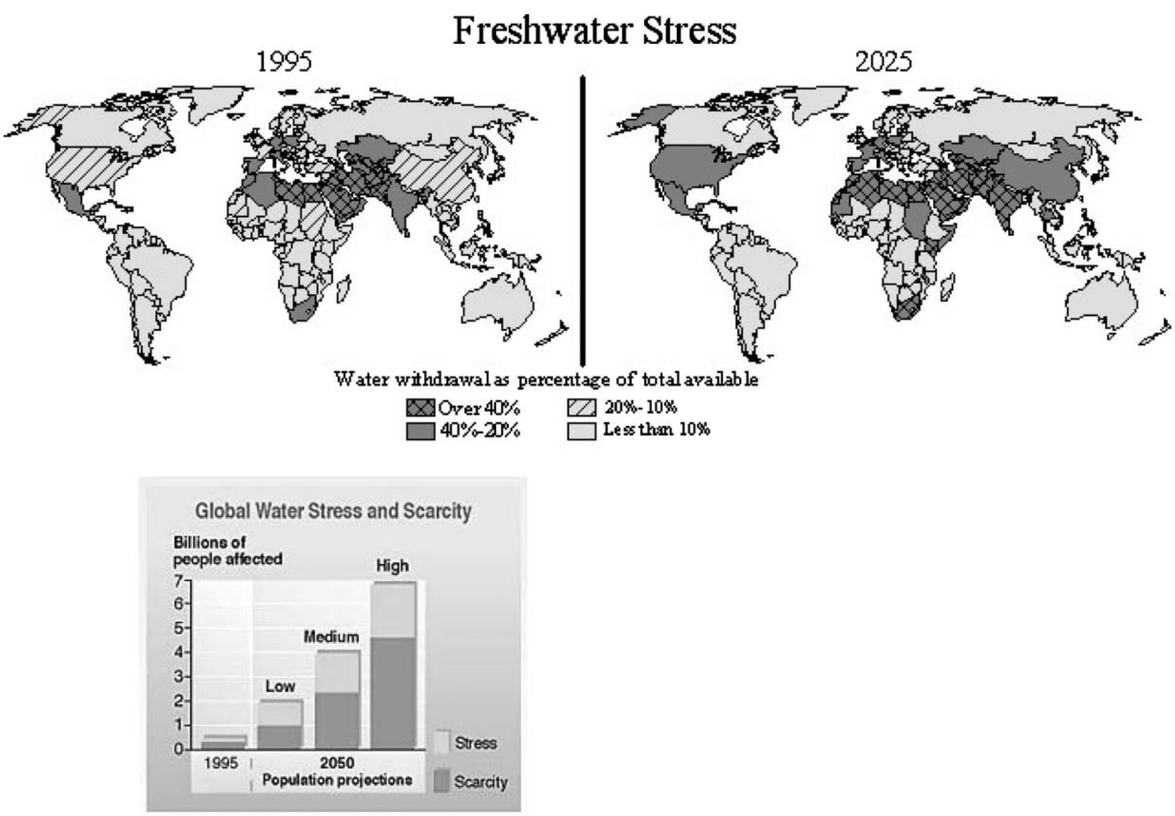

Figure 3 | (a) Predicted freshwater scarcity by geographic region (b) Estimated global population affected by water scarcity and water stress. Adapted from: www.unep.org/vitalwater/21.htm (UNEP 2002).

with about 8% of the world's population. The IWMI predicts that many of these countries will need to divert water from irrigation in order to meet domestic and industrial water needs and consequently will need to import more food (Seckler *et al.* 1998). Large parts of India and China fall into this category, and the capacity of these countries to develop additional water supplies, increase the efficiency of their water use and wisely manage their water resources is seen to be a key determinant of global food security in the 21st century (Seckler *et al.* 1998). Another 24 countries were classified with "economic water scarcity" and theoretically have sufficient water sources to meet their needs. However, these countries will need double their water development projects and do not have the necessary financial resources to do this.

In addition to the impact on human health and food production, water scarcity leads to intense political pressures and instability. In his World Water Day message on March 22, 2002, UN Secretary General Kofi Annan warned that global security depends on solving the water crisis and stated that "Fierce national competition over water resources has prompted fears that water issues contain the seeds of violent conflict" (ENS 2002). How we cope with increasing water shortages and yet maintain sufficient water for health, hygiene, agriculture and industry is a critical challenge for the near future. Different strategies will be needed for the range of climatic, economic and cultural settings affected by water scarcity. Some progress has been made in that total global water withdrawals began to stabilize in the 1970s and 1980s, and in some industrialized countries, water withdrawals have declined due to changes in irrigation practices, water reuse and water conservation (Gleick 2003; Postel 2000).

Irrigation practices

Given the heavy water demand of agriculture, it is obvious that increasing irrigation efficiency and water productivity is a key consideration. The IWMI report on water availability estimated that increased irrigation effectiveness could reduce the need for developing additional water supplies by 50% (Seckler *et al.* 1998). This is especially critical for major grain-producing areas of India and China where furrow and flood irrigation are common. Approaches for reducing water demand for agriculture include increased use of drip irrigation and the development of crop varieties with higher yields and better drought tolerance (Seckler *et al.* 1998; Hinrichsen *et al.* 1997; SIWI *et al.* 2004). The use of urban wastewater for agriculture can also be considered as a strategy to reduce water demand for irrigation and is common practice in Israel, around Mexico City, Accra, Ghana and other areas. This approach benefits from recycling organic nutrients in wastewater but also carries the risk of exposure to microbial pathogens if inadequately treated wastewater is used on produce or fruit which are eaten raw. The WHO has developed microbiological guidelines for wastewater used for agriculture and suggested health protection measures for farmers and consumers. However, the application of these guidelines in field situations in developing countries is often not practical and alternative risk management strategies need to be considered (Drechsel *et al.* 2002). Finally, some parts of the world will need to critically examine their agricultural practices and consider replacing high water consumption crops with those which require less water. The export and import of high water consumption crops is essentially the movement of water between different regions of the world. The consequences of this water movement need to be weighed against trade and other economic considerations.

Water reuse

Increasing water scarcity has led to greater interest in potable and non-potable water reuse in the United States and elsewhere. This is generally defined as the use of highly treated wastewater for irrigation and landscaping (non-potable reuse) or to supplement surface or groundwater sources used as drinking water supplies (potable reuse). In the United States, potable water reuse is currently practiced in parts of California, Arizona, Georgia, Virginia, and Florida. Singapore, a country with serious physical water scarcity, has been implementing indirect potable water reuse since 1998 (NEWater 2005). Direct potable reuse, where highly treated wastewater is sent directly to a water treatment plant, has only been practiced in Windhoek Namibia. The public health implications of using reclaimed water as a component of a potable water supply have been extensively reviewed in a report by the National Research Council (NRC 1998) which concluded that "planned, indirect potable reuse is a viable application of reclaimed water – but only when there is a careful, thorough, project-specific assessment that includes contaminant monitoring, health and safety testing, and system reliability evaluation".

Water conservation

A major area where water conservation needs to be implemented is in the repair of leaking water distribution systems as described in the previous section. Some cities in developing countries lose between 40 and 70% of their water in transit (Hinrichsen *et al.* 1997). Municipal water conservation can reduce water use by the introduction of efficient plumbing fixtures. The use of low flush, dual flush and vacuum flush toilets can provide tremendous water savings compared to conventional flush toilets which account for 20 to 40% per capita water use in industrialized countries. In the United States, the federal Energy Policy Act of 1992 mandated uniform water efficiency standards for almost all toilets, urinals, showerheads and faucets manufactured after January 1994. In addition, many states and local governments in the U.S. require the use of water-efficient products in new constructions and renovations. Other water conservation approaches include rainwater collection systems for toilet flushing and gardening, greywater recycling for gardening, and landscaping in arid and semi-arid regions using native plants with low water needs. Water conservation also extends to industrial water use. Many industries are water-intensive. Yet, in some industrialized countries, industrial water use is declining as new production processes find ways to reduce water use by recycling water and improving water productivity (Gleick 2003; Hinrichsen *et al.* 1997).

Implementing innovative, low-cost sanitation approaches

Water quality and sanitation are irrevocably intertwined. Poor sanitation leads to water contamination. In many parts of the world, the main source of water contamination is due to sewage and human waste. UNICEF *et al.* (2004) estimates that 1 billion urban dwellers and 900 million people in rural populations must be provided with sanitation in order to reach the MDG for sanitation in 2015 (UNICEF *et al.* 2004). Creative new approaches are desperately needed to address this basic requirement. Dry sanitation is an attractive option for many parts of the world, because of the water scarcity concerns discussed above, and the tremendous infrastructure needs and costs associated with waterborne sewerage and wastewater treatment. Ecological sanitation (EcoSan) is both a new and old concept and is based on four main principles:

(1) Conservation of water
(2) Containment of human excreta to prevent environmental contamination and disease transmission
(3) Treatment of human excreta to inactivate microbial pathogens
(4) Recycling nutrients from human excreta (faeces and urine) for agriculture to promote better crop production, home gardens and ultimately improved nutrition.

In many parts of Asia, human excreta has been used as a fertilizer for centuries. Composting toilets were introduced in Sweden during the 1940s for use in summer homes (Winblad *et al.* 2004). In the 1970s and1980s this concept was introduced to parts of Latin America and Africa in various designs (Winblad *et al.* 2004). The two main designs for EcoSan toilets are: a double vault design based on a traditional Vietnamese design (Figure 4), and a solar single or multiple vault design (Figure 5). The primary concept behind these designs is that the excreta is stored and treated for months or years while the organic matter decomposes and the microbial pathogens die-off. Then the vault can be safely emptied and reused. With the typical double vault or multiple vault design, one vault is used for a period of months or years until it is full. The first vault is then sealed, the toilet seat is moved above the other vault, and excreta is collected in the second vault until it is full. At this time, the first vault is opened and emptied. The stored excreta may be used for fertilizer or soil conditioner or may be buried.

EcoSan toilets have advantages as sanitation options in urban and peri-urban areas because they are permanent structures which can be attached to the house. Unlike pit latrines which must be covered once they become filled and

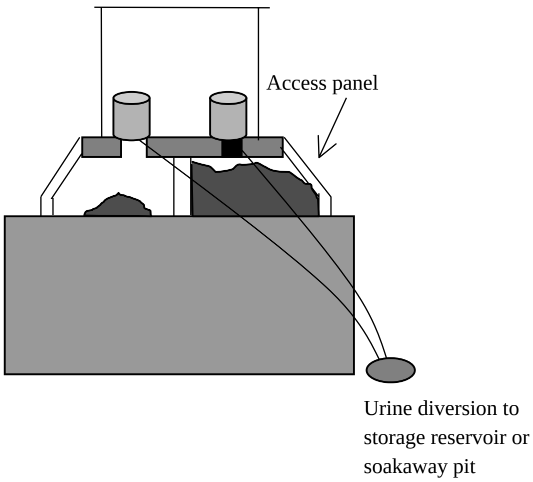

Figure 4 | Schematic diagram of a double vault, urine-diverting toilet.

another pit dug in a different location, EcoSan toilets can be used indefinitely if they are well maintained. The reduced or absence of odors associated with EcoSan toilets make them acceptable as a sanitation option which can be incorporated within the house structure. EcoSan toilets are also a good sanitation option for areas with shallow bedrock or high water tables where pit latrines cannot be installed.

Some EcoSan designs are composting toilets where, if the appropriate balance of carbon, nitrogen and moisture is maintained, then high temperatures due to thermophilic microbial activity are achieved in the core of the excreta pile. The high temperatures promote more rapid die-off of pathogenic microorganisms. Carbon may be added in the form of sawdust and organic household and garden waste. Some composting systems also add soil or ash. Most EcoSan toilets, however, use a desiccating approach which incorporates urine diversion to a separate collection tank or soakaway pit in order to keep the storage vault drier, reduce the volume of material added to the vault and reduce odor. Urine diversion is also an important part of the nutrient recycling goal of EcoSan designs. Urine contains about 80% of the nutrients (nitrogen, phosphorus and potassium) excreted by humans and therefore has greater fertilizer value than faeces. Urine is also far less likely to contain microbial pathogens, hence the health risks associated with using urine for agriculture are much less than those associated with faeces.

The main challenge of using ecological sanitation is achieving effective pathogen destruction in order that

Figure 5 | Photographs of a double vault solar toilet in rural El Salvador.

neither handling of stored excreta when emptying the vault nor the use of stored excreta for agriculture results in the transmission of infectious agents. Guidelines for the safe use of urine and faeces in EcoSan systems have recently been published (Schonning *et al.* 2004). In desiccating EcoSan toilets, pathogen die-off is due to high pH, low moisture and high temperatures. Daily operation and maintenance of desiccating EcoSan toilets requires the regular addition of lime or ash to the vault to raise the pH to 10 or higher. Solar EcoSan toilets, when properly built and positioned, can achieve temperatures in the vault of up to 44°C which promote more rapid microbial die-off (Moe *et al.* 2003). In a field study of 156 EcoSan toilets in El Salvador, we demonstrated that the primary factors affecting microbial die-off in double-vault urine diverting toilets were high pH (>11) and length of storage time (Moe *et al.* 2003). In solar toilets, high peak temperature (>36°C) and high pH were the primary factors affecting microbial die-off. Survival and transmission of *Ascaris* is a key consideration when evaluating the safety of stored excreta for agricultural use because *Ascaris* ova are extremely hardy and persistent in the environment. Our studies of solar EcoSan toilets in El Salvador indicated that high peak temperatures were effective in destroying *Ascaris* ova.

There is increasing evidence of the agricultural benefits of EcoSan for small-scale agriculture. During storage, the excreta gradually transforms into "humus" or "biosolids" which can add nutrients, organic matter and moisture-retaining capacity to soil. There is evidence that plants grown in soils enriched with humus require less watering and survive drought better than plants grown in soil without humus (Winblad *et al.* 2004). Recent agricultural studies of the use of urine as fertilizer for several different vegetables and grains in Zimbabwe, Sweden and Ethiopia indicate increased crop yields ranging from two- to six-fold compared to crops irrigated only with water (Winblad *et al.* 2004).

The nutritional benefits and health impact from EcoSan have not been systematically evaluated or quantified. One pilot study in El Salvador indicated that households which used double vault, urine-diverting toilets or solar toilets had a lower prevalence of hookworm, *Giardia* and *Entamoeba histolytica* infections than households with pit latrines or no sanitation. In addition, households with solar toilets had lower prevalence of *Ascaris* and *Trichuris* infections compared to households with pit latrines, double vault urine diverting non-solar toilets, or no sanitation (Corrales *et al.* 2003).

Sustainable water supplies and sanitation for megacities

Perhaps one of the most daunting challenges facing the water and sanitation sector is the provision of services to megacities, commonly defined as cities with >10 million people. Currently, there are 20 megacities worldwide (UN Department of Economic and Social Affairs 2004). However, population projections for the next two decades, indicate that 25% of the world's population will be concentrated in between 22 and 27 megacities by 2015 (Figure 6) (Elgendy 2002; UN Department of Economic and Social Affairs 2004). Most of these megacities will be located in developing countries in Asia. There are several important differences between early megacities and new megacities. Cities like London and New York grew gradually, over a century, in industrialized countries with growing economies. These cities had the economic and human resources to expand their water and sanitation services. However, new megacities in the developing world have explosive growth and are unable to build the necessary infrastructure to keep pace with population growth. Between 1975 and 2000, New York City grew at an average annual rate of 0.47%. In contrast, during this same period, Lagos, Nigeria and Dhaka, Bangladesh grew at an average annual rate of over 6% per year (Elgendy 2002; UN Department of Economic and Social Affairs 2004). Additionally, most of the new megacities are in developing countries with poor economies which cannot support the timely construction or maintenance of water and sanitation services.

Although urbanization potentially offers economies of scale for water supply and sanitation systems, much of the recent growth in megacities is in slum and squatter settlements which are particularly challenging to service. High percentages of populations in large cities in developing countries currently do not have access to safe water or wastewater collection, and it is not clear whether technological solutions or financial resources are available to address this problem. The following two examples

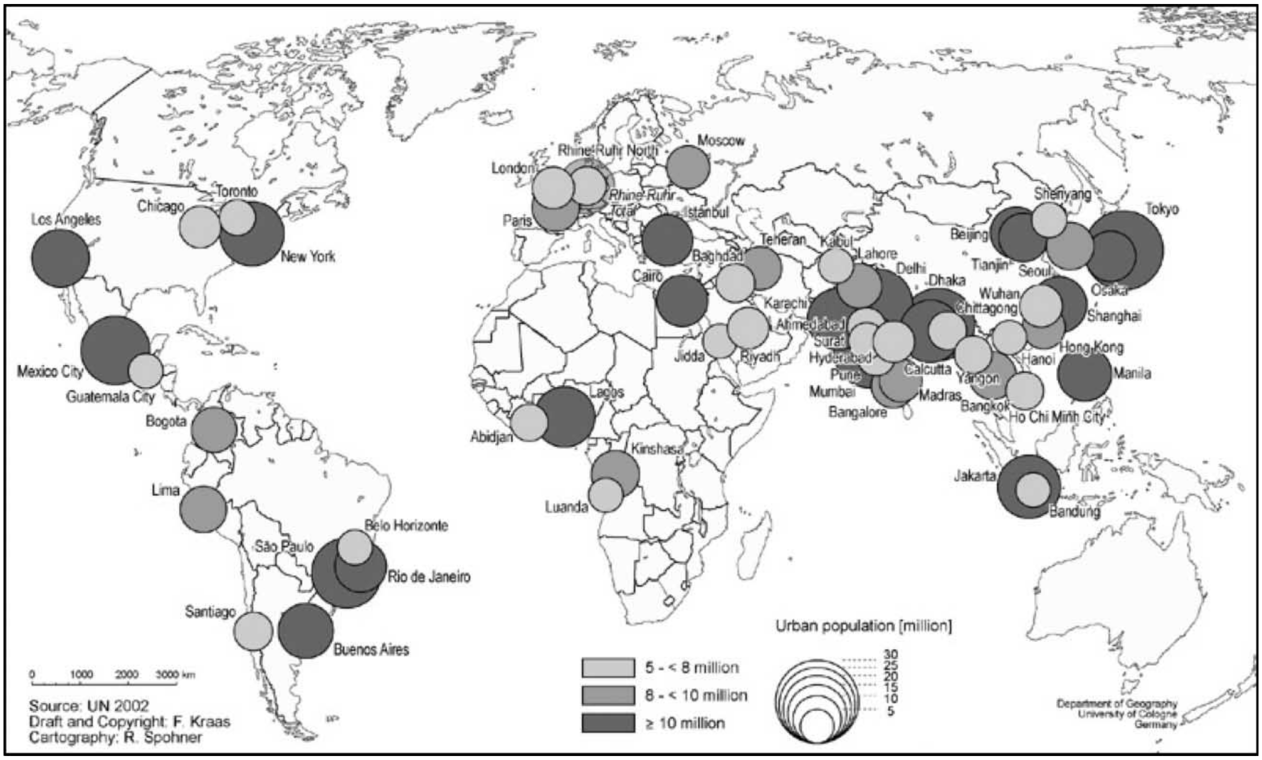

Figure 6 | Locations of current and projected megacities in 2015 From: http://www.megacities.uni-koeln.de/documentation/megacity/maps.htm.

illustrate water and sanitation problems common in megacities in developing countries. In Jakarta, Indonesia (population 12.3 million) only 2.6% of the population is served by existing sewerage systems (Pollard 2004). Jakarta currently produces about 1.3 million cubic meters of sewage each day, and this is expected to grow to 2.5 million cubic meters per day by 2010. Currently, there are three sewage treatment plants which handle only 40,000 cubic meters per day. There are an estimated 1 million septic tanks in the city. Uncontrolled and unregulated development of on-site sanitation is a problem. There is high willingness to pay for removal of sewage from homes but low willingness to pay for sewage treatment and low political will to invest in sanitation. In Lagos, Nigeria (population 12 million), the public water supply covers only about 35% of the metropolitan population and more than 60% of the water produced is lost through leaks and illegal connections. The other 65% of the population rely on private wells, boreholes and water vendors. Lagos has no central wastewater collection system. About 30% of households use pit latrines and 53% of households use flush or pour-flush toilets. Less than 12% of households have a working water-borne sanitation system. All wastewater eventually ends up in the storm water drainage system and the Lagos lagoon (World Bank 2000).

There is growing concern about how to deal with the water and sanitation crisis in megacities like Jakarta and Lagos. The 2004 World Water Week symposium in Stockholm convened special seminars on water management in megacities and sustainable sanitation. However, there is little published information recording which systems and strategies have been successful for the water supply and sanitation challenges in megacities. One report from the Water Science and Technology Board of the National Research Council reviewed water and sanitation services for megacities in the developing world and concluded that there is a need for more flexible, adaptable and affordable technology choices for megacities, especially for providing service to informal settlements in metropolitan areas (NRC 1996). The report also recommended that conservation of water be a priority for all megacities and could be encouraged by appropriate pricing and metering of users.

Disparities in water and sanitation access

Levels of inequity in access to safe water and sanitation

Inequitable access to water and sanitation is the product of disparities in fresh water resources, income, power and institutional capacity between and within countries. The global burden of poor access to safe water and sanitation falls primarily on the poorest of the poor. Estimated coverage of improved water and sanitation is 79% and 49% respectively in the low and middle-income countries, compared to 98% for both in high-income countries (UNICEF *et al.* 2004). A similar pattern exists within individual developing countries, where coverage differs based on geography and household characteristics. In developing countries, urban households are 30% more likely to have an improved water source and 135% more likely to have improved sanitation facilities, compared to rural households (UNICEF *et al.* 2004). At the household level, UNICEF estimates that households in the lowest wealth quintile are 5.5 times more likely to lack improved water access and 3.3 times more likely to lack adequate sanitation, compared with households in the highest wealth quintile in the same country (based on Demographic and Health Surveys in 20 developing countries). Blakely and colleagues estimated the lack of access to water and sanitation by household income level in countries in medium and low-income regions (Blakely *et al.* 2005). They concluded that households earning less than US $1 per day are almost nine times more likely to lack improved water or sanitation, in comparison to those earning more than US $2 per day. Within households, the burden of poor access falls disproportionately on women and children, who are responsible for the majority of water collection, and children, who are most affected by the related health burden.

Equity and the millennium development goals

Reaching the MDG would require providing water for 1.6 billion people and sanitation for 2.1 billion between 2002 and 2015, primarily among poor households in the world's poorest countries (UN Millennium Project 2005). However, even if we reach the MDG for water and sanitation, over 10% of the world's population will still rely on unimproved water sources and 25% will lack access to basic sanitation (UNICEF *et al.* 2004). These people are likely to have less available fresh water resources, less community and household financial resources, less access to government and NGO institutions. What can be done to ensure that the poorest of the poor are not passed over by these improvements? At a minimum, universal access to affordable household water treatment and safe storage of water can be provided for those still relying on existing unimproved sources. While this is not a long-term solution, it could provide essential protection to households which do not have access to improved water from piped systems or wells. With respect to sanitation, well-maintained, shared facilities can be provided in key settings such as schools, which would promote awareness and demand for improved sanitation among young people as well as promoting school attendance for girls. In addition, goals should be established for ensuring equity in improved access, and these goals should be monitored to determine whether they are being met.

Financial sustainability and equity

Reducing the disparities in access to water and sanitation is also complicated by the need to improve the financial sustainability of providing services. The two principles of equity and financial sustainability are potentially at odds with one another. The long-term viability of public water and sanitation services requires user fees and inputs from beneficiaries. These are essential to ensure that services are adequately valued, maintenance is provided, overuse of scarce resources is avoided, and limited external resources can be stretched as much as practical. This often takes the form of water fees or contributions of time and money to the initial project establishment. At the same time, these fees can be obstacles to the poorest communities and households, resulting in inequitable benefits. Historically, this has led to subsidized water tariffs which are unsustainable and limit the incentives for providers to extend services to lower income areas (Olmstead 2003). The heart of the problem lies in the dual nature of water as a human right and a scarce natural resource, the management of which entails costs. Water is a human necessity, but it cannot be provided in an unlimited fashion.

Several steps can be taken to reduce this potential dilemma. Firstly, a range of lower cost technologies should be available to allow households and communities to choose their level of service and cost. In particular, this includes those technologies with low start up costs for individuals, such as point-of-use water treatment (Hutton *et al.* 2004). Secondly, for larger community water systems, water tariff structures can be adjusted to ensure basic needs, while discouraging overuse through block tariff pricing which subsidizes initial water allotments and raises rates as household consumption rises (Olmstead 2003). Thirdly, parallel social investments must be made alongside water and sanitation investments to ensure that communities and households benefit from reduced water collection time associated with improved access. A WHO cost-benefit analysis estimated that freeing up productive time because of reduced water collection distances can more than offset the costs of installing water and sanitation improvements (Hutton *et al.* 2004). However, in order to truly generate this financial sustainability, there must be productive opportunities for using the newly available time (whether in education or income generation). Last, creative financing mechanisms (such as micro-loan programs) must be established to allow the lowest income communities to invest in water and sanitation improvements.

BARRIERS TO PROGRESS

Although there are many country-specific barriers to progress in water and sanitation access, the four universal barriers are: (1) inadequate investment in water and sanitation infrastructures, (2) lack of political will to tackle the tough problems in this area, (3) the tendency to avoid new technological or implementation approaches and apply conventional water and sanitation interventions, without community involvement, over and over again even when they are inappropriate for the specific environment and community needs, and finally (4) failure to conduct evaluations of water and sanitation interventions to determine whether they are successful and sustainable.

In recent years, international investments in water and sanitation have been declining despite growing awareness of water issues. Official development assistance for water supply and sanitation projects from countries of the Organization for Economic Cooperation and Development and the major international financial institutions has dropped from $3.4 billion per year (average between 1996 and 1998) to $3.0 billion per year (average between 1999 and 2001) (Gleick 2003). Furthermore, Gleick points out that about half of this water-related aid goes to ten countries, whereas only 12% of this aid goes to the countries where a high proportion of the population has no access to improved water supplies (Gleick 2003). This observation suggests that water aid is used more as a political tool than as a means to reduce disparities in access.

Greater political will is needed at all levels, from international to community, to dedicate the necessary resources for safe water and sanitation - from rebuilding aging water infrastructure in industrialized and middle-income countries to providing water and sanitation to the poorest of the poor in developing countries. Political will is also needed to institute and enforce policies which promote water conservation, safe water reuse, equitable water sharing and sustainable development of megacities.

Another barrier related to political will is a general lack of consumer awareness of the health hazards associated with poor water quality and inadequate sanitation. Consumers in both industrialized and developing countries are generally not well-informed about the impact of water and sanitation on health or potential water and sanitation choices. Consumers may be more likely to value water taste and convenience or the perceived status of a flush toilet over health and sustainability concerns. We need to educate consumers not only about water and sanitation-related health risks, but also about the range of choices for providing safe water and sanitation and the costs associated with these choices. Greater demand for safe water and sanitation by well-informed consumers will force politicians and industry working in the water and sanitation sectors to respond to this demand with appropriate and affordable products and solutions. Cairncross has advocated a marketing approach for sanitation so that "people choose to receive what they want and are willing to pay for" (Cairncross 2003; Cairncross 2004). Recent surveys in the Philippines and Benin revealed that some of the top consumer reasons for wanting improved sanitation were related to convenience, comfort, privacy, safety for women and girls, less embarrassment with visitors, dignity and social status rather than health considerations. Successful sanitation intervention programs need to recognize and respond to these priorities. Marketing sanitation products which respond to consumer needs and offer choice will result in more successful interventions than subsidized programs which install a single, “one size fits all” solution.

Finally, we must learn from the mistakes of the past. The globe is littered with failed water and sanitation projects supported by well-intentioned but ill-informed non-governmental agencies or by foreign governments who link financial aid to specific multi-national engineering firms who install unsustainable conventional water or wastewater treatment plants. There are many examples of broken water pumps where necessary parts for repair can not be obtained in the country, gasoline powered pumps in areas where the cost of gasoline is prohibitive, flush toilets that discharge into cesspools in the back yard, and composting latrines used as chicken coops. As we enter the new International Decade for Action: Water for Life 2005–2015, (WHO 2005) it is critical that we conduct evaluations of water and sanitation interventions and collect the necessary information for making good investments and wise policy decisions in water and sanitation. The recommendations below identify critical knowledge gaps and suggest research to address these problems. We cannot afford to continue making costly mistakes in the water and sanitation sector when between 4000 and 6000 children die each day from water and sanitation-related diseases. Further research and evaluation of the water and sanitation challenges discussed here are needed to inform consumers and politicians about the health and economic impacts of the current water and sanitation crises and potential solutions.

KNOWLEDGE GAPS, RESEARCH QUESTIONS AND RESEARCH RECOMMENDATIONS

Water quality in distribution systems

There are many research needs in the area of water quality in distribution systems. These can be classified into three general areas:

Maintaining water quality in distribution systems

Water distribution systems have been associated with both epidemic and endemic waterborne disease. There are many factors which affect water quality in distribution systems. We need to improve our understanding of the various roles of these factors and how to effectively control them. Pressure loss appears to introduce microbial contamination into water distribution systems and results in increased diarrhoeal disease (Hunter *et al.* 2005). Storey and Asbolt have demonstrated pathogens embedded in biofilms (Storey *et al.* 2003), and research by Payment suggests that residual chlorine disinfectant in distribution systems is not effective protection against pathogens in distribution systems (Payment 1999). Many distribution systems include areas where the pipes are nearing the end of their expected lifetime, and aging distribution systems appear to be more vulnerable to main breaks. Given these observations, the following research questions need to be addressed:

- What factors introduce pathogens and favor persistence/multiplication of pathogens in water distribution systems?
- What are effective strategies to prevent pressure loss in water distribution systems?
- How can we effectively inactivate pathogens entering the distribution system?
- How do alternative pipe materials affect the development of biofilms? What is the impact of distribution system flushing programs on biofilms and water quality?
- What are effective strategies for water utilities to identify and prioritize pipe replacement needs in order to maximize public health protection?
- What are effective pricing strategies to cover pipe replacement costs and how can this be marketed to the public?

Monitoring water quality in distribution systems

The U.S. Environmental Protection Agency is currently revising the Total Coliform Rule which addresses monitoring water quality within the distribution system. This revision has raised questions about the value of total coliforms as indicators of distribution system water quality and the need to identify better ways to monitor and predict distribution system water quality.

- What are effective indicators of water quality in distribution systems?

- Can we predict vulnerable areas of the distribution system by looking at areas of low pressure, pressure loss events, long residence time, dead end pipes, history of main breaks, pipe age and pipe material?
- How can epidemiologic studies examine the health effects associated with distribution system water quality and how can we use these studies to identify risk factors and effective indicators of water quality in distribution systems?

Water quality in the distribution system vs. home water treatment

For some cities and countries, it may be more feasible to maintain medium quality, "economic water" ("e-water") in the distribution system for most household water needs and practice home treatment of small volumes used for drinking. A study of household water chlorination in Nukus, Uzbekistan reported that 38% of households received piped water with no detectable levels of chlorine, and people in houses without a chlorine residual in their piped water experienced 60% more cases of diarrhoea than did those with a chlorine residual in their piped water (Semenza *et al.* 1998). Further research is needed to define under what conditions home water treatment is sustainable, economically feasible and has a positive health impact.

- Should middle and low-income countries focus on maintaining high quality water in the distribution system or should resources be focused on providing high quality water in the home by point-of-use treatment of drinking water?
- What are the economic costs and benefits of providing e-water in the distribution system and point-of-use treatment for drinking water?
- What are the health costs and benefits of providing e-water in the distribution system and point-of-use treatment for drinking water?

Water scarcity and health

Facing the challenge of water scarcity requires research in three main areas: improving efficiency of agricultural, industrial and domestic water use; developing technology for implementing and monitoring safe water reuse and developing technologies and economic policies to promote effective water conservation. Epidemiologic studies of the possible health risks associated with potable water reuse and the use of wastewater for agriculture are clearly needed in order to better understand how to protect public health, as these practices become more widespread. Additional research needs include:

- What are low-cost technologies for improving irrigation efficiency that are suitable for low-income countries?
- How can we effectively reduce the risks from wastewater irrigation for farmers and consumers in low-income countries?
- What technologies provide the most rigorous and reliable treatment for wastewater used to augment drinking water supplies?
- What monitoring strategies are most effective for microbial pathogens and chemical contaminants found or likely to be found in treated wastewater used to augment drinking water supplies?
- What economic policies are most effective in promoting water conservation in municipal and industrial settings?
- What economic policies are most effective in promoting the development and use of water-saving devices in homes and public buildings?
- What are effective approaches for promoting equitable multi-national water use and reducing political tensions associated with water scarcity?

Implementation of safe, ecological sanitation

Toilets based on ecological sanitation principles can be a sustainable, low-cost sanitation option for a variety of settings. However, further evaluation is needed for many aspects of this approach.

- How can EcoSan toilets be designed in order to maximize microbial die-off?
- How do household use and maintenance practices for EcoSan toilets affect microbial die-off?
- How does climate affect microbial die-off in EcoSan toilets?
- How do high pH conditions affect the fertilizer value of biosolids from EcoSan toilets?

- What is the health impact of different EcoSan toilets in various cultural and climate settings?
- What is the impact of EcoSan toilets on the quality of life of women and girls?
- What is the impact of EcoSan toilets on nutrition in communities where the biosolids and urine are used as fertilizer for household gardens?
- What factors determine the social acceptance of EcoSan toilets and how can EcoSan toilets be designed to maximize their acceptability and use by different populations?
- What are effective approaches for marketing dry sanitation in low-income and middle-income countries?

Sustainable water supplies and sanitation for megacities

Currently, there appears to be very little research on sustainable approaches to provide safe water and sanitation for megacities. The 1996 report from the National Research Council describes several World Bank projects which attempt to provide water and sewerage in slum areas of large cities (NRC 1996). Clearly, there is a critical need for further innovation, implementation and evaluation in this area. A useful starting point would be pilot studies of small to mid-sized decentralized water and sanitation systems which use affordable technology, can be installed and maintained on a neighborhood level and provide the flexibility needed for informal settlements in large urban areas.

Disparities in water and sanitation access

A combination of research and evaluation information is essential to improve access, affordability and sustainability of water and sanitation improvements for the poorest households. Systematic and standardized country-level monitoring data is needed to understand existing disparities and measure progress to reduce it. The evaluation of progress in meeting the MDG for improving access should be complemented by explicit monitoring of whether those improvements are reaching the poorest of the poor.

Additional research is needed to design and evaluate low cost water and sanitation technologies, such as point-of -use water treatment and ecological sanitation. Low cost technologies are not always optimal solutions for all households, but they provide opportunities for progress - particularly for the poorest of the poor.

In addition to improving technologies, there is a need to improve the strategies for disseminating them. While many improvements in access will continue to come through centralized community level projects, innovative marketing approaches (such as social marketing) provide an opportunity for dissemination of household-level water treatment, water storage, and sanitation solutions. Continued applied research is needed to identify specific market-based approaches that are more successful in reaching the poorest households.

Lastly, applied research is needed to identify and improve strategies to increase affordability of household investments in water and sanitation improvements, through cost sharing strategies, microfinancing, and savings arrangements. These have been used to increase access to other health services and can be useful in reducing financial barriers to water and sanitation access.

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